Recent Advances in the Behavioral Study of Infant Audition: The Development of Sound Localization Skills

Les progrès récents dans l'étude du comportement de l'audition de l'enfant: le développement des capacités de localisation des sons

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Résumé

Notre connaissance de la façon dont les capacités de localisation des sons se développe durant les premières années suivant la naissance a beaucoup progressé au cours des dix dernières années. Dans le cadre de cet article, nous étudions les principales conclusions en la matière, et notamment la localisation du son le long du plan horizontal, par rapport au plan vertical, l'effet de l'otite moyenne sur les capacités de localisation, et le développement de la recherche sur une illusion, l'effet de préséance, qui joue un rôle primordial dans la localisation dans l'environnement naturel. Le cas échéant, les conséquences cliniques de ces conclusions sont soulignées.

Abstract

In the past 10 years there have been numerous advances made in our knowledge of how sound localization skills develop during the first few years following birth. In this article we review key findings in this area, with particular attention to: sound localization along the horizontal as compared to vertical plane, the effect of otitis media on localization skills, and developmental research on an illusion, the precedence effect, which plays an important role in localization in the natural environment. Where appropriate, clinical implications of the findings are highlighted.

Sound localization abilities are present in nearly every animal that possesses a hearing mechanism (see Erulkar, 1972). These skills allow organisms to direct attention toward significant events in the environment, such as nearby prey and approaching predators, and facilitate learning about important auditory-visual correspondences, such as the vocal and facial features of a primary caretaker. Several early reports in the clinical pediatrics literature indicated that human newborns possess some sound localization skills (Brazelton, 1973; Hammond, 1970). However, it is only since 1979 that investigators have systematically studied these skills in human infants under controlled experimental conditions. Since that time, considerable advances have been made in our understanding of the acoustic cues that infants use in localizing sounds and the accuracy with which they perform these tasks.

In the following sections we will review literature on infants' localization of sounds along the horizontal axis and the vertical axis. In addition, we will consider research examining the effect of otitis media with effusion on localization performance, and developmental work on the precedence effect, which is an auditory illusion that operates in sound localization and may have clinical utility in identifying listeners with temporal lobe lesions.

Developmental Changes in Localization Along the Horizontal Axis

Research with young infants indicates that the ability to orient the head toward lateralized sound (i.e., right vs left of midline) is present even in newborns. Muir and Field (1979) were the first to demonstrate this under rigorously controlled experimental conditions. Awake, alert fullterm neonates were held, in a nearly supine position, between two loudspeakers located at 90 degrees relative to midline. The experimenter holding the baby wore masking headphones to prevent his knowing from which side the sound was presented. On a trial, a tape recording of a rattle sound was presented until the infant made a head turn response or for a maximum of 20 seconds; the rattle, a plastic bottle partly filled with popcorn kernels, produces a fairly broadband sound with peak energy at about 2700 Hz (cf. Morrongiello & Clifton, 1984). Scoring the videorecords indicated that neonates turned their heads toward the side from which the sound was presented on a significant number of trials (see also Clifton, Morrongiello, Kulig, & Dowd, 1981a, 1981b; Morrongiello & Clifton, 1984). Thus, newborn infants can determinate the general direction from which a sound is presented and will orient their head towards lateralized sound.

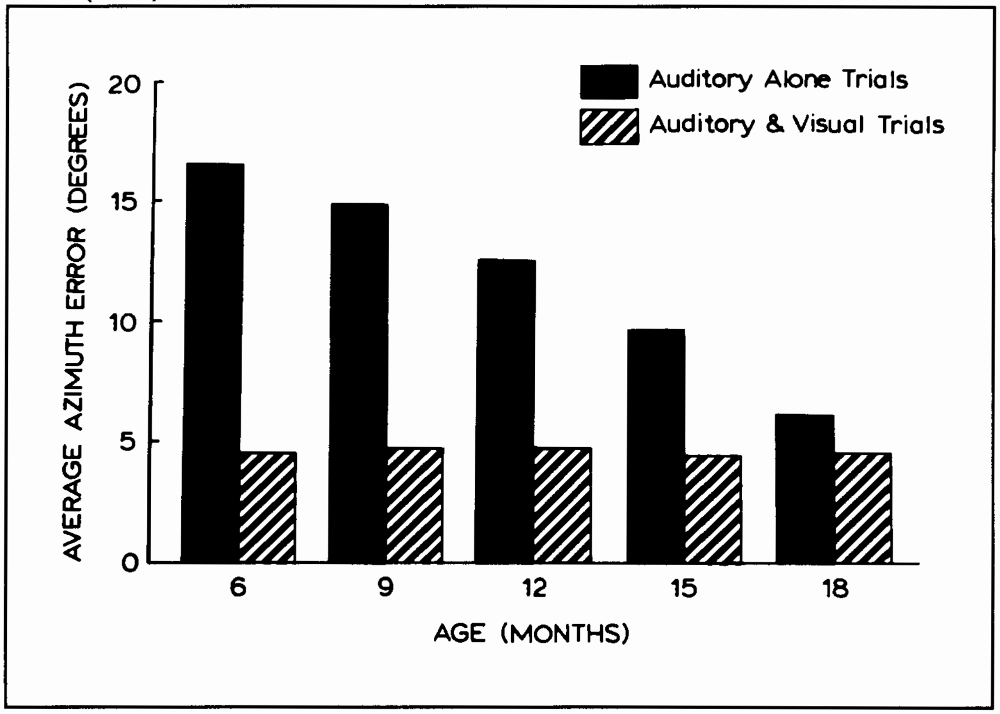
This behavior, however, has since been shown to be influenced by a number of factors, including sound duration (Clarkson, Clifton, & Morrongiello, 1985) and frequency. For example, presenting a low-frequency bandpass rattle (i.e., frequencies less than 1600 Hz), results in significantly less head orientation to sound in comparison to that observed in response to a mid-frequency bandpass rattle (i.e., 1000-3000 Hz), a high-frequency bandpass rattle (i.e., frequencies above 1800 Hz) or the unfiltered broadband rattle (Morrongiello & Clifton, 1984). The likelihood of lateralized responses to sound depends too on the distribution of lateralized versus non-lateralized sound presentations (Clarkson, Morrongiello, & Clifton, 1982). The likelihood of a lateralized response increases as the probability of lateral sounds increases from .25 to .75 relative to nonlateralized-sound trials. Because of this, Clarkson et al. (1982) have suggested that lateral sound trials occur on at least 50% of all trials when testing neonates. Finally, several studies have demonstrated that the presence of salient visual and tactile stimulation can significantly disrupt infants' head orientation to sound (Fischer-Fay, 1981; Muir, unpublished, cited in Muir & Clifton, 1985). Thus, although newborns are capable of head orientation toward lateralized sound, the likelihood of their demonstrating this behavior depends on sound duration, sound frequency, the relative distribution of lateralized and nonlateralized trials, and the extent to which there is competing visual and tactile stimuli.

Extending this research to older infants has provided important insights into the nature of the turn-to-sound response observed in newborns. Using the same procedure with infants 2, 3, 4, and 5 months of age, Muir and his colleagues observed a decline in the frequency of head orientation responses toward lateralized sound at about 2 to 3 months of age, followed by a reinstatement of this behaviour at about 4 months, resulting in a U-shaped developmental function (Field, Muir, Pilon, Sinclair, & Dodwell, 1980; Muir, Abraham, Forbes, & Harris, 1979). Other experimenters subsequently noted that the head orientation response of the 5-month-old differs in several important ways from that of the newborn. The re-emergence of this response is marked by a significant decrease in latency of the response, from 7 sec in the newborn to about 3 sec at 5 months (Morrongiello & Clifton, 1984). Furthermore, unlike the newborn who continues to produce the response over many trials, in 5-month-olds the behaviour quickly drops out unless it is visually reinforced (Clifton, Morrongiello, & Dowd, 1984). Thus, for older infants head orientation to sound seems to be a *voluntary* behaviour that facilitates visual exploration, whereas in newborns the consistency and robustness of the response is suggestive of other neonatal *reflexive* behaviours that are subcortically mediated and drop out with increasing age. In humans, the auditory cortex is substantially undeveloped at birth, relative to subcortical structures, and undergoes significant changes during the first few years of life (Conel, 1939-1963; Dekaban, 1970; Hecox, 1975. For these reasons, there has been considerable speculation that the U-shaped function may reflect postnatal development of the central auditory system and indicate age-related increasing involvement of the auditory cortex in processing information about the spatial locus of a sound (for further discussion see Clifton et al., 1981a, 1981b; Muir & Clifton, 1985).

Although young infants discriminate sound laterality, this tells us little about their ability to localize a sounding object in space. Knowing the general direction in which to focus attention represents only a first step in the process of sound localization. Accurate localization of a sound in space requires that one encode not only the general direction from which the sound occurred, but also the precise azimuth, elevation, and distance of the sound source. To examine localization accuracy per se, two test procedures have been used with adults and recently extended to infants: (1) an *absolute accuracy* procedure, in which the observer must indicate the exact spatial locus of a sound, such as by pointing or orienting the head to face the sound source, and (2) a *localization acuity* procedure, in which one determines the smallest angular shift in sound location that the listener can discriminate reliably, otherwise known as *minimum audible angle*, MAA (cf. Mills, 1958). In the latter case the sound typically starts at midline and then moves either to the right or left of this location. The listener usually is asked to indicate only the direction in which the sound has moved, not its exact location. If she can do this at greater than chance levels (i.e., 50%), then the magnitude of the sound shift has exceeded her MAA. These two test procedures place very different response demands on the listener and, consequently, they do not necessarily yield comparable estimates of localization accuracy (Perrott, Ambarasoom, & Tucker, 1987). Nonetheless, they both have provided important insights into infants' localization skills.

Using an absolute accuracy procedure to evaluate infants' localization of a series of clicks, Morrongiello and Rocca (1987a) found systematic improvements between 6 and 18 months of age for sounds positioned between 18 and 90 degrees from midline. Infants were tested in a darkened chamber and presented two types of trials: *auditory alone* trials, in which only the sound cue was provided to indicate location, and *auditory-visual* trials, in which a visual localization cue (i.e., light display at the loudspeaker) accompanied the auditory stimulus. When a visual localization cue accompanied the sound, infants at all ages were able to orient the head to face this location within 4 to 5 degrees. This finding was important because it indicated that infants at all ages were capable of orienting the head with the same degree of precision, demonstrating that accurate localization was not constrained by motor limitations per se. When only a sound cue was provided to indicate location, however, the average sound localization error (averaged over azimuth position, which differentially influenced performance) was about 16 to 17 degrees for 6-month-olds, and systematically declined with age

Figure I. Average absolute azimuth error (in degrees) collapsed over signal location, as a function of trial type at each age (in months). These data are from Morrongiello & Rocca (I987a).



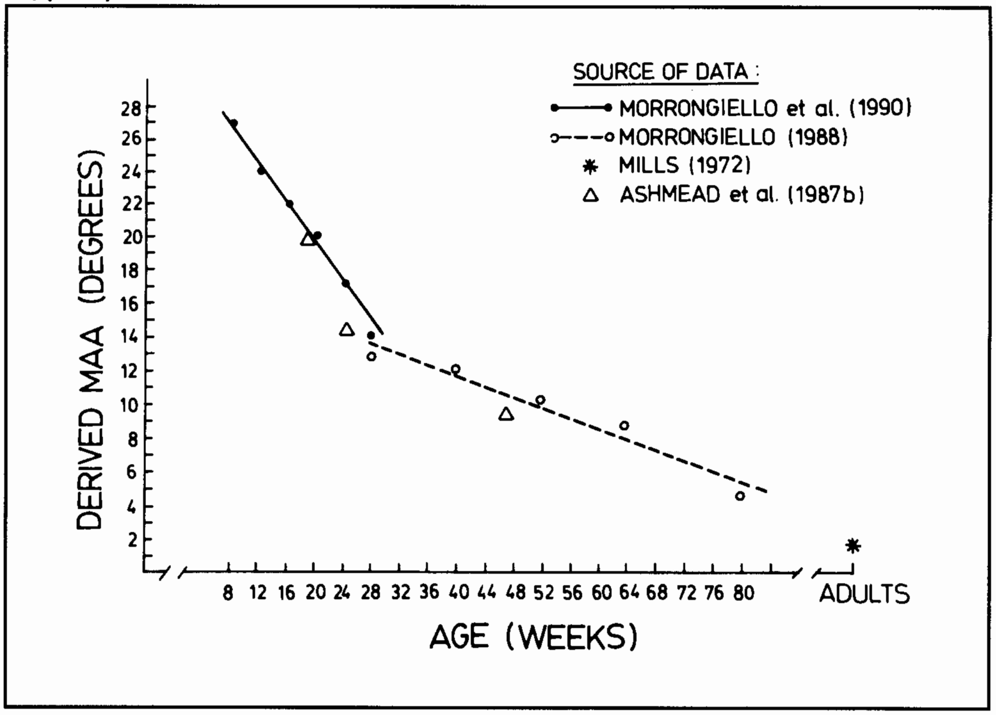
until, at 18 months, infants performed as well as when a visual localization cue was presented simultaneously (see Figure 1). These findings suggest that young infants rely heavily on visual localization cues when orienting to sounding objects in the environment. With increasing age infants may be better able to construct a spatial map of object locations based purely on sound cues.

Similar developmental trends have been observed using MAA procedures to examine localization acuity in infants (Ashmead, Clifton, & Perris, 1987a; Ashmead, LeRoy, Whalen, & Odom, 1987b; Morrongiello, 1988). In this procedure, Morrongiello had infants seated on the parent's lap in a darkened chamber facing a loudspeaker array, with one loudspeaker at midline, 0 degrees, and several others off to the right and left of midline. The parent wore masking headphones to prevent the reliable detection of direction of sound shift. On a trial, white noise bursts were presented at midline with a light display, thereby providing the infant with a visual and auditory localization cue. Once the infant's head was centered at midline, the light turned off and the sound moved to be presented from another loudspeaker off to the right or left of midline. An experimenter observed the infant's head and eye movements and decided for each trial whether the infant oriented toward the right or left; the experimenter knew when a trial was being presented but was naive as to direction of sound shift. Correct directional responses resulted in the infant's seeing another light display in the direction in which she had responded, which served to reinforce her following the sound when it moved from midline. Incorrect responses yielded no light display. A Method of Constant Stimuli psychophysical procedure was used to determine the smallest location shift that infants could discriminate reliably above chance level (.50).

The results are shown in Figure 2 (dotted line), along with data from adults (Mills, 1972) and other infants (Ashmead et al., 1987b) that was gathered using a Method of Limits psychophysical procedure. As can be seen there are systematic improvements in localization acuity with increasing age between 6 and 18 months, and there is fairly good correspondence between Ashmead et al.'s (1987) and Morrongiello's data. Whether infants at 18 months perform at adult levels remains to be determined. Since they were not tested with sound shifts less than 4 degrees, their estimated MAA must be cautiously interpreted. Consequently, we do not know at what age infant MAA performance reaches adult levels.

Extending this research to infants under 6 months revealed data consistent with these developmental trends (Morrongiello, Fenwick, & Chance, 1990). Because head orientation to sound is unreliable in infants 2 to 3 months of age, the headturn paradigm was not appropriate for this age group. Consequently, an observer-based procedure was used (cf. Olsho, Koch, Halpin, & Carter, 1987). Infants were presented

Figure 2. Derived minimum audible angle thresholds (in degrees) as a function of age (in weeks). For information on how these estimates were derived, see Morrongiello et al., (1990).



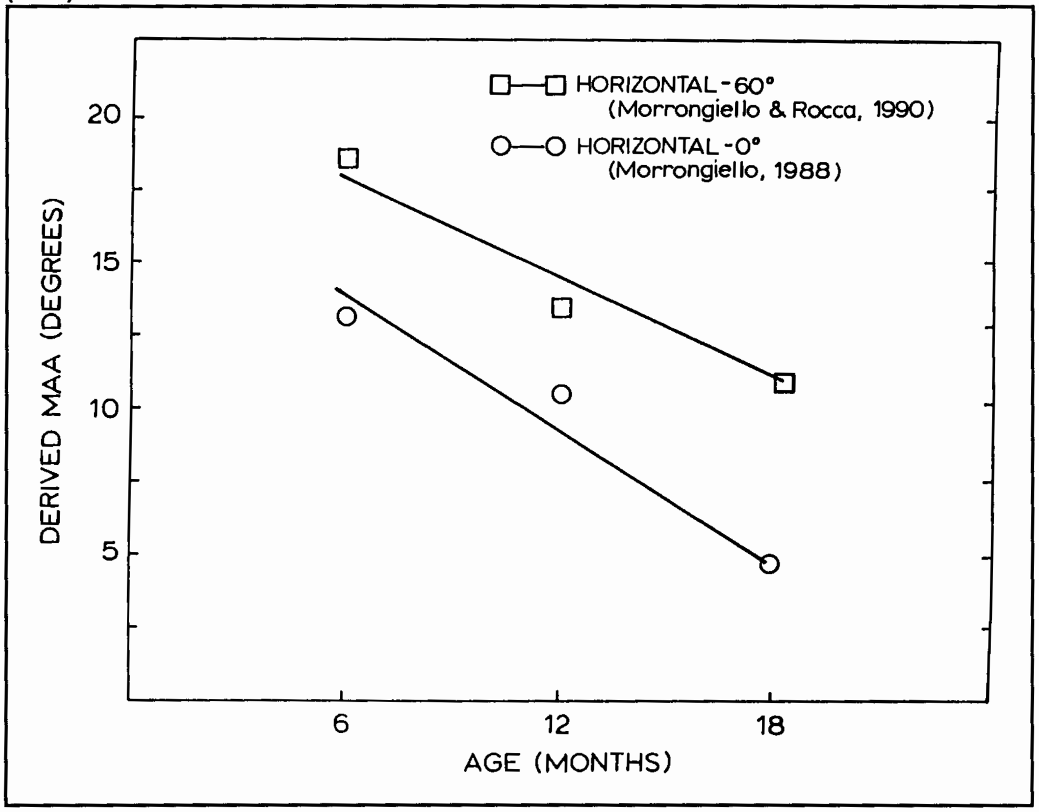
with an equal number of randomly ordered sound-shift (experimental) and no-shift (control) trials. The experimenter had to decide, based on observation of any of the infant's behaviours (e.g., alerting, quieting, eye movement, directional body movements) whether or not a sound-shift trial had occurred. If the observer judged correctly that a sound-shift trial had occurred, then the infant was presented a brightly colored light display to reinforce her repeating on the next experimental trial whatever behavior had cued the observer that the sound had changed location. Correct judgements by the observer on no-shift trials did not produce any such reinforcement for the baby. For the present study, MAA was defined as the smallest magnitude of sound shift for which the observer correctly judged the infant's behaviour significantly above chance level (.50).

As can be seen in Figure 2 (solid line), the younger the infant, the poorer was localization acuity. Furthermore, comparing the slopes of these two functions indicated a significant difference in the rate of development of localization acuity across these two age ranges. For the younger ages the rate of change in localization acuity was more rapid than for the older age range. This difference in rate of development may relate to differences in testing procedures across the two age ranges. However, infants at 5 to 6 months performed comparably (i.e., within 2 degrees) in both the observer-based MAA procedure used with the younger age range and the MAA procedure used with the older age range. Nonetheless, the best test of whether the rate of improvement in localization acuity actually changes between 4 and 6 months of age would be to do longitudinal testing of infants. To our knowledge, this has not yet been done. Suffice it to say, the developmental function in Figure 2 is fairly continuous between 2 and 18 months and reveals no abrupt age shifts or reversals in performance. This continuity is especially striking too if one considers the discontinuity that has been noted for head orientation to sound during this age range (e.g., Clifton et al., 1981b; Field et al., 1980; Muir et al., 1979).

In adults, localization acuity is best near midline and steadily worsens for sounds positioned off midline and within hemifields. For example, adults can discriminate a sound shift from midline of only 1 to 2 degrees. By contrast, for a sound at 60 degrees azimuth adults require a location shift on the order of 4 to 6 degrees for reliable discrimination, and at 90 degrees azimuth, discrimination is as poor as 40 degrees for some frequencies (Mills, 1972). Thus, for adults, localization acuity along the horizontal axis is much poorer within hemifields as compared to near midline.

In order to determine if infants organize auditory space in the same way as adults, MAAs were determined for a sound within hemifields (Morrongiello & Rocca, 1990). To test infants a Go/No-Go conditioned head turn procedure was used (Moore & Wilson, 1978). In this situation the infant was seated on a parent's lap facing an experimenter who was

Figure 3. Derived minimum audible angle thresholds (in degrees) as a function of age (in months). For information on how these estimates were derived, see Morrongiello & Rocca (1990).

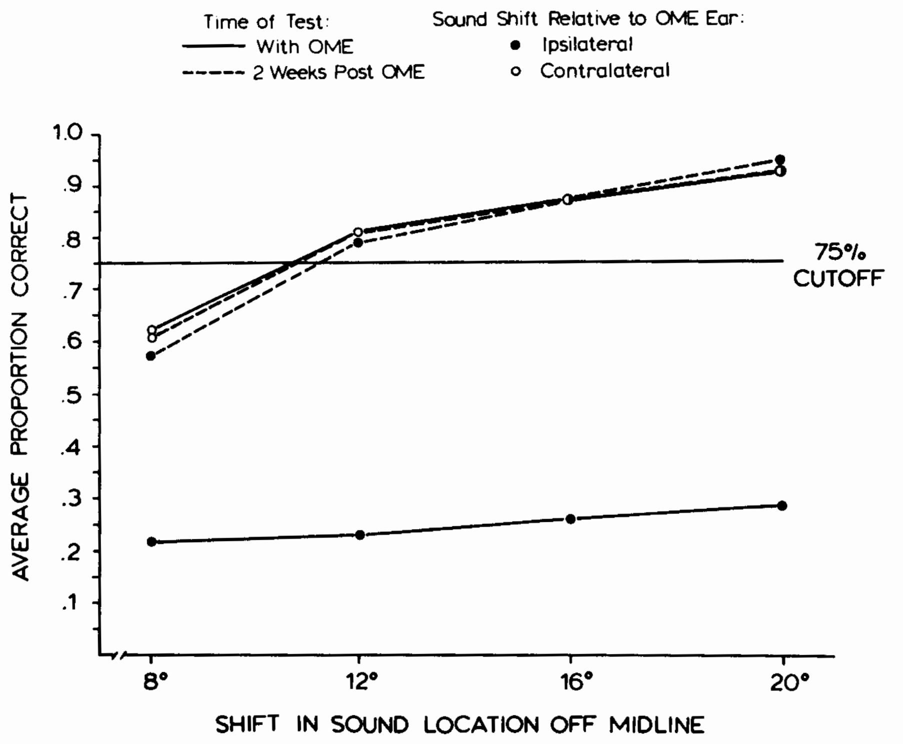


presenting silent toys to the infant; both the parent and experimenter wore masking headphones to prevent their detection of trials. White noise bursts were constantly presented from a loudspeaker at 60 degrees azimuth, relative to the infant's midline. On experimental trials, the sound shifted in location to a loudspeaker to the right or left of this 60 degree speaker. A head turn by the infant toward the loudspeaker array on experimental trials resulted in presentation of a visual reinforcer (i.e., mechanical toy), which served to maintain the infants' attention and motivation to listen for a sound shift. On control trials, the sound continued to be presented at 60 degrees, and head turns were recorded but not reinforced. Control trials provided an index of spontaneous head turn rate or chance performance level against which performance on experimental trials could be compared.

As can be seen in Figure 3, which shows the current data and that reported above for MAA at midline, infants showed poorer localization acuity for a sound at 60 degrees azimuth than near midline. Comparing the slopes of these two functions, however, revealed no differences. Thus, while absolute performance levels were poorer at 60 degrees than at midline, the rate of developmental change in localization acuity was comparable across these two areas along the horizontal axis. Although different testing procedures were used and, consequently, one must be cautious in making comparisons across studies, these findings suggest that infants organize auditory space along the horizontal axis in much the same way that adults do, namely, with localization acuity greatest near midline. Furthermore, consistent with previous findings based on other test procedures, localization acuity for a sound within hemifields improved with increasing age, suggesting developmental changes in this aspect of auditory functioning.

In summary, the results of research on infants' localization of sounds along the horizontal axis indicate that, for a number of measures of localization accuracy, resolution of auditory space systematically improves with increasing age during the first 18 months of life. The extent to which newborn infants accurately localize sound remains to be determined (for discussion of some preliminary data see Muir & Clifton, 1985). At 2 months, however, infants seem fairly poor in localizing sound in the absence of visual localization cues. By 18 months, infants are as accurate in orienting to the location of a sound as to the location of a visual stimulus. The age at which infants reach adult levels of localization acuity remains to be determined.

Figure 4. Average proportion correct response (eye and/or head orientation in direction of sound shift) for each angle condition as a function of OME status and direction of sound shift relative to OME ear. These data are from Morrongiello (1989).



The Effect of Otitis Media with Effusion on Horizontal Localization

One clinical occurrence that can have a significant impact on localization acuity along the horizontal axis is middle ear infection or otitis media with effusion (OME). OME is a common infectious disease in early childhood and refers to an accumulation of fluid in the middle ear space. Mild to moderate conductive hearing loss typically accompanies OME. For example, using a behavioural test for hearing, Huber and colleagues found that the presence of a conductive loss in young infants correctly predicted OME in 87% of the cases (Huber, Strangler, & Routh, 1978).

OME can negatively affect localization performance because it produces a binaural imbalance, which distorts the primary acoustic cues used in horizontal localization. Research with adults indicates that localization of a sound along the horizontal axis depends on two binaural cues: an interaural difference in the time of arrival of the sound wave at each ear and an interaural difference in sound pressure (Green, 1976; Shelton & Searle, 1978). For example, a sound off to the right of midline arrives first and is louder at the right than the left ear. With a monaural hearing loss, however, the balance of these cues is disrupted with the consequence that the sound is perceived as displaced in location toward the well functioning ear (Butler, 1986, 1987).

To examine if disrupted binaural hearing produces comparable effects on sound localization in infants, infants 6 to 18 months of age who had OME were tested (Morrongiello, 1989). Infants were tested at the time of an episode of OME (diagnosis by otoscopic exam) and two weeks later. All infants were on antibiotics in the interim. In this way we hoped to determine if three or fewer episodes of OME produced any lasting effects on localization acuity. To examine localization acuity infants were given a MAA test with the sound at midline, as described previously.

As can be seen in Figure 4, consistent with adult data, when the sound shifted ipsilateral to the infected ear, the infant mislocalized it toward the well functioning ear about 75% of the time. By contrast, a sound shift toward the well functioning ear was correctly localized a majority of the time. Two weeks after the episode of OME, there was no difference in group performance as a function of whether the sound shifted ipsilateral or contralateral to what had been the infected ear. Thus, with three or fewer episodes of OME there appeared to be no lasting negative effects on localization acuity. Although additional research is needed on this topic, particularly with chronic OME cases, the results from this one study highlight the plasticity of the human auditory system and indicate its capacity to tolerate at least some degree of binaural imbalance during development.

Development of the Perception of the Precedence Effect Illusion

The precedence effect (PE) is an auditory illusion that facilitates sound localization in a reverberant setting (see Mills, 1972). With the PE the first sound wave is given precedence in determining the spatial locus of a sounding object (Blauert, 1971; Wallach, Newman, & Rosenzweig, 1949). In the natural environment, for example, we would be unable to determine the actual spatial locus of a sound unless we gave differential weighting to the first sound wave to strike the ears, relative to subsequent reverberant waves from the source. As long as subsequent waveforms arrive within a minimal time interval, they do not influence the perceived location. If, however, their arrival exceeds this minimal time interval, then they are heard as echoes. The time interval over which the PE operates varies with signal characteristics but is usually between 1 and 50 msec (Gardner, 1968).

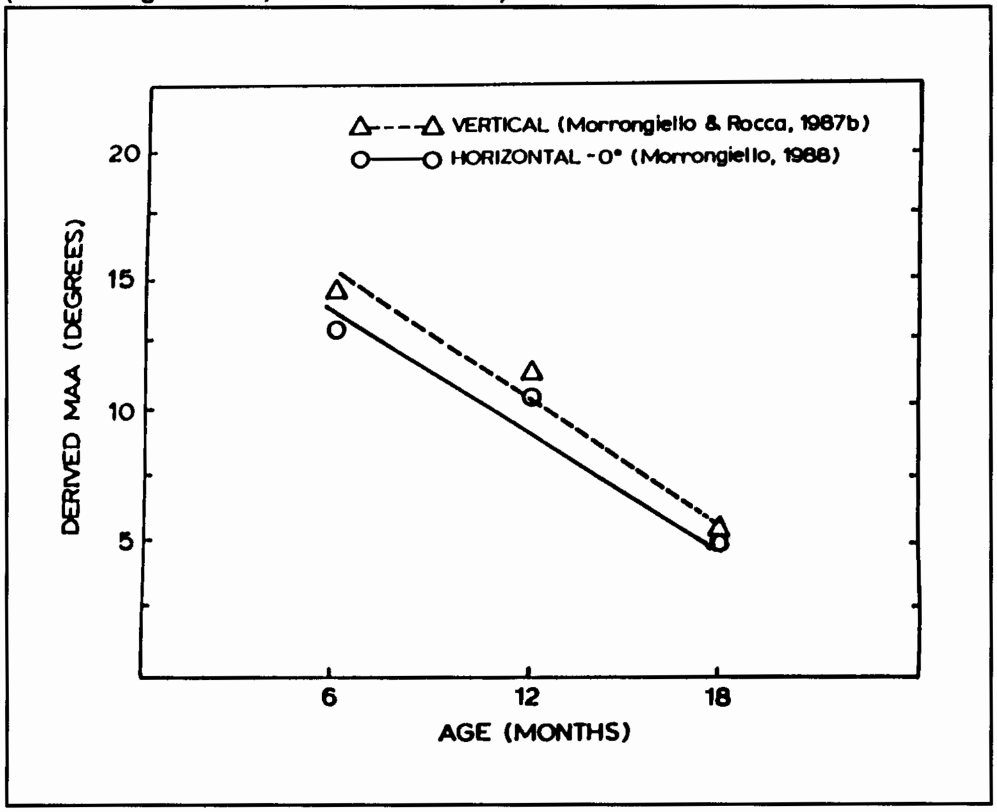
The PE may prove useful clinically and in developmental research because it seems to involve cortical processing (for further discussion see Clifton, 1985). Research with lower-order animals indicates that unilateral lesions of the auditory cortex result in the inability to localize toward the leading sound if this is contralateral to the damaged cortex, although the same animals are not impaired in localizing sounds presented from a single loudspeaker either ipsilateral or contralateral to the ablated cortex (Cranford, Ravizza, Diamond, & Whitfield, 1971; Whitfield, 1978; Whitfield, Cranford, Ravizza, & Diamond, 1972; Whitfield, Diamond, Chiveralls, & Williamson, 1978). Furthermore, single units have been located in the cat's auditory cortex that respond selectively to delayed clicks when the contralateral click led by 5 to 10 msec (Whitfield, 1974). This effect has been demonstrated too in research on the PE in children with temporal lobe epilepsy (Hochster & Kelly, 1981). Finally, it has been noted with human adults that unilateral lesions of the temporal lobe produce deficits in localizing sound in the contralteral half space (Jerger, 1960; Sanchez-Longo & Forster, 1958; Wortis & Pfeffer, 1948). These diverse findings suggest then that the PE may be useful in indicating the presence of cortical processing problems, structural damage, or abnormal early growth and development of the auditory cortex.

Because the auditory cortex of human infants is immature at birth and undergoes dramatic changes during the first few years of life, Clifton reasoned that one might expect both early difficulty in localizing sounds that are presented so as to produce the PE illusion and developmental improvements with increasing age. To test this hypothesis responses to the PE illusion was examined in newborns (Clifton, et al., 1981a) and 2- and 6-month-olds (Clifton et al., 1984). Infants were presented two types of trials: (1) *PE* trials in which the same sound was fed through two loudspeakers, each one 90 degrees to the left and right of midline, with one loudspeaker output leading the other by several milliseconds; and (2) *single source* (SS) trials in which the same sound was presented but from one loudspeaker only. For listeners who experience the PE illusion, these two trials seem identical, as though a single sound was presented from one loudspeaker. That is to say, for the PE they orient towards the leading loudspeaker without even recognizing the presence of the lagging one. Because infants at 2 months may not head turn toward sound, heart rate changes were recorded at this age to determine if these responses differentiated PE and SS trials.

The findings indicated developmental changes in infants' head orientation to sounds that yield the PE illusion. Newborns and 2-month-olds did not orient toward the leading side, suggesting that they may not experience the illusion. On most trials they did not head turn at all, and on a few trials they turned contralateral to the leading loudspeaker. By contrast, at 6 months infants responded to PE trials as adults did, quickly turning the head toward the leading loudspeaker on a significant number of trials. For SS trials, the newborns and 6-month-olds readily turned the head towards these lateralized presentations. As reported previously, however, at 2 months, the incidence of this behaviour had declined significantly. Unfortunately, cardiac responding at 2 months did not differentiate PE and SS trials. Thus, by 6 months infants respond to the PE illusion just as adults do and orient their head towards the leading loudspeaker. Newborns seem unable to lateralize this complex sound, although they have no difficulty with SS sounds. At 2 months, infants behave as newborns, suggesting that the transition period for responding to the PE illusion occurs between 2 and 6 months of age. This is not to say, however, that there are not additional developmental changes beyond 6 months in responding to the PE illusion. In fact, the delay interval over which listeners experience the PE illusion and respond to the leading sound only changes between 6 months, 5 years, and adulthood (Morrongiello, Clifton, & Kulig, 1984).

These findings are not surprising if the precedence effect does require the auditory cortex. For example, myelination of the auditory cortex does not begin until about 3 months, and it continues rapidly during the first 2 years of life and throughout childhood (Gibson, 1981; Yakovlev & Lecours, 1967). To

Figure 5. Derived minimum audible angle thresholds (in degrees) as a function of age (in months). Estimated MAAs for the vertical axis were derived as for the horizontal axis (see Morrongiello et al., 1990 for discussion).



the extent then that the precedence effect involves cortical processing, it may prove a useful clinical indicator of CNS development and dysfunctioning.

Developmental Changes in Localization Along the Vertical Axis

There has been considerable speculation as to whether or not vertical localization development lags behind that of horizontal localization. Northern and Downs (1978), for example, indicate that lateral head movements emerge in infancy before vertical ones (see also Watrous, McConnell, Sitton, & Fleet, 1975). This does not necessarily mean, however, that acuity in localization per se differs along these axes. Infants may be comparably able to discriminate a sound shift along both axes, but better able to execute a horizontal than vertical head movement. To evaluate this possibility MAAs for the median vertical plane were obtained for infants 6 to 18 months of age (Morrongiello & Rocca, 1987b). Infants were tested using the same stimulus (white noise bursts) and procedure as for our horizontal MAA study (aforementioned) except that they were required to indicate a sound shift above or below eye level by making a vertical head or eye movement.

As can be seen in Figure 5, at all ages, localization acuity was better for the horizontal than vertical plane; since 18-month-olds were not tested at values less than 4 degrees in the horizontal and vertical tasks and their MAA estimates are based on few subjects who did not perform at ceiling levels, we cannot say whether a difference in performance across axes is evident at this age as found for younger infants and, once again, the estimates for this age must be cautiously interpreted. The rate of change in acuity with increasing age (i.e., the slope of these functions) did not differ across axes. Thus, absolute precision in localization is poorer, but the rate of development does not differ for the vertical relative to the horizontal axis. Although there are few data on adults' vertical localization skills (Wettschureck, 1973), it is of interest to note for them also that vertical acuity is poorer than horizontal acuity is at midline, MAA of about 4 degrees vs 1 to 2 degrees, respectively. It would seem then that, in humans, resolution of auditory space is greater along the horizontal than vertical axis and that this difference is present by 6 months of age.

Although developmental improvement in localization acuity proceeds at comparable rates for the horizontal and vertical axes, in fact, localization of a sound along the vertical axis

Table 1. Proportion correct responses (eye and/or head movement in direction of sound shift) at each age (in months) as a function of signal bandwidth and angle of vertical shift in sound location from 0 degrees (i.e., midline at ear level). The value designated by an asterisk indicates the smallest location shift reliably detected (chance = 0.50). The numbers in parentheses are the standard deviations.

	4 kHz				4-8 kHz				8-12 kHz			
Age	4°	8°	12°	16°	4°	8°	12°	16°	4°	8°	12°	16°
6	0.46	0.45	0.45	0.52	0.51	0.47	0.50	0.58	0.49	0.55	0.52	*0.77
	(0.16)	(0.17)	(0.15)	(0.14)	(0.14)	(0.16)	(0.15)	(0.14)	(0.15)	(0.14)	(0.12)	(0.11)
9	0.48	0.42	0.47	0.51	0.53	0.50	0.57	*0.65	0.48	0.55	*0.77	0.87
	(0.14)	(0.16)	(0.14)	(0.15)	(0.12)	(0.15)	(0.16)	(0.14)	(0.14)	(0.12)	(0.13)	(0.12)
12	0.44	0.47	0.45	0.45	0.49	0.52	*0.65	0.72	0.51	0.47	*0.82	0.87
	(0.15)	(0.17)	(0.16)	(0.16)	(0.15)	(0.14)	(0.12)	(0.13)	(0.14)	(0.14)	(0.12)	(0.13)
15	0.47	0.45	0.47	0.45	0.51	0.57	*0.67	0.70	0.55	*0.82	0.85	0.86
	(0.15)	(0.16)	(0.17)	(0.17)	(0.13)	(0.14)	(0.12)	(0.10)	(0.13)	(0.11)	(0.12)	(0.13)
18	0.54	0.55	0.50	0.52	0.55	0.50	*0.68	0.72	*0.74	0.82	0.85	0.90
	(0.16)	(0.16)	(0.17)	(0.15)	(0.11)	(0.15)	(0.12)	(0.11)	(0.12)	(0.10)	(0.12)	(0.13)

depends on very different cues than for the horizontal axis. Research with adults highlights the significance of pinna-based spectral cues and the necessity of frequencies greater than 5 to 7 kHz for accurate localization along the medial vertical plane. Because of the size, shape, and position of the pinna, high frequencies maximally interact with this structure to produce spectral cues that indicate sound elevation (Fisher & Freedman, 1968). Consequently, if one occludes the pinna or limits signal frequencies to less than 5 kHz, adults show significant increases in vertical localization errors (Gardner, 1973; Gardner & Gardner, 1973; Roffler & Butler, 1968a, 1968b).

If high frequency information is essential for vertical localization in infants, then one might predict an increase in localization errors when the spectrum of a sound is limited to low frequencies. To test this hypothesis MAAs were obtained for infants under three filtered-noise conditions: 4kHz, 4 to 8 kHz, and 8 to 12 kHz (Morrongiello, 1987). Infants 6 to 18 months were tested as before (aforementioned). A 3-way interaction involving age, frequency, and angle condition indicated that MAA performance varied across age as a function of sound frequency. As can be seen in Table 1, infants at all ages were unable to localize the sound above chance (.50) when frequencies were limited to less than 4 kHz. As has been noted for adults then, the low frequency content of a signal apparently contributes little to infants' perception of sound elevation. By contrast, infants from 9 months could localize some sounds along the vertical axis if frequencies greater than 4 kHz were present, and the sound shifted by at least 16 degrees. Furthermore, MAA performance was significantly better (i.e., infants discriminated a smaller sound shift) for the signal comprising frequencies above 8 kHz than for the signal having frequencies between 4 and 8 kHz. At every age except 12 months, MAAs were smaller, indicating better localization acuity, for the 8 to 12 kHz signal as compared to the 4 to 8 kHz signal. Owing to the small size of an infant's pinna, one would expect that the higher the frequency (i.e., the shorter the wavelength), the better the spectral cues produced to indicate sound elevation. These findings suggest that infants, like adults, depend primarily on high frequency perception in determining sound elevation.

Possible Mechanisms Contributing to Developmental Changes in Localization Performance

The developmental improvements observed may reflect changes in a number of aspects of infant functioning that span both sensory and nonsensory domains. Improvements in localization acuity along the horizontal axis might reflect age-related changes in infants' encoding of interaural time and/or intensity cues. Age-related improvements in temporal processing have been reported for both monaural tasks (e.g., duration discrimination: Morrongiello & Trehub, 1987; auditory fusion: Davis & McCroskey, 1980), as well as binaural tasks (e.g., resolving interaural timing differences in the PE: Morrongiello et al., 1984). In addition, there is evidence of improvements with age in monaural intensity resolution skills (Sinnott & Aslin, 1985) and infants' discrimination of interaural intensity differences (Bundy, 1980, but see Clifton et al., 1981b for discussion of limitations in interpreting these data). Thus, indirect evidence suggests that age-related changes in encoding interaural time and intensity cues may contribute to the observed developmental improvements in localization along the horizontal plane.

Improvements in vertical localization, however, are more difficult to link to changes in the acoustic cues that play a primary role in localization, namely, pinna-based high frequency spectral cues. The results of several studies highlight the exceptional high frequency hearing that is present even in very young infants and suggest that significant changes in sensitivity are restricted to low frequency hearing (less than 4000 Hz), which would not be expected to impact on vertical localization performance (e.g., Schneider, Trehub, & Bull, 1980; Trehub, Schneider, & Endman, 1980). Perhaps changes in the size and shape of the pinna with age (Pryor, 1966) significantly affect the cues produced that specify sound elevation. This is an area in which there is virtually no research.

Our observation that the rate of developmental change is the same for the horizontal and vertical axes might indicate too that a common mechanism is contributing to performance changes across these dimensions. Perhaps, with accumulated auditory-visual and sensory-motor experiences infants develop an increasing appreciation for how auditory cues correlate with the precise location of objects in space. In other words, there may be an extended learning or calibration process in which a sight-sound spatial map is built up or its use is perfected.

The notion of an ongoing calibration process in auditory space perception gains indirect support from several sources. First, for both vertical and auditory depth perception, there is evidence with adults indicating difficulty in localization upon the initial presentation of unfamiliar sounds, with improvement in performance over trials (Coleman, 1962; Hebrank & Wright, 1974). Thus there is some evidence indicating the significance of listening experience for localization performance. Second, evidence from adults reveals that under conditions of visual rearrangement from displacement prisms, there is increasing compensation in sound localization with accumulated visual exposure (e.g., Held, 1955; Rekosh & Freedman, 1967; Pick, Warren, & Hay, 1969). Similar auditory-visual interactions in localization have been observed for guinea pigs (Kelly, 1986) and barn owls (Knudsen & Knudsen, 1985). These findings again highlight the plasticity that exists in spatial coding. Furthermore they indicate the importance of multimodal interactions in auditory space perception and suggest that there may be a common mapping of auditory-visual space (see also Shelton & Searle, 1980; Whittington, Hepp-Reymond, & Flood, 1981). Thus, several lines of evidence provide indirect support for the hypothesis that the observed developmental trends in localization acuity may reflect, at least in part, an ongoing calibration process that contributes to the refinement of an auditory-visual map of space.

Finally, one must consider too that the observed changes in localization performance with age may reflect developmental changes in non-sensory factors, such as attention or motivation to perform the tasks. Although we have found no evidence in support of this explanation for the observed trends (e.g., subject attrition does not vary with age, the incidence of training trials does not typically vary with age), it cannot be dismissed out of hand (e.g., see Olsho, Koch, & Carter, 1988). One strategy to test this notion might be to extend this research and examine other responses that can indicate localization, such as reaching (Perris & Clifton, 1988) and crawling (Morrongiello, unpublished data) to sounding, invisible objects. Confirmation of the noted developmental trends using other response measures and testing procedures would support their validity. On the other hand, failure to replicate these trends need not challenge their validity. Research with animals, for example, indicates the importance of differentiating head orientation to sound from the ability to approach the precise location of the sound source (e.g., Heffner, 1978; Thompson & Masterton, 1978; Thompson & Welker, 1963). Nonetheless, extending the study of sound localization in infants to examine other behavioral responses would facilitate our developing a more thorough understanding of this important aspect of auditory functioning, and such research might provide insights into the contribution to performance, if any, of nonsensory factors.

Summary

While sound localization abilities are of fundamental importance for survival and learning about sight-sound correspondences in the natural environment, it is only in the last ten years that significant progress has been made in our knowledge of the development of these abilities in human infants. In that period we have come to learn that infants organize auditory space in a manner similar to adults, although localization accuracy and acuity undergo significant changes during the first 18 months after birth.

Infants' ability to localize sound along the horizontal axis depends on the encoding of interaural time and intensity differences. Apparently, even neonates can utilize these cues, at least to determine the general direction from which a sound is presented. Developmental improvements in horizontal localization between 6 and 18 months of age, however, would suggest continued improvements in infants' use of these binaural cues. Similarly, sound localization along the vertical axis, depending on an interaction of sound wave characteristics with the pinna, improves over the first 18 months of life. This is probably due, in part, to enhanced cues resulting from age-related changes in pinna size and shape. While development of sound localization abilities proceeds rapidly during infancy, adult-like performance is still not present by 15 months of age. Thus, there is a fairly lengthy developmental course for the acquisition of these important skills.

Because different aspects of sound localization are mediated by different structures of the auditory and the central nervous systems, sound localization tasks may provide a window on CNS and auditory system functioning. For example, high frequency hearing loss would likely be reflected in deficits in sound localization along the vertical axis. Unilateral hearing problems can be expected to create difficulties in localization along the horizontal axis. Finally, the inability to localize sounds presented so as to produce the precedence effect illusion may indicate abnormalities in temporal lobe functioning. Thus, the behavioural study of sound localization development may have significant implications for researchers and practitioners alike.

Acknowledgements
The authors would like to acknowledge the collaborators who contributed to the research reported herein, and the research assistants who have worked so hard to see these projects through to successful completion. The first author is the recipient of a University Research Fellowship award from The Natural Sciences and Engineering Research Council of Canada, which also has been the primary funding source for this research.

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