

# Chapter 27

---

## *Development of Binaural and Spatial Hearing in Infants and Children*

**Ruth Y. Litovsky**

*Boston University and Eaton Peabody Laboratory,  
Massachusetts Eye and Ear Infirmary,  
Boston, Massachusetts*

**Daniel H. Ashmead**

*Vanderbilt University Medical Center, Nashville, Tennessee*

(Received February 1994; revised January 1995)

Auditory localization is a fundamental ability enabling animals to find the sources of environmental sounds. It is only since the early 1980s that auditory development has been studied systematically. In the present chapter we review recent trends in research on development of auditory localization in humans. The primary focus is on three specific issues. First, we discuss sensitivity to interaural sound localization cues. Recent work has shown that sensitivity to interaural cues is well developed during early infancy, in contrast to sound localization in free field, which matures relatively slowly. The implications of this discrepancy are discussed. Second, recent studies, which have utilized infants' reaching behavior in the dark to measure distance perception, have shown that infants are capable of discriminating distance by 6 months of age. We discuss which cues may be relevant to infants for this task. Finally, developmental changes in the precedence effect (a sound localization phenomenon related to suppression of echoes) are reviewed. The precedence effect develops slowly during infancy and childhood, and to the extent that it may reflect integrity of central auditory processing, it may be useful for detection of auditory deficits. A general theme evident in this review is that developmental work, like work with adults and lab animals, shows sound localization to be very much an active, constructive process on the part of the listener.

### INTRODUCTION

Auditory localization is a fundamental ability enabling animals to find the sources of environmental sounds. Although visual development in humans and other species has been intensively studied for several decades, the development of

hearing, especially spatial hearing, has received attention only since about 1980. Convincing demonstrations that infants orient their eyes (Crassini and Broerse, 1980) and head (Muir and Field, 1979) toward sound as soon as they are born led to a considerable amount of research on the development of hearing, including sound localization in infants and young children. Much of this research, especially with newborns, was reviewed by Clifton (1992). In the present chapter we briefly review recent trends in this research and then focus primarily on work reported during the past five years or so, concentrating on three specific issues: sensitivity to interaural sound localization cues, auditory distance perception, and the precedence effect (a sound localization phenomenon related to suppression of echoes). A general theme evident in this review is that developmental work, like work with adults and lab animals, shows sound localization to be very much an active, constructive process on the part of the listener.

## I. OVERVIEW OF DEVELOPMENTAL TRENDS

Perhaps the most obvious and compelling sign that someone can localize a sound is that they shift their gaze toward its source. Measures of head and eye turning toward sound sources have figured prominently in studies of the development of sound localization. The first experimental demonstration that newborn infants look toward sound sources was Wertheimer's (1961) brief report. Although newborn sound localization had been included in standardized neonatal assessment scales (Brazelton, 1973), several attempts at demonstrating this ability experimentally showed mixed results (Butterworth and Castillo, 1976; McGurk, Turnure, and Creighton, 1977). Muir and Field (1979) showed convincingly that newborns turn their heads toward the hemifield containing a sound source, a finding that was soon confirmed by Clifton, Morrongiello, Kulig, and Dowd (1981). Although reliable, this orienting response was not extremely robust, for it occurred on only half the trials (with no response at all on most other trials), and its latency was typically around 8 s. Several reviews of these findings are available (Clarkson, 1992; Clifton, 1992; Muir, 1982, 1985; Muir and Clifton, 1985).

Although newborns do orient toward sound sources, the development of sound localization is far from complete at that age. Both the newborns' posture and state are important factors in their tendency to orient to sounds. In addition, stimulus characteristics are important; for example, newborns do not orient toward brief, transient sounds (see Clarkson, 1992), and conspecific stimuli are especially effective in eliciting a response in many species, including kittens (Olmstead and Villablanca, 1980), puppy dogs (Ashmead, Clifton, and Reese, 1986), guinea pigs (Clements and Kelly, 1978), chicks (Gottlieb, 1981), and humans (Zelazo, Brody, and Chaika, 1984). But the apparent immaturity of newborns' sound localization is most dramatically illustrated by the nonmonotonic developmental trend of head orienting toward sound sources. The head orienting response is reliably elicited from the newborn period up to about 1 month, but then it "disappears" from about 1 to 3 months, reappearing at approximately 4 months (Field, Muir, Pilon, Sinclair, and Dodwell, 1980; Muir, Clifton, and Clarkson, 1989), at which time

the latency of 4-month-olds' head turns toward sounds is about a second or less, much more brisk than that of newborns. Although several explanations for this "U-shaped" developmental function have been offered (including the onset of habituation and visual competition; Muir, 1985; Muir *et al.*, 1989), the most widely accepted hypothesis focuses on maturation of central (cortical) mechanisms (Muir and Clifton, 1985). According to this theory, the newborn head-orienting response is one of the neonatal subcortically mediated reflexes and is suppressed by about 1 month. It is assumed to be replaced by "higher" cortical mechanisms for sound localization, which are more volitional and less reflexive in nature. This interpretation implies that the starting point for experimental analysis of "mature" sound localization begins at around 4 months after birth. Further evidence supporting this interpretation is that at about 4 months infants first localize precedence-effect sounds (described in Sec. II.C) in an adult-like manner. Also, starting at 4–5 months of age, head turning can be used as an operant response in discrimination learning paradigms for studying auditory development. The most commonly used technique was first described by Moore, Thompson, and Thompson (1975), known as visual reinforcement audiometry. Infants are trained to turn their heads in response to an auditory stimulus and are reinforced with attractive mechanically activated toys.

A common method used to study sound localization in infants is the minimum audible angle task, which measures the smallest change in the position of a sound that can be reliably detected. The task involves a reliably correct two-alternative discrimination (usually right vs. left), where the infant's response is scored by an adult observer who watches the infant and is blind to the actual position of the sound sources. For the horizontal dimension, or azimuth, the minimum audible angle is about 1° in adults (e.g., Mills, 1958; Perrott, Marlborough, Merrill, and Strybel, 1989), and this level of precision has also recently been reported for 5-year-old children (Litovsky, 1996). During infancy, there is a dramatic change in the horizontal minimum audible angle (see Table 1 for a summary), from about 20° to 25° at 4 months to less than 5° at 18 to 24 months (Ashmead, Clifton, and Perris, 1987; Ashmead, Davis, Whalen, and Odom, 1991; Litovsky, 1996; Morrongiello, 1988a; Morrongiello and Rocca, 1990). Thus, even after "mature" sound localization emerges at about 4 months after birth, there is a protracted developmental period during which precision of localization improves. This led us to speculate on whether developmental changes in sensitivity to binaural cues for sound localization are involved, as well as on a need for perceptual calibration of the cues. These issues are particularly interesting when we consider that during this period infants' heads grow rapidly, so that the correspondence between binaural cue values and sound directions changes (Ashmead *et al.*, 1991; Clifton, Gwiazda, Bauer, Clarkson, and Held, 1988). We discuss these issues in Sec. II.A.

Finally, although the minimum audible angle identifies the limits of auditory spatial acuity, it is not very instructive regarding the development of localization accuracy, by which we mean knowing precisely where a sound is coming from. Little work has been done on the accuracy of sound localization by infants or young children, primarily due to behavioral measurement problems. Infants cannot be instructed to indicate where they perceive a sound source to be, so we

TABLE 1: Developmental trend in minimum audible angle (MAA) thresholds.

Age	MAA	Study
5 months	19.8°	Ashmead <i>et al.</i> (1991)
6 months	12.0°	Morrongiello (1988a)
	14.5°	Ashmead <i>et al.</i> (1991)
	19.0°	Ashmead <i>et al.</i> (1987)
	12.0°	Morrongiello (1988a)
9 months	12.0°	Morrongiello (1988a)
12 months	8.0°	Morrongiello (1988a)
	9.4°	Ashmead <i>et al.</i> (1991)
15 months	6.0°	Morrongiello (1988a)
18 months	4.0°	Morrongiello (1988a)
	5.6°	Litovsky (1996)
5 years	1.5°	Litovsky (1996)
Adult	1–2°	Mills (1958)
		Perrott <i>et al.</i> (1989)
		Hartmann and Rakerd (1989)
		Litovsky and Macmillan (1994)
	< 1°	

must rely on easily elicited behaviors. An obvious candidate is accurate head orientation, or pointing toward a sound source. Morrongiello and Rocca (1987) used this task and reported that accuracy improved across the age range of 6 to 18 months. However, this measure relies on a motor system, which is undergoing its own set of changes, and there are measurement problems such as uncertainty about when during a trial to assume that the infant has “decided” where the sound source is. For these reasons, we think head turning is better suited as a measure in discrimination tasks than as a graded response showing localization accuracy. Another candidate measure for investigating localization accuracy is reaching, which is inherently a spatially goal-directed behavior. This measure is discussed later under the topic of auditory distance perception.

II. SELECTED ISSUES IN THE DEVELOPMENT OF BINAURAL HEARING

In this section we review in more detail three topics that have been extensively studied in recent years.

A. Sensitivity to interaural sound localization cues

As was noted earlier, the precision of sound localization as measured by the minimum audible angle improves dramatically during infancy. Infants around 4 months old do not discriminate whether the position of a sound source changed leftward or rightward of midline unless the position change is larger than about 20°. In contrast, 18- to 24-month-olds discriminate changes smaller than 5°, and unpracticed adults and 5-year-olds easily discriminate a change of 1–2°. An

obvious question is whether these age-related changes reflect improvements in perceptual sensitivity to the underlying sound localization cues. For localization in the horizontal plane, the principal cues are interaural time differences and interaural level differences. Here we summarize findings on infants' sensitivity to these cues and discuss them in the context of plasticity in the mapping of specific cue values onto actual locations of sound sources.

Only a handful of studies exist on infants' sensitivity to interaural difference cues, using presentation of signals independently to the two ears. Bundy (1980) tested infants aged 8 and 16 weeks, presenting them with large reversals in interaural time differences ( $+300\ \mu\text{s}$  to  $-300\ \mu\text{s}$ ) or interaural level differences ( $+6\ \text{dB}$  to  $-6\ \text{dB}$ ).

Although the infants did not look in the direction of the leading or louder sounds, a measure of overall looking time at a visual display suggested that they detected the reversals in cue values. This trend was significant on both cues for the 16-week-olds, but only on the interaural time difference cue for the 8-week-olds, showing that young infants can detect changes in interaural cues presented under dichotic conditions. However, interpretation of the study is complicated by several methodological factors, including the possibility that the level difference discrimination may not have been interaural, but could have been mediated by perception of the change in level at a single ear. Thus, the question of whether infants actually utilize interaural time and interaural intensity cues to lateralize sounds remained unanswered.

In a more recent study, Ashmead *et al.* (1991) reported sensitivity to interaural time differences in infants aged 16, 20, and 28 weeks. The procedure was similar to a minimum audible angle test, in that it involved a discrimination paradigm with a diotic click train (sounds through two earphones at the same time and presumably perceived at the "center" of the head), followed by a dichotic click train (with an interaural time difference favoring one ear). An observer, who watched the infant but did not know the side of the leading sound, voted as to which side contained the leading sound, mostly based on the infant's eye and head movements. Correct votes resulted in reinforcement for the infant, consisting of a pleasant video/audio show on the appropriate side. Threshold values for interaural time discrimination were in the range of 50–75  $\mu\text{s}$  for all age groups (compare with typical adult values of 10–20  $\mu\text{s}$ ). For these same ages, the actual interaural time differences that correspond to minimum audible angles obtained in free field are much greater, about 100–140  $\mu\text{s}$ , as shown in Fig. 1 (from Ashmead *et al.*, 1991, Fig. 3). Interestingly, Gray and Jahrsdoerfer (1986) reported a similar pattern with adult aural atresia patients who underwent surgery to eliminate the atresia. These patients had fairly precise postoperative interaural time discrimination but poor free-field sound localization.

The results from Ashmead *et al.* (1991) imply that sensitivity to interaural time differences *per se* is remarkably good during the early stages in the development of sound localization. We later discuss why it is unlikely that this sensitivity is a limiting factor in the development of sound localization precision. In a second study, Ashmead, Grantham, Murphy, Tharpe, Davis, and Whalen (1996) investigated 6-month-old infants' sensitivity to interaural level differences. They also

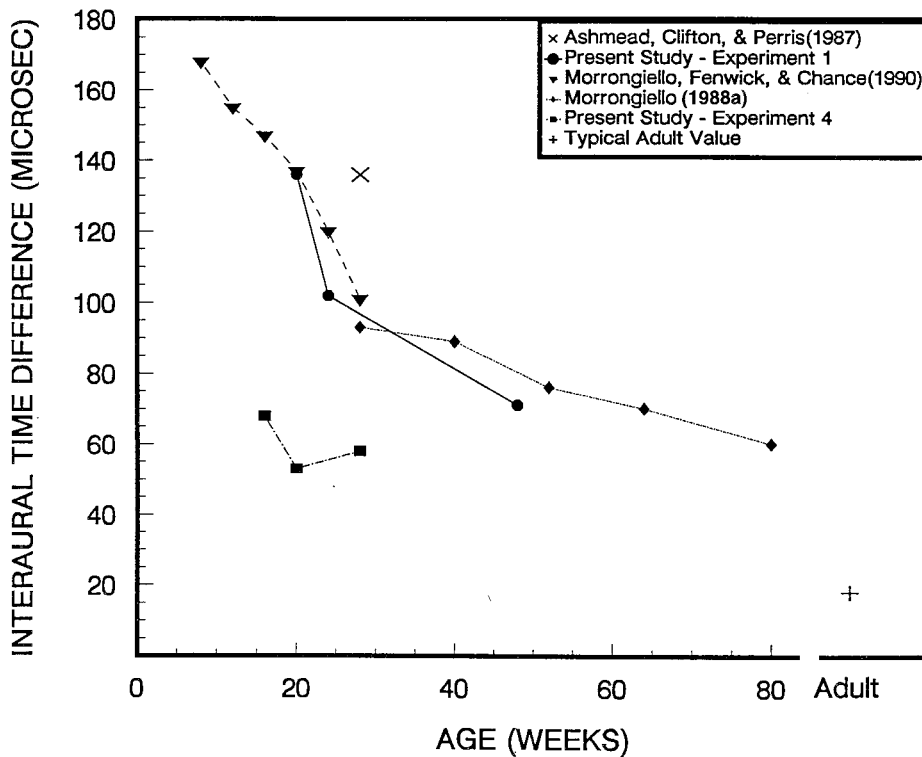


FIG. 1. Thresholds for interaural time discrimination from Ashmead *et al.* (1991, Experiment 4, triangles) compared to interaural time differences corresponding to free-field minimum audible angles (other symbols) as a function of age.

used a discrimination paradigm in which an interaural level difference of zero in the stimulus was changed abruptly to a level difference favoring one ear (overall signal levels were varied to preclude a monaural basis for the discrimination). Infants had thresholds of about 7 dB, which is considerably higher than typical adult values of 0.5 dB or so. We cannot say precisely how this 7 dB threshold value relates to the actual interaural level differences infants experience naturally in the free field. However, it seems likely that the angle changes in free field experienced by 6-month-olds with the minimum audible angle correspond to interaural level differences that are much smaller than 7 dB. This would suggest that interaural level differences probably play a minimal role in localization precision at the age of 6 months. This claim is further supported by another experiment from this study, showing that 6-month-olds did not tend to mislocalize sounds when the input to one ear was artificially attenuated, a manipulation that should have mainly affected interaural level differences. One possibility that remains to be ruled out is potential competition between interaural cues, because at all interaural level differences the interaural time difference was zero, which might have dominated over the level cue.

At this point, the findings on sensitivity to interaural cues suggest that infants are more sensitive to interaural time differences, but less sensitive to interaural level differences, than we would predict from their free-field minimum audible

angles. The discrepancy between the free-field and dichotic studies led us to conclude that age-related changes in the precision of free-field sound localization cannot simply be accounted for by sensitivity to interaural time and level cues. A more likely explanation is the need for ongoing recalibration of the relation between values of sound localization cues and the actual locations of sound sources in the environment. If recalibration is constantly occurring in the nervous system, it would be reasonable to have a period during which localization is not as precise as the underlying cue sensitivity might otherwise allow, particularly if the cue values themselves are changing rapidly. Two groups of investigators have called attention to the large, rapid changes in interaural cue values that must occur during human infancy (Ashmead *et al.*, 1991; Clifton *et al.*, 1988). In neither case were the interaural cues measured directly. Rather, interaural time differences at various ages during development were estimated from measures of head circumference, using a widely accepted spherical model (Woodworth, 1938). Figure 2 shows estimated interaural time differences expressed as a percentage of a typical adult value. The rapid change in this cue value during the first year after birth suggests that if the sound localization system "locked on" to very precise relationships between cue values and sound source directions during that time, the recalibration process would be rather burdensome. An alternative approach would be to permit considerably more error in sound localization during the time when

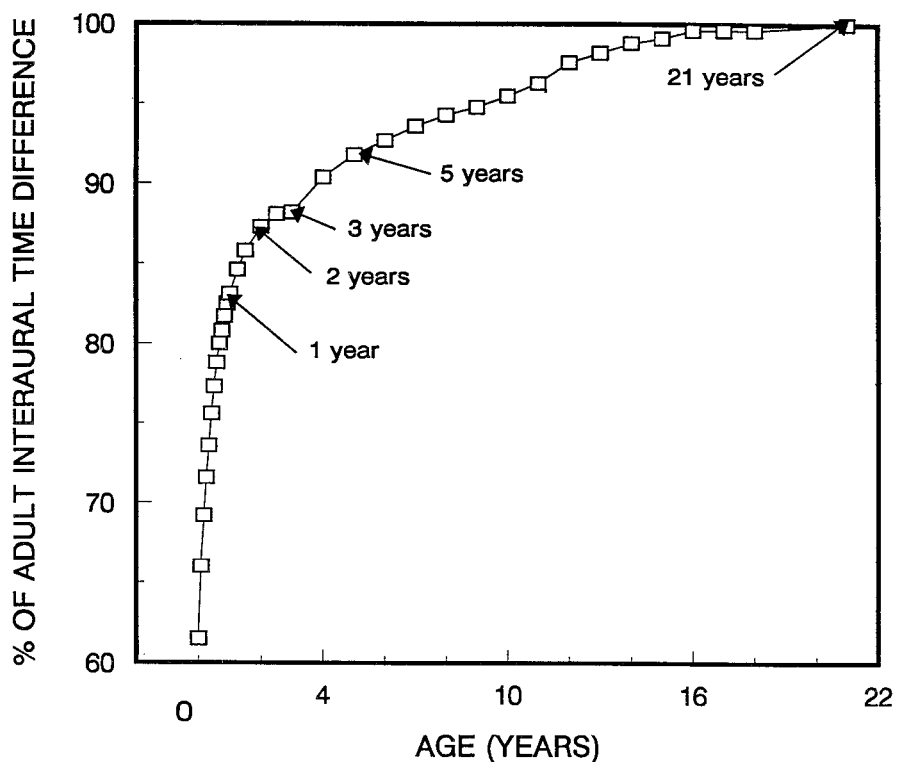


FIG. 2. Interaural time difference as a proportion of adult (21 years) interaural time difference, for ages from birth to 21 years, estimated from head circumference data of Eichorn and Bayley (1962). (From Ashmead *et al.*, 1991, Fig. 4.) Reprinted with permission.

head growth is causing rapid changes in both the binaural (interaural time, level, and spectral differences) and monaural (spectral) cues. If we consider that during infancy an organism need merely direct its attention in the general direction of important events, then from an evolutionary perspective it may be adequate to have a relatively crude sound localization system.

Evidence for this idea comes from neurophysiological work conducted in several laboratories. The superior colliculus of a variety of species is thought to contain a spatial map based on a conglomeration of visual, auditory, and somatosensory inputs (King and Moore, 1991). In fact, auditory neurons in the superior colliculus of a newborn guinea-pig are very broadly tuned for sound location, but within a few weeks after birth a refined map of auditory space emerges (Withington-Wray, Binns, and Keating, 1990). This space map, which has a similar developmental trend in other species as well, is known to be susceptible to altered localization cues during experience. For example, in barn owls (Knudsen and Knudsen, 1985) and ferrets (King, Hutchings, Moore, and Blakemore, 1988) reared with an occluded ear (producing abnormal binaural cues), normal visual input plays a major role in alignment of the auditory space map. This finding supports the notion that auditory localization is one aspect of a complex array of sensorimotor functions that play a role in an organism's ability to find the source of a sound.

In addition to interaural differences in time and level, a third interaural cue thought to be important for sound localization in humans and other animals is differences in the spectra of auditory stimuli as they enter the two ear canals. These cues are considered important for localization of elevation, as well as front/back discrimination and distance perception (Blauert, 1983). These cues have been quantified in recent years through work on direct measurement through probe microphones inserted into the ear canals. Indeed, this was one of the dominant themes at the conference on which this volume is based (for example, Brugge, Reale, and Hind, Chapter 22, this volume; Duda, Chapter 3, this volume; Shaw, Chapter 2, this volume; and Wightman and Kistler, Chapter 1, this volume). No systematic measurements like this have been reported for infants, so our conclusions about the potential effects of changes in head size and shape on localization cues are based on indirect evidence. However, Ashmead and Grantham (1994) recently collected preliminary data on a 1-month-old infant. Measurements were made at the entrance to each ear canal using probe microphones. Sounds (noise bursts) were presented from 45° or 60° to the right. Figure 3 shows the interaural transfer functions, which have positive values when the levels are higher in the right ear; it shows a clear difference in the low- to mid-frequency range (below 8 kHz) between the two locations. Estimates of interaural time differences were also computed from the interaural phase shift function, and they agree reasonably well with predictions from classical spherical models. Although these findings are preliminary, they indicate that direct measurement of sound localization cues is a feasible task in infants. This new approach might facilitate studying how these cues change during early infancy and how these changes might be related to the development of binaural hearing. These measurements might also be useful in studying the development of sound localization in the vertical plane, which has received little attention (Morrongioello, 1988b).



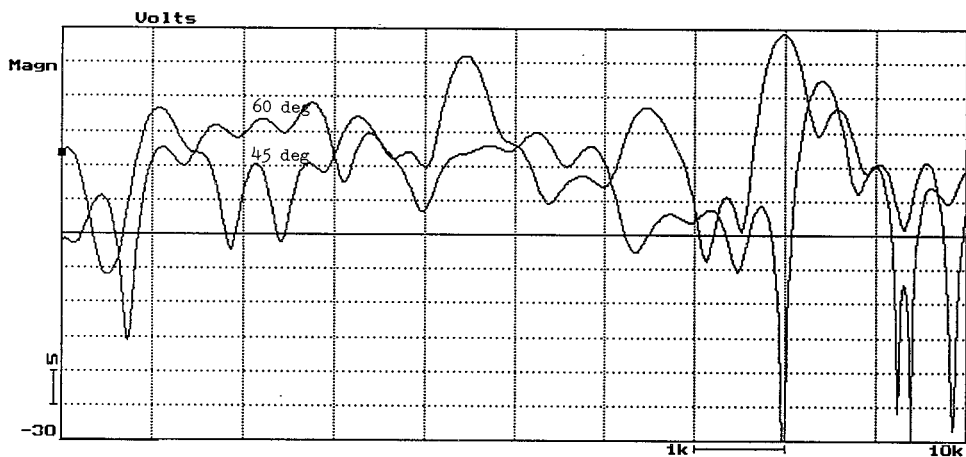


FIG. 3. Interaural transfer functions for sound sources at 45° and 60° to the right, in a 3-week-old infant. Positive values indicate a higher sound level in the right ear than in the left ear. (Ashmead and Grantham, 1994)

In summary, sensitivity to interaural cues that presumably underlie free-field sound localization is well developed early in life and is therefore probably not the limiting factor for developmental changes in free-field sound localization. Rather, the need for ongoing recalibration of the relation between cue values and sound locations may play an important role. One approach toward addressing this question is the study of sound localization abilities of congenitally totally blind individuals, because they would have no opportunity for visually based calibration. Unfortunately, we are not aware of any measures of this type performed with acceptable psychoacoustic methods.

## B. Auditory distance perception

Sound localization is inherently three-dimensional in that we experience not only the horizontal and vertical directions of a sound but also its distance. Despite this everyday phenomenology, the directional aspects of sound localization have been investigated far more than those related to distance. Indeed, the acoustical bases for auditory distance perception by adults are not well understood. (For reviews, see Coleman, 1962; Blauert, 1983, pp. 116–137. For recent work, see Ashmead, Davis, and Northington, 1995; Little, Mershon, and Cox, 1992; Shaw, McGowan, and Turvey, 1991.) For developmental work on auditory distance perception there is the added question regarding what response measure might veridically reflect an infant's or young child's perceptual experience of distance. In this section we review recent findings on infants' distance perception as measured by their reaching behavior for sound-producing objects.

Anyone who has been around infants knows that they are quite proficient at reaching for objects and successfully grasping them by about 5 to 6 months after birth. A number of studies on visual depth perception have shown that infants

make an impressive distinction between objects that are within versus beyond reach (see Yonas and Granrud, 1985, for a review). They display this distinction by only attempting to grasp objects that are within reach, not ones that are beyond reach, which implies that they can relate distance perception to their motor performance. These findings make reaching a promising measure for investigating infants' auditory distance perception. However, in order to study auditory distance perception *per se*, one must eliminate all visual input. In the series of studies discussed next, this was accomplished by presenting infants with sounding objects in complete darkness.

The first systematic study of infants' reaching for sounds, by Perris and Clifton (1988), did not focus on distance perception, but rather was aimed at demonstrating that infants reach willingly and accurately for unseen sounding objects, and thus it established the methodology used in later studies. Infants aged 6 months were trained in the light to reach for a visible sounding object (rattle) with a removable finger puppet attached to it. When tested in the dark with the sounding object placed in any of six directions (separated by 30°), infants touched the objects on their first reaching attempt on 77% of the trials, which was well above chance. Two subsequent studies extended this experimental paradigm to study distance perception. Clifton, Perris, and Bullinger (1991) presented 6-month-olds with sounding objects, 45° to the left or right, either within reach (10 cm from the torso) or beyond reach (100 cm). Infants reached correctly on the majority of the within-reach trials, but they did not attempt to reach at all on most of the beyond-reach trials. This study proved that by 6 months infants can rely on auditory information alone to make a dichotomous distance discrimination. It remained unclear what the effective distance information was. Recently Clifton, Rochat, Robin, and Berthier (1994) measured 6-month-olds' hand movements while reaching for objects in a lighted room, glowing objects in a dark room, and sounding objects in a dark room. They used a motion analysis system that allowed fine-grained measurement of reaching movements. Although infants were less accurate when they could not see the object (third condition just listed), they still showed a smooth deceleration of the hand movement at the end of a reach for a sounding object. Thus, rather than merely swiping at the object, they appeared to have some notion of exactly where it was located. This further reinforces the value of the reaching response as a measure of the accuracy of infants' sound localization.

Litovsky and Clifton (1992) focused on sound pressure level, a distance cue known to be relevant for adults. Sound pressure varies inversely with distance, with a change of approximately 6 dB for every halving or doubling of distance (e.g., see Coleman, 1962). In everyday language, if one assumes a sound to be constant at its source, it would be louder when in close proximity but softer when further away. In the Litovsky and Clifton study, sounds in the near and far positions (15 and 100 cm, respectively) had a natural difference of 7 dB. Unknown to the subjects, the sound pressure from the source (a small loudspeaker) could be manipulated to simulate different distances. All infants first heard and saw the sounding objects in the light, straight ahead, with the natural level cues corresponding to the near and far positions. The infants reached accurately for the near

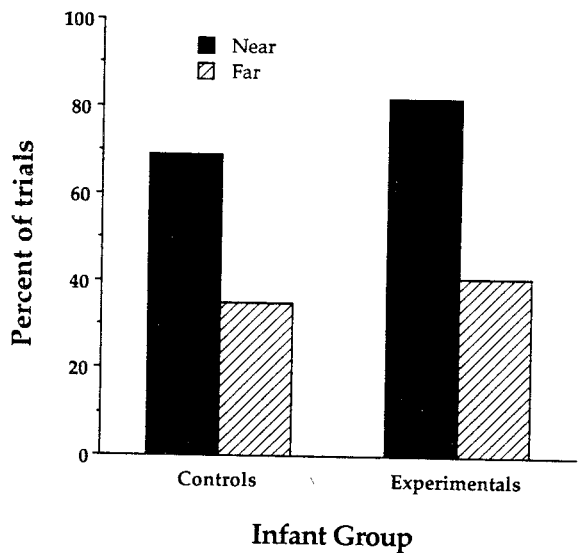
objects on virtually all trials, indicating that the near object was readily contacted. On dark trials the objects were presented 45° to the left or right. For the control group of infants, the near and far objects had their natural sound levels, louder and softer, respectively. The experimental group was presented with inconsistent combinations of sound pressure and distance. On half the near trials the sound was naturally loud, but on the other half it was reduced by 7 dB (measured from the position of the subjects' head). The reverse was true for the far trials, half of which were naturally soft and half increased by 7 dB. As is shown in Fig. 4, all infants reached more for the near than for the far objects, even when the sound pressure was misleading. In other words, the infants were not fooled by the sound pressure manipulation, and they seemed to utilize other distance cues. This contrasted sharply with findings for a group of adults run under similar conditions, who were asked to make verbal judgments about distance. The adults judged the louder objects to be near and the softer objects to be far, regardless of the actual distance. In summary, by 6 months infants have a basic capacity for discriminating between sound-producing objects that are within versus beyond reach. Because infants do not appear to rely on one distance cue, sound pressure, as strongly as adults, it seems likely that there is considerable experience-dependent development in the processes underlying auditory distance perception. In terms of methodology, the infants' reaching behavior has turned out to be a valuable tool for studying auditory distance perception.

### C. The precedence effect

The precedence effect refers to an auditory illusion that occurs when two similar sounds are presented from different locations at slightly different times. Only one sound image is actually "heard," and its perceived location is dominated by the leading sound. This phenomenon is most intriguing because the second sound is above threshold, and, if presented in isolation, would be localized at its correct position. Thus, the nervous system plays an interesting trick on our experience of the world by actively shutting out prominent auditory information. Although this effect is typically studied in the laboratory by using two discrete sound sources (different loudspeakers), the underlying auditory processes presumably work in everyday life to suppress our perception of sounds reflected off surfaces such as walls, ceilings, and floors (Blauert, 1983, pp. 222–237; Zurek, 1987). Several chapters in this book focus on the precedence effect in human adults; thus we refrain from reviewing that literature in depth and focus on developmental aspects of the precedence effect.

A fundamental finding on the development of the precedence effect is that it does not appear to be present during early infancy. This has been demonstrated for human newborns (Clifton *et al.*, 1981) and young dogs (Ashmead *et al.*, 1987). In both studies, infants or puppies were presented with sounds from loudspeakers located 90° to the left and right. On "single-source" trials, the sound came from one loudspeaker only. On precedence-effect trials, the sound came from both loudspeakers with a 7 ms delay between them. With this delay, adults perceive the sound to emanate entirely from the loudspeaker having the leading sound.

A) INFANTS



B) "EXPERIMENTAL" ADULTS

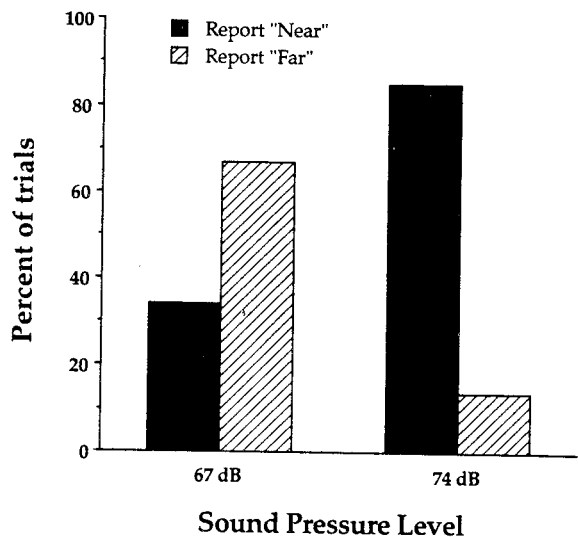


FIG. 4. (A) Infant data: Percent of Near and Far trials on which 6-month-olds reached in the dark for a sound producing object. Both Control and Experimental infants (see text for explanation) reached significantly more on the Near than on the Far trials. (B) Verbal reports of Experimental adults are plotted for Near-Far trials combined as a function of sound pressure level. Independent of the actual distance of the sound-producing object, on trials where the stimulus was at 67 dB SPL, the predominant judgment was "Near," whereas on the trials where the stimulus was at 74 dB SPL, the predominant judgment was "Far." (From Litovsky and Clifton, 1992.) Reprinted with permission.

Finally, on control trials the sound came from both loudspeakers at the same time. Infants and puppies turned reliably toward the active loudspeaker on single source trials, but on precedence-effect trials they typically did not turn at all (which was also the case on control trials). Despite the fact that infants and puppies “perk up” when they hear sounds in the precedence-effect configuration, they do not appear to localize the sound image toward the leading speaker, as adults do. It has since been shown that infants turn toward the leading side of precedence-effect sounds beginning at about 4 months of age (Muir *et al.*, 1989). The timing of appearance of the precedence effect is tightly coupled with the age at which head-turning toward single source sounds reappears (discussed earlier).

Another aspect of the precedence effect that has been investigated developmentally is the echo threshold. When the delay between the leading and lagging sounds is longer than the echo threshold, directional information from the lagging sound is no longer suppressed and the listener hears two distinct sounds at their respective locations. For adults, this value is 5–9 ms for clicks, 10–12 ms for noise, 20 ms for speech, and 40 ms for music (see Blauert, 1983, p. 231; Zurek, 1987). The echo threshold changes during development, as shown in Fig. 5. For simple stimuli such as clicks, the echo threshold is higher at 6 months (25 ms) than at 5 years or in adulthood (about 12 ms) (Clifton, 1985). For more complex stimuli of longer duration the echo threshold also differs somewhat between 5 years (30 ms) and adulthood (25 ms) (Morrongiello, Kulig, and Clifton, 1984). Burnham,

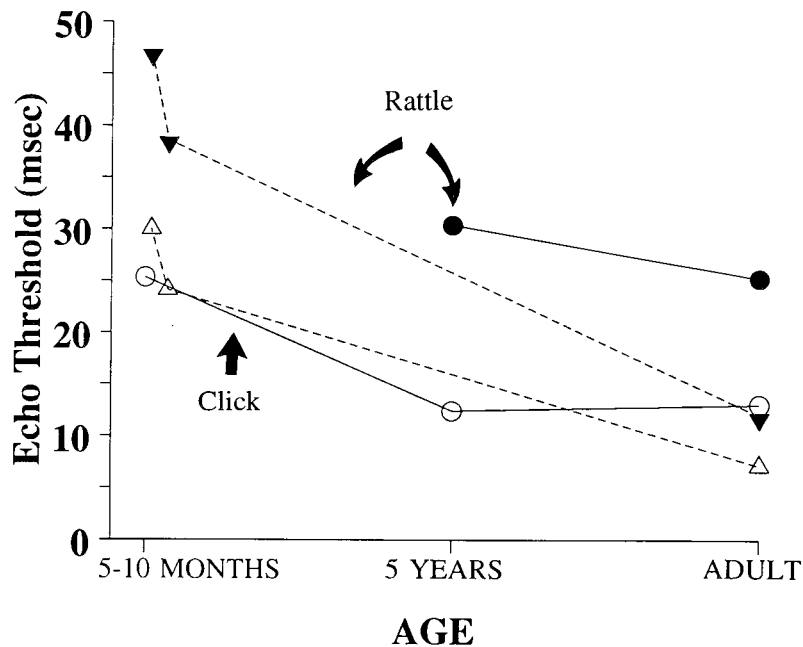


FIG. 5. Echo thresholds for precedence-effect stimuli are compared at three age ranges for two different stimulus types. For click stimuli, echo thresholds decrease between 5–10 months and 5 years, but not between 5 years and adult. Thresholds also decrease with age for the rattle stimulus between all three ages. The difference between click and rattle thresholds is noticeable at all ages as well. (Circles were redrawn with permission from Morrongiello *et al.*, 1984; triangles were redrawn with permission from Burnham, *et al.*, 1993.) Reprinted with permission.

Taplin, Henderson-Smart, Earnshaw-Brown, and O'Grady (1993) recently suggested that echo thresholds change developmentally as a function of maturation from time of conception, rather than from experience since birth. They found that the echo thresholds of preterm infants tested about 9.5 months after birth were more similar to full-term infants matched for conceptual age than to full-term infants matched for age since birth. Taken together, developmental studies of the echo threshold indicate that there is considerable age-related change in processing of sounds presented in the precedence-effect configuration, even beyond the period of infancy. It is possible that in everyday listening situations, infants and young children may experience more difficulty than older children and adults at suppressing "extra" sounds in reverberant settings. In fact, it has been shown that children's speech comprehension (Neuman and Hochberg, 1983) and sound localization (Besing and Koehnke, 1995) are diminished in a reverberant environment.

Developmental studies of the precedence effect have been motivated by the idea that it reflects maturation of the central auditory system (Clifton, 1985; Muir *et al.*, 1989). This is based on neurobehavioral evidence that cats without an intact auditory cortex do not localize stimuli presented in a precedence-effect configuration toward the leading sound (Cranford and Oberholtzer, 1976; Cranford, Ravizza, Diamond, and Whitfield, 1971; Whitfield, Cranford, Ravizza, and Diamond, 1972). Also, people with temporal-lobe lesions show deficits in performance on precedence-effect tasks (Hochster and Kelly, 1981). Finally, myelination of auditory cortex in humans begins about 3 months after birth, with considerable development up to 2 years (Dekaban, 1970; Yakovlev and Lecours, 1967). This convergence of behavioral and neural evidence suggests that the auditory cortex may play a substantial role in the onset of the precedence effect in humans at 3 to 4 months after birth. The cortex may also be involved in continued refinement of the precedence effect for several years thereafter.

The role of the auditory cortex in the ontogeny of precedence-effect processing has been further supported by recent neurophysiological studies of brainstem auditory processing in the cat recorded from single cells in the inferior colliculus of adult cats, using stimuli that mimic the precedence effect (Litovsky and Yin, 1993, 1994; Yin, 1994; Yin and Litovsky, 1993). Auditory stimuli were presented either dichotically (separate stimuli to each ear) or in free-field while animals were anaesthetized. At long delays, when the "echo" would presumably be heard, most cells responded to both the leading and lagging sounds. As the delay was decreased, the response to the lagging sound was suppressed, as shown in Fig. 6. Thus, the inferior colliculus, a subcortical structure, codes for suppression of the lagging sound in adult cats. Litovsky (1994) recently reported that cells in the inferior colliculus of young kittens also show suppression of lagging sounds, even within the first postnatal week, prior to the onset of behavioral orientation toward sounds (Olmstead and Villablanca, 1980). Representative data from 14 kittens are compared with those of 14 adult cats in Fig. 7. The echo thresholds for individual cells (delay at which response to the lagging sound was suppressed by 50%) ranged from about 2 to 70 ms in both adult cats and kittens; however, the overall suppression was significantly weaker in kittens than cats, with respective

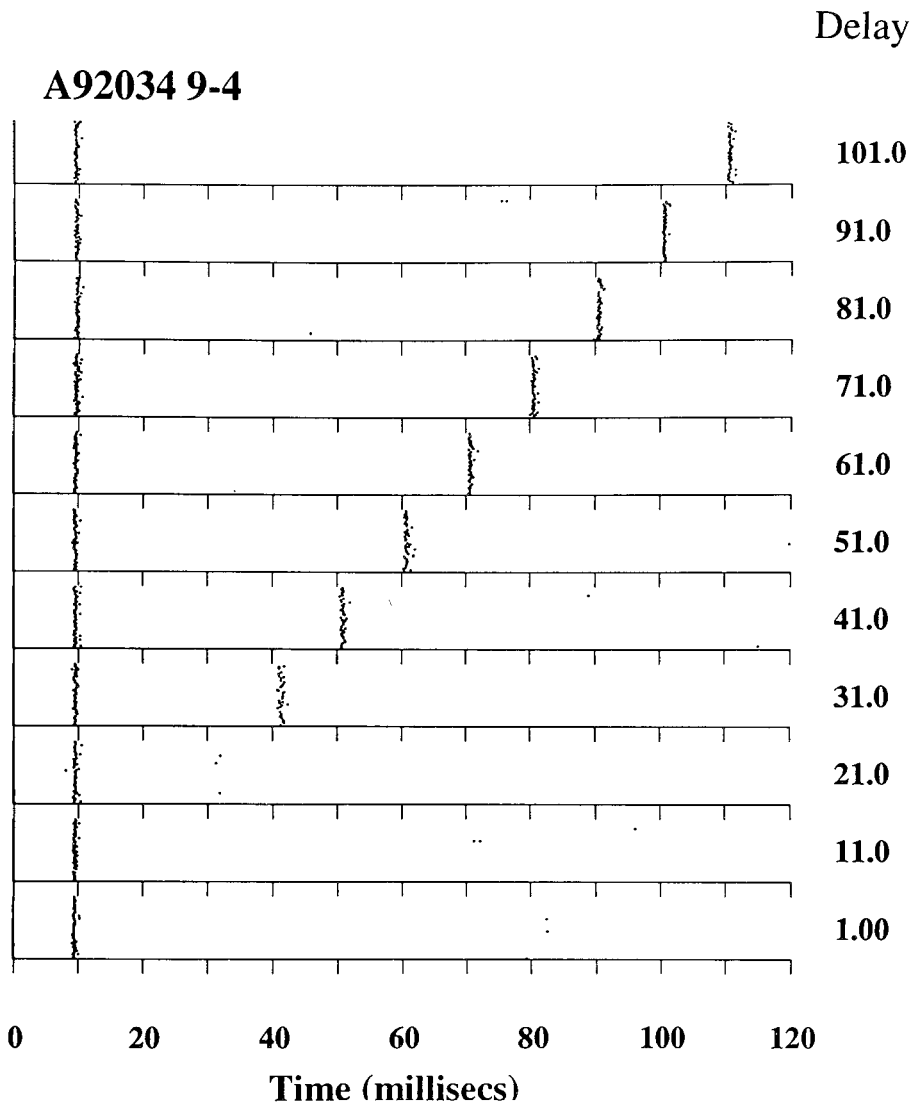


FIG. 6. The response of one neuron in the inferior colliculus of the cat. Stimuli were two dichotic pairs of clicks, both with an interaural time delay favoring the contralateral ear, where the neuron responded vigorously to the stimuli. Each set of responses represents 50 trials, with the second click pair being delayed relative to the first one. The delay was varied from 1 to 101 ms. For all delays the neuron responded to the first click pair. For delays of 41 to 101 ms the neuron also responded to the second, or lagging, click pair reliably. However, the response to the lagging stimulus was decreased at 31 ms, and disappeared at delays of 21, 11, and 1 ms (Litovsky, 1994).

means of 22.6 and 36 ms. These findings suggest that in cats the initial stages of echo suppression are processed in the inferior colliculus. The difference in mean thresholds might suggest that precedence is somewhat weaker early in life. The fact that IC neurons show precedence at all, and that newborns do not display the behavior, suggests that there is a decoupling between the capacity of the young nervous system to encode stimuli so as to suppress lagging sounds and its capacity to manifest this coding in terms of orienting toward the leading sound. The exact

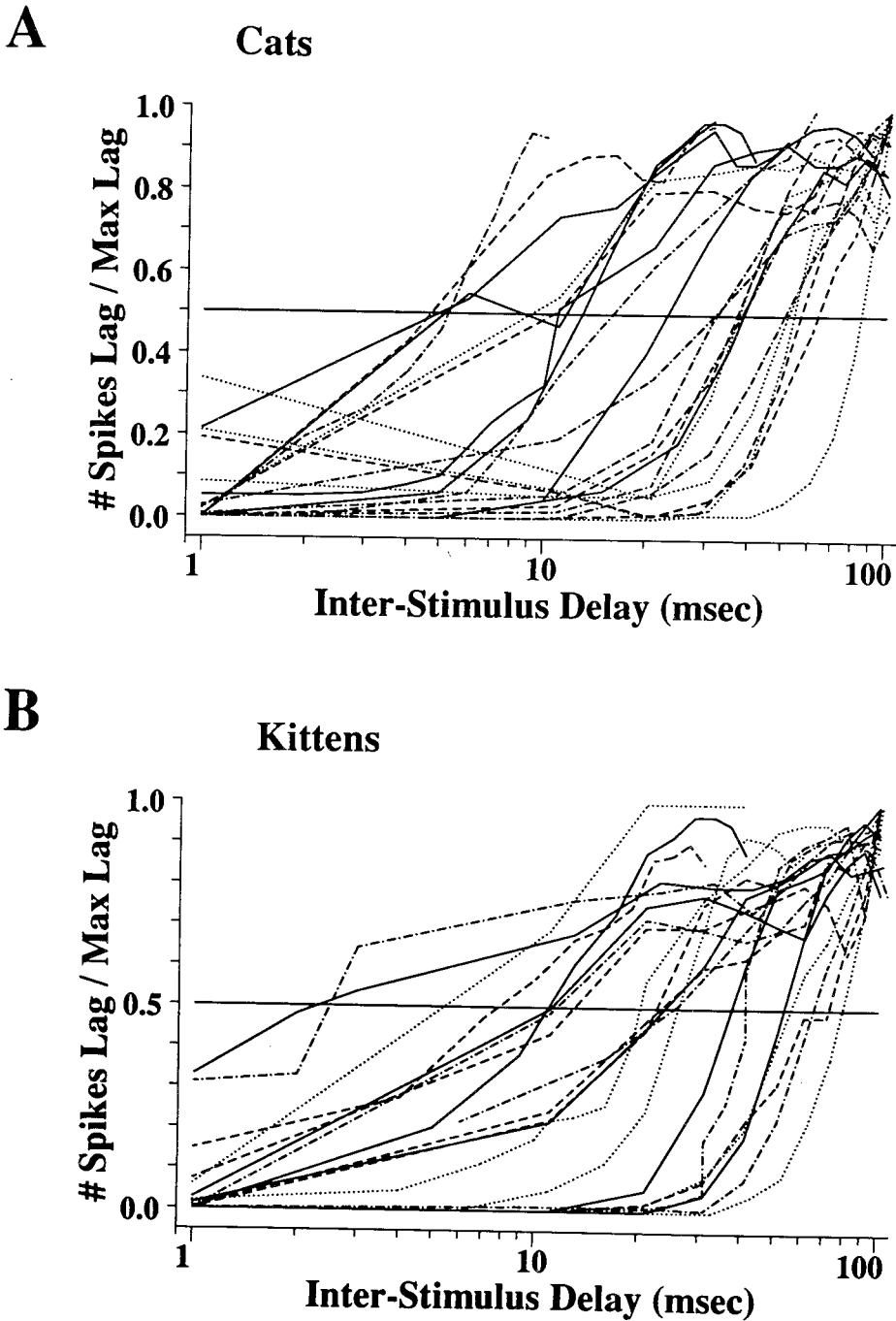


FIG. 7. The stimulus configuration from Fig. 6 was presented to a population of neurons in both adult cats and young kittens (ages 8–28 days). For each neuron the response to the lagging stimulus at every delay was divided by the “maximal lagging” response of the neuron, that is, response to the second click pair at the longest delay. Representative neurons from (A) 14 adult cats and (B) 14 kittens were then plotted as a function of delay. The point at which the functions recover to 50% of the maximal response is marked by a horizontal line in each figure, with means of 32 ms and 29 ms in cats and kittens, respectively (Litovsky, 1994).



role of the auditory cortex (or other cortical areas for that matter) in enabling overt behavioral localization is not known, but it may involve linking information that is encoded about auditory events with appropriate behavioral responses. This pattern of results is similar to the one described in Sec. II.A, where we noted that infants appear to have good sensitivity to interaural time differences yet rather imprecise sound localization. The act of localizing a sound source and making an appropriate response involves much more than sensitivity to the underlying acoustic cues.

In addition to the auditory cortex, development in other brain regions may influence some aspects of the development of the responses to precedence-effect stimuli. For example, the frontal cortex is considered critical for suppression of distracting stimuli (Guitton, Buchtel, and Douglas, 1985; Luria, 1973), an idea that has attracted much attention in recent work on perceptual-motor and cognitive development (Diamond, 1990). There is also growing evidence that the precedence effect has a cognitive component. In particular, there is a "buildup" of echo suppression while adults listen to sounds presented repeatedly (Clifton and Freyman, Chapter 12, this volume). Clifton, Freyman, Litovsky, and McCall (1994) suggested that this buildup effect depends on the listener's expectations of what types of sounds could be echoes. Presumably adults "size up" the acoustic properties of a room over the course of 5 or 10 s and adjust their suppression to the appropriate range of delays for that room. The buildup effect has not been studied in infants, but to the extent that it reflects an active cognitive process, perhaps dependent on experience, we would not expect to see it in early infancy. Supporting evidence for this prediction is that the buildup effect has not been observed in the activity of single cells in the cat inferior colliculus (Litovsky and Yin, 1993, 1994; Yin, 1994; Yin and Litovsky, 1993), so it appears to be mediated at a higher level.

So far, we have discussed work on the precedence effect as measured with echo thresholds, which reflect whether the sounds are heard as a single event or as two separate events. An alternative approach is to consider how the lagging sound can exert an effect on the leading one. This happens for sounds that are within the delay range of the precedence effect. For adults, sound localization is affected strongly by the presence of lagging sounds, even though the lagging sounds are not heard as separate auditory events (Hartmann, 1983; Rakerd and Hartmann, 1985; Litovsky and Macmillan, 1994; Wallach, Newman, and Rosenzweig, 1949). That is, we hear one "fused" sound whose perceived location is determined by a weighted sum of the leading and lagging stimuli (Shinn-Cunningham, Zurek, and Durlach, 1993). Litovsky (1996) measured this effect in 18-month-olds, 5-year-olds, and adults, using a version of the minimum audible angle procedure described earlier. Each subject was tested in three conditions. One was the classic single source test in which a sound location changed from midline to the left or right. In the other conditions the stimuli were in pairs that satisfied conditions of the precedence effect. In both conditions the first sound on each trial was a single source sound from midline. In the "lead discrimination" condition, the shifted stimulus consisted of a leading sound from the left or right and a lagging sound from midline. For "lag discrimination" the opposite occurred;

the leading sound was from midline and the lagging sound was from the left or right. The data are summarized in Fig. 8. At all ages the minimum audible angle was greater (worse) in the lead discrimination condition than the single source condition, suggesting that the lagging sound at midline interfered with the precision of localization. However, the discrepancy between the conditions decreased with age, suggesting either that the “pulling” by the lag sound is smaller in older people, or that suppression of the lagging sound is stronger in older people. In addition, at all ages lag discrimination minimum audible angles were greater (worse) than both lead discrimination and single source, but they decreased significantly between 18 months, 5 years, and adults, suggesting that with increased age listeners’ ability to extract subtle directional information from an “inaudible” echo improves.

These findings can be related to the work with newborns’ responses to precedence-effect stimuli discussed earlier (Clifton *et al.*, 1981). In that situation, newborns were presented with the leading and lagging stimuli on either side, and they did not orient to the leading sound, but rather, they looked straight ahead (see earlier discussion). It is conceivable that newborns “have” the precedence effect, such that they do not hear the lagging sound separately from the leading sound. However, another aspect of the precedence effect may be very weak. That is, they may be incapable of suppressing the influence of the lagging sound, thus they may perceive one sound whose location is determined almost equally by the lead and lag, and that sound appears near midline. This issue could be investigated by presenting newborns with sounds from symmetrical locations, but no such findings have been reported.

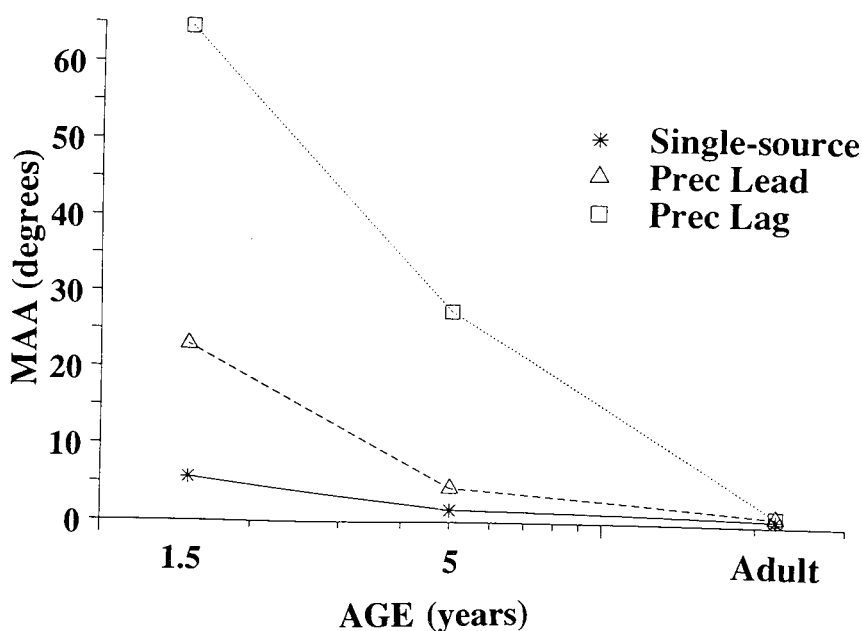


FIG. 8. Minimum audible angle thresholds at 18 months, 5 years, and adult are plotted for three stimulus conditions: single source (asterisks), precedence-lead discrimination (triangles), and precedence-lag discrimination (squares). (From Litovsky, 1995.) Reprinted with permission.

In summary, the precedence effect has proved extremely useful for investigating the development of sound localization. Mature sound localization clearly depends on processes such as the suppression of later arriving sounds. The developmental acquisition of these processes occurs over a time span of at least months and probably years, perhaps requiring considerable auditory experience and cognitive elaboration. To the extent that the precedence effect may reflect integrity of auditory processes, it may also be a useful task for detection of auditory deficits in a clinical setting.

### III. SUMMARY

Perhaps the most important general point to emerge from the work described in this chapter is that the development of sound localization is very much a constructive process. Whether it be calibration of changing values of directional cues, utilization of sound level as a cue for distance, or weighting of leading and lagging sounds in the precedence effect, adult-like sound localization seems to be a constructive act on the part of the listener. We have been led to this conviction on the basis of developmental evidence, but it is very much in keeping with recent work on sound localization in adults and laboratory animals, including much of the work described in other chapters of this volume. Localization depends on integrating information across different cues, across frequency regions, and even across time (as listeners and sound sources move).

### ACKNOWLEDGMENTS

This work was supported by National Institutes of Health grant DC00078 to Ruth Litovsky, grant HD23191 to D. Ashmead, and grant DC01437 to Fred Bess (with D. Ashmead and D. W. Grantham co-investigators).

### REFERENCES

- Ashmead, D. H., Clifton, R. K., and Perris, E. E. (1987). "Precision of auditory localization in human infants," *Dev. Psychol.* 23, 641-647.
- Ashmead, D. H., Clifton, R. K., and Reese, E. (1986). "Development of auditory localization in dogs: Single source and precedence effect sounds," *Dev. Psychobiol.* 19, 91-104.
- Ashmead, D. H., Davis, D. L., and Northington, A. (1995). "The contribution of listeners' approaching motion to auditory distance perception," *J. Exp. Psychol. Hum. Percept. Perform.*, 21, 239-25.
- 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. Dev.* 62, 1211-1226.
- Ashmead, D. H., and Grantham, D. W. (1994). "Direct measurement of binaural sound localization cues in a 3-week-old human infant," unpublished observations, Vanderbilt University, Nashville, TN.
- Ashmead, D. H., Grantham, D. W., Murphy, W. D., Tharpe, A. M., Davis, D. L., and Whalen, T. A. (1996). "Human infants' spatial hearing: The role of interaural level differences," *Child. Dev.*, submitted.
- Besing, J. M., and Koehnke, J. (1995). "Effects of Otitis media on binaural performance in children," *Ear Hear.*, 16, 220-229.
- Blauert, J. (1983). *Spatial Hearing* (MIT Press, Cambridge, MA).
- Brazelton, T. B. (1973). *Neonatal Behavioral Assessment Scale* (Spastics International Medical Publications, London).

- Bundy, R. S. (1980). "Discrimination of sound localization cues in young infants," *Child Development* **51**, 292-294.
- 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 Behav. Dev.* **16**, 213-232.
- Butterworth, G., and Castillo, M. (1976). "Coordination of auditory and visual space in newborn human infants," *Perception* **5**, 155-160.
- Clarkson, M. (1992). "Infants' perception of low pitch," in *Developmental Psychoacoustics*, edited by L. A. Werner and E. W. Rubel (American Psychological Association, Washington, DC), pp. 159-188.
- Clements, M., and Kelly, J. (1978). "Auditory spatial responses of young guinea pigs (*Cavia porcellus*) during and after ear-blocking," *J. Comp. Physiol. Psychol.* **92**, 34-44.
- Clifton, R. K. (1985). "The precedence effect: Its implications for developmental questions," in *Auditory Development in Infancy*, edited by S. E. Trehub and B. Schneider (Plenum Publishing, New York), pp. 85-99.
- Clifton, R. K. (1992). "The development of spatial hearing in human infants," in *Developmental Psychoacoustics*, edited by L. A. Werner and E. W. Rubel (American Psychological Association, Washington, DC), pp. 135-158.
- Clifton, R. K., Freyman, R. L., Litovsky, R. Y., and McCall, D. D. (1994). "Listeners' expectations about echoes raise or lower echo thresholds," *J. Acoust. Soc. Am.* **95**, 1525-1533.
- Clifton, R. K., Gwiazda, J., Bauer, J. A., Clarkson, M., and Held, R. (1988). "Growth in head size during infancy: Implications for sound localization," *Dev. Psychol.* **24**, 477-483.
- Clifton, R. K., Morrongiello, B. A., Kulig, J., and Dowd, J. M. (1981). "Newborns' orientation toward sound: Possible implications for cortical development," *Child. Dev.* **52**, 833-838.
- Clifton, R. K., Perris, E. E., and Bullinger, A. (1991). "Infants' perception of auditory space," *Dev. Psychol.* **27**, 187-197.
- Clifton, R. K., Rochat, P., Robin, D. J., and Berthier, N. E. (1994). "Multimodal perception in the control of infant reaching," *J. Exp. Psychol. Hum. Percept. Perform.*, **20**, 876-886.
- Coleman, P. D. (1962). "An analysis of cues to auditory depth perception in free space," *Psychol. Bull.* **60**, 302-315.
- Cranford, J., and Oberholtzer, M. (1976). "Role of neocortex in binaural hearing in the cat. II: The 'precedence effect' in sound localization," *Brain Res.* **111**, 225-239.
- Cranford, J., Ravizza, R., Diamond, I., and Whitfield, I. (1971). "Unilateral ablation of the auditory cortex in the cat impairs complex sound localization," *Science* **172**, 286-288.
- Crassini, B., and Broerse, J. (1980). "Auditory-visual integration in neonates: A signal detection analysis," *J. Exp. Child. Psychol.* **29**, 144-155.
- Dekaban, A. (1970). *Neurology of Early Childhood* (William & Wilkins, Baltimore).
- Diamond, A. (1990). "Developmental time course in human infants and infants monkeys, and the neural basis of inhibitory control in reaching" in *The Development and Neural Bases of Higher Cognitive Functions*, Vol. 608 *Annals of the New York Academy of Sciences*, edited by A. Diamond (New York Academy of Sciences, New York), pp. 637-677.
- Eichorn, D. H., and Bayley, N. (1962). "Growth in head circumference from birth through young adulthood," *Child. Dev.* **33**, 257-271.
- Field, J., Muir, D., Pilon, R., Sinclair, M., and Dodwell, P. (1980). "Infants' orientation to lateral sounds from birth to three months," *Child. Dev.* **51**, 295-298.
- Gottlieb, G. (1981). "Roles of early experience in species-specific perceptual development," in *Development of Perception: Psychobiological Perspectives: Vol. 1: Audition, Somatic Perception, and the Chemical Senses*, edited by R. Aslin, J. Alberts, and M. Petersen (Academic Press, New York), pp. 5-44.
- Gray, L., and Jahrsdoerfer, R. (1986). "Effects of congenital aural atresia on the ability to localize sounds," *Otolaryngol. Head. Neck. Surg.* **94** (August special issue), 46.
- Guillon, D. H., Buchtel, A., and Douglas, R. M. (1985). "Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal directed saccades," *Exp. Brain Res.* **58**, 455-472.
- Hartmann, W. M. (1983). "Localization of sound in rooms," *J. Acoust. Soc. Am.* **74**, 1380-1391.
- Hartmann, W. M., and Rakerd, B. (1989). "On the minimum audible angle—A decision theory approach," *J. Acoust. Soc. Amer.* **85**, 2031-2041.
- Hochster, M., and Kelly, J. (1981). "The precedence effect and sound localization by children with temporal lobe epilepsy," *Neuropsychologia* **19**, 49-55.
- King, A. J., Hutchings, M. E., Moore, D. R., and Blakemore, C. (1988). "Developmental plasticity in the visual and auditory representations in the mammalian superior colliculus," *Nature* **332**, 73-76.
- King, A. J., and Moore, D. R. (1991). "Plasticity of auditory maps in the brain," *Trends Neurosci.* **14**, 31-37.
- Knudsen, E. I., and Knudsen, P. F. (1985). "Vision guides the adjustment of auditory localization in young barn owls," *Science* **230**, 545-548.
- Litovsky, R. Y. (1994). "Evidence for physiological correlates of the precedence effect in the inferior colliculus of kittens," *J. Acoust. Soc. Am.* **95**, S2843.
- Litovsky, R. Y. (1996). "Developmental changes in minimum audible angle under conditions of the precedence effect," *J. Acoust. Soc. Am.*, under review.
- Litovsky, R. Y., and Clifton, R. K. (1992). "Use of sound-pressure level in auditory distance discrimination by 6-month-old infants and adults," *J. Acoust. Soc. Am.* **92**, 794-802.

- Litovsky, R. Y., and Macmillan, N. A. (1994). "Minimum audible angle for clicks with simulated echoes: Effects of azimuth and standard," *J. Acoust. Soc. Am.* **96**, 752-758.
- Litovsky, R. Y., and Yin, T. C. T. (1993). "Single-unit responses to stimuli that mimic the precedence effect in the inferior colliculus of the cat," presented at the meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, FL.
- Litovsky, R. Y. and Yin, T. C. T. (1994). "Physiological correlates of the precedence effect: Free-field recordings in the inferior colliculus of the cat," presented at the meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, FL.
- Little, A. D., Mershon, D. H., and Cox, P. H. (1992). "Spectral content as a cue to perceived auditory distance," *Perception* **21**, 405-416.
- Luria, A. R. (1973). *Higher Cortical Functions in Man* (Basic Books, New York).
- McGurk, H., Turnure, C., and Creighton, S. (1977). "Auditory-visual coordination in neonates," *Child. Dev.* **48**, 138-143.
- Mills, A. (1958). "On the minimum audible angle," *J. Acoust. Soc. Am.* **30**, 237-246.
- Moore, J. M., Thompson, G., and Thompson, M. (1975). "Auditory localization of infants as a function of reinforcement conditions," *J. Speech Hear. Res.* **40**, 29-34.
- Morrongiello, B. (1988a). "Infants' localization of sounds along the horizontal axis: Estimates of minimum audible angle," *Dev. Psychol.* **24**, 8-13.
- Morrongiello, B. (1988b). "Infants' localization of sounds along two spatial dimensions: Horizontal and vertical axes," *Infant Behavior and Development*, **11**, 127-143.
- Morrongiello, B. A., Fenwick, D. K., and Chance, G. (1990). "Sound localization acuity in very young infants: An observer-based testing procedure," *Dev. Psychol.* **26**, 75-84.
- Morrongiello, B., Kulig, J., and Clifton, R. K. (1984). "Developmental changes in auditory temporal perception," *Child. Dev.* **55**, 461-471.
- Morrongiello, B., and Rocca, P. (1987). "Infants' localization of sounds in the horizontal plane: Effects of auditory and visual cues," *Child. Dev.* **58**, 918-927.
- Morrongiello, B. A., and Rocca, P. T. (1990). "Infants' localization of sounds within hemifields: Estimates of minimum audible angle," *Child. Dev.* **61**, 1258-1270.
- Muir, D. (1982). "The development of human auditory localization in infancy," in *Localization of Sound: Theory and Application*, edited by R. W. Gatehouse (Amphora Press, Groton, CT), pp. 220-243.
- Muir, D. (1985). "The development of infants' auditory spatial sensitivity," in *Auditory Development in Infancy*, edited by S. E. Trehub and B. Schneider (Plenum Publishing, New York), pp. 51-83.
- Muir, D., and Clifton, R. K. (1985). "Infants' orientation to the location of sound sources," in *Measurement of Audition and Vision in the First Postnatal Year of Life: A Methodological Overview*, edited by G. Gottlieb and N. A. Krasengor (Ablex, Norwood, NJ), pp. 171-194.
- Muir, W. D., Clifton, R. K., and Clarkson, M. G. (1989). "The development of a human auditory localization response: A U-shaped function," *Can. J. Psychol.* **43**, 199-216.
- Muir, D., and Field, J. (1979). "Newborn infants orient to sounds," *Child. Dev.* **50**, 431-436.
- Neuman, A. C., and Hochberg, I. (1983). "Children's perception of speech in reverberation," *J. Acoust. Soc. Am.* **73**, 2145-2149.
- Olmstead, C. E., and Villablanca, J. R. (1980). "Development of behavioral audition in the kitten," *Physiol. Behav.* **24**, 705-712.
- 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 Behav. Dev.* **11**, 477-495.
- Perrott, D. R., Marlborough, K., Merrill, P., and Strybel, T. Z. (1989). "Minimum audible angle thresholds obtained under conditions in which the precedence effect is assumed to operate," *J. Acoust. Soc. Am.* **85**, 282-288.
- Rakerd, B., and Hartmann, W. M. (1985). "Localization of sound in rooms, II: The effect of a single reflecting surface," *J. Acoust. Soc. Am.* **78**, 524-533.
- Shaw, B. K., McGowan, R. S., and Turvey, M. T. (1991). "An acoustic variable specifying time-to-contact," *Ecol. Psychol.* **3**, 253-261.
- Shinn-Cunningham, B. G., Zurek, P. M., and Durlach, N. I. (1993). "Adjustment and discrimination measurements of the precedence effect," *J. Acoust. Soc. Am.* **93**, 2923-2932.
- Wallach, H., Newman, E. B., and Rosenzweig, M. R. (1949). "The precedence effect in sound localization," *J. Am. Psychol.* **57**, 315-336.
- Wertheimer, M. (1961). "Psychomotor coordination of auditory and visual space at birth," *Science* **134**, 1692.
- Whitfield, I. C., Cranford, J., Ravizza, R., and Diamond, I. T. (1972). "Effects of unilateral ablation of auditory cortex in cat on complex sound localization," *J. Neurophysiol.* **35**, 718-731.
- Withington-Wray, D. J., Binns, K. E., and Keating, M. J. (1990). "A four-day period of bimodality auditory and visual experience is sufficient to permit normal emergence of the map of auditory space in the guinea pig superior colliculus," *Neurosci. Lett.* **116**, 280-286.
- Woodworth, R. S. (1938). *Experimental Psychology* (Holt, New York).
- Yakovlev, P., and Lecours, A. (1967). "The myelogenetic cycles of regional maturation of the brain," in *Regional Development of the Brain in Early Life*, edited by A. Minkowski (F. A. Davis, Philadelphia), pp. 3-70.

- Yin, T. C. T. (1994). "Physiological correlates of the precedence effect and summing localization in the inferior colliculus of the cat," *J. Neurosci.* **14**, 5170-5186.
- Yin, T. C. T., and Litovsky, R. Y. (1993). "Physiological correlates of the precedence effect: Implications for neural models," *J. Acoust. Soc. Am.* **93**, 2293.
- Yonas, A., and Granrud, C. (1985). "Reaching as a measure of infants' spatial perception," in *Measurement of Audition and Vision During the First Year of Postnatal Life: A Methodological Overview*, edited by G. Gottlieb and N. Krasengor (Ablex, Norwood, NJ), pp. 301-322.
- Zelazo, P. R., Brody, L. R., and Chaika, H. (1984). "Neonatal habituation and dishabituation of head turning to rattle sounds," *Infant Behav. Dev.* **7**, 311-321.
- Zurek, P. M. (1987). "The precedence effect," in *Directional Hearing*, edited by W. A. Yost and G. Gourevitch (Springer-Verlag, New York), pp. 85-105.