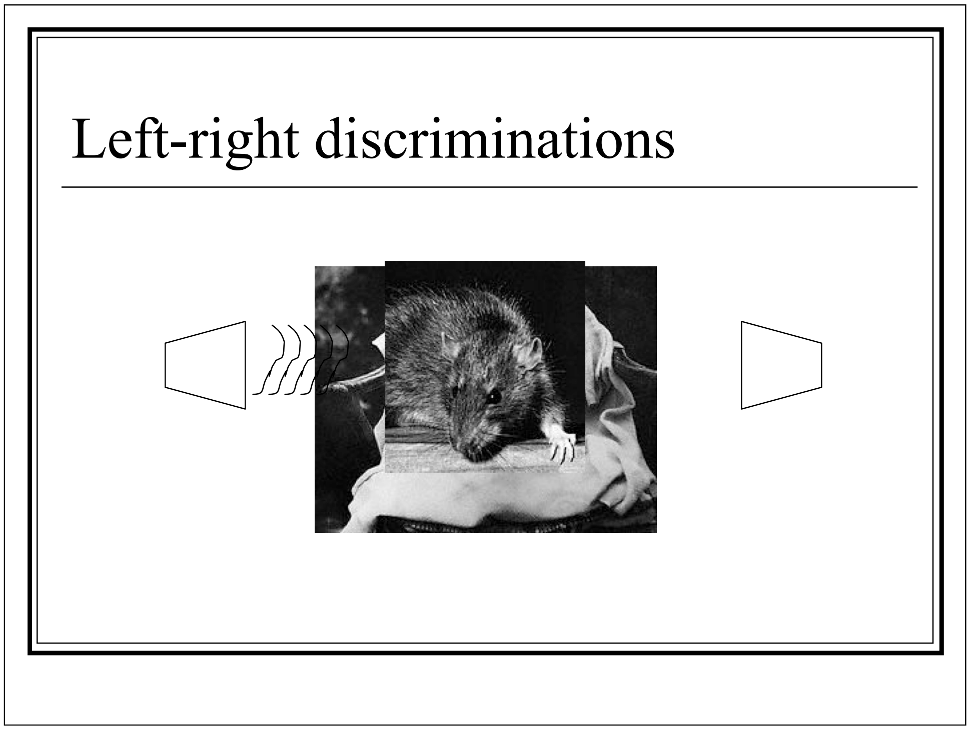
Development of sound localization

Acoustics, primary coding, neural computation could contribute to development of the ability to locate sound sources in space

Topics in development of sound localization

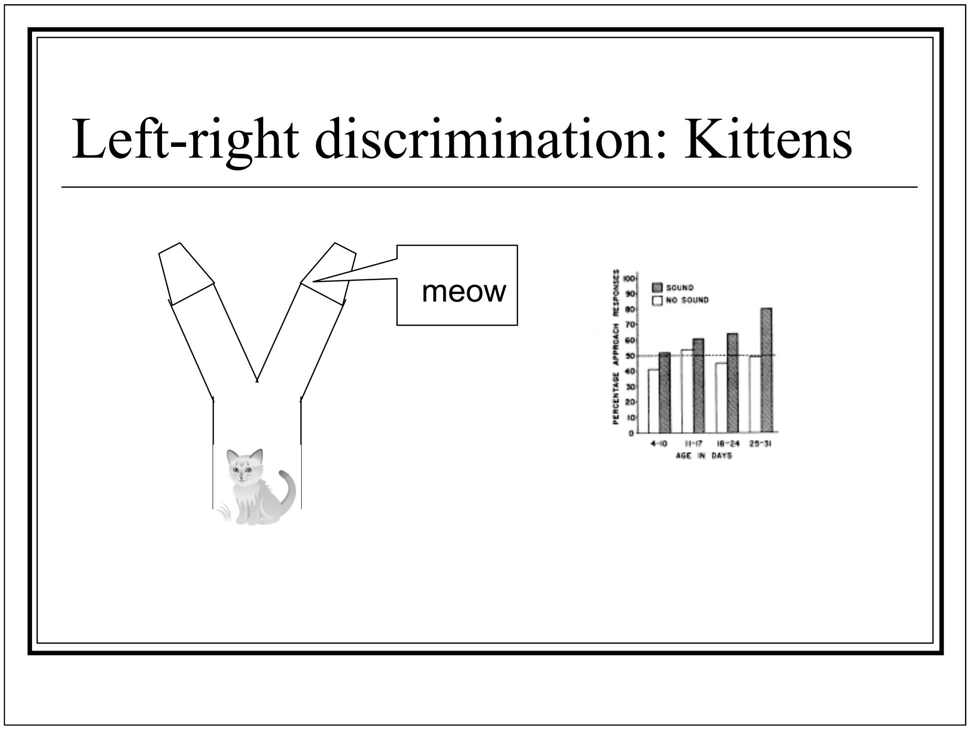
- When can infants first locate sounds?
- How accurate is localization during development?
- How could the development of binaural cue processing contribute?
- Other: distance perception and precedence effect

The development of sound localization has been of general interest for several reasons. One of these is the issue of how we come to associate a certain pattern of sound with a particular position in space. Does this require experience with sounds at different positions? Do we learn the connection between a particular pattern of sound and a pattern of light, or a pattern of motor activity?



Left-right discriminations

Early experiments on the development of sound source localization asked whether infants could tell a sound to the left from a sound to the right. Typically, such experiments used head turns or eye movements as a response. I'll start by describing a few studies of other mammals, to give you a sense of when sound localization starts relative to the onset of cochlear function.

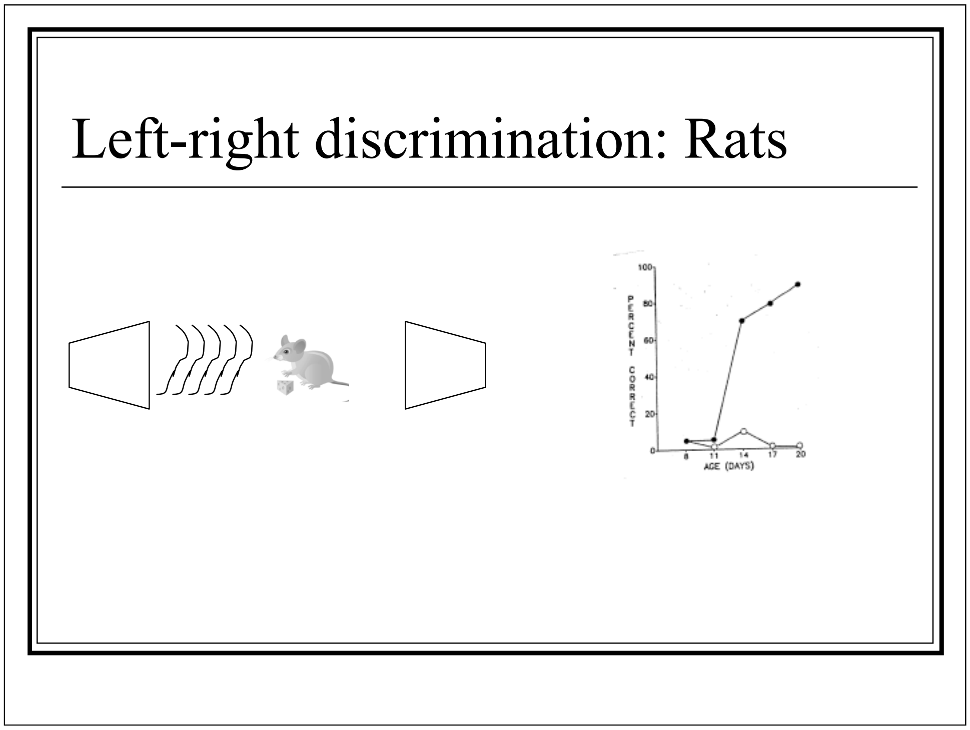


Left-right discrimination: Kittens

These are data from Clements and Kelly (1978) They trained kittens to approach a loudspeaker playing a 3-week-old kitten cry in a Y-maz., Level was 75 dB SPL. They also included no sound trials to control for the kitten's preference to go left or right.

Remember that you really can't get much of a response from the cat cochlea until a kitten is several days old. At 4-10 days, the kittens approach the correct speaker abut 50% of the time, but then this sound level might be close to threshold for a 4-day-old kitten. But then from 11 days up to 31 days, there is a progressive improvement in the kitten's localization of the correct speaker, although even at 31 days, they are not perfect in the task. This suggests, however, that localization-- at least grossly--follows close on the heels of the first cochlear responses.

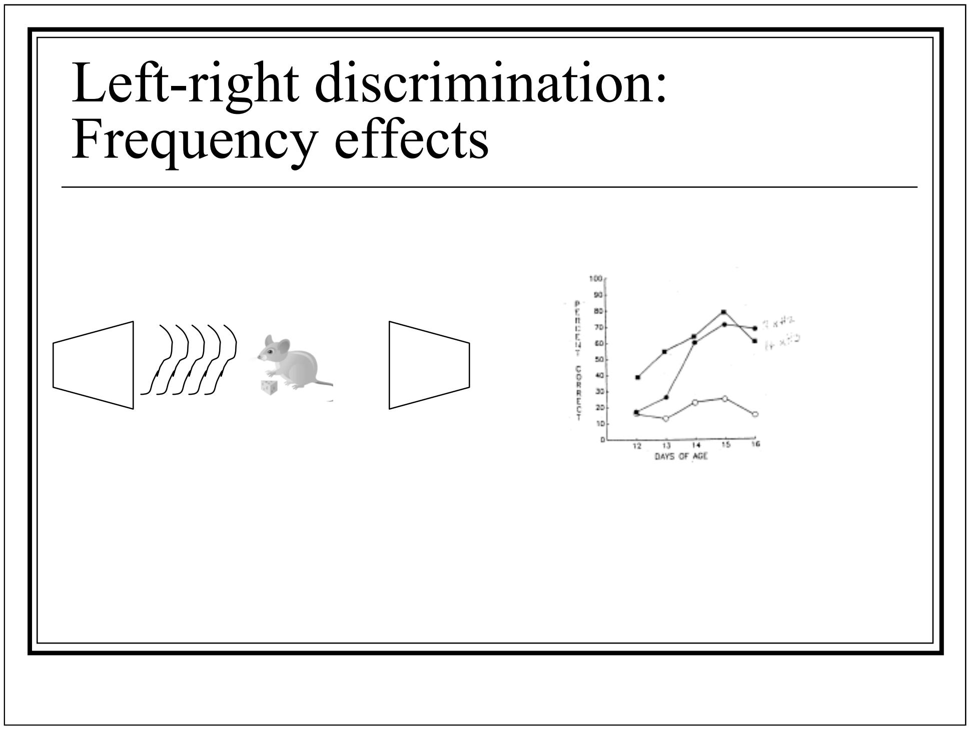
1.Clements, M. and J.B. Kelly, Directional responses by kittens to an auditory stimulus. Dev Psychobiol, 1978. **11**: p. 505-511.



Left-right discrimination: Rats

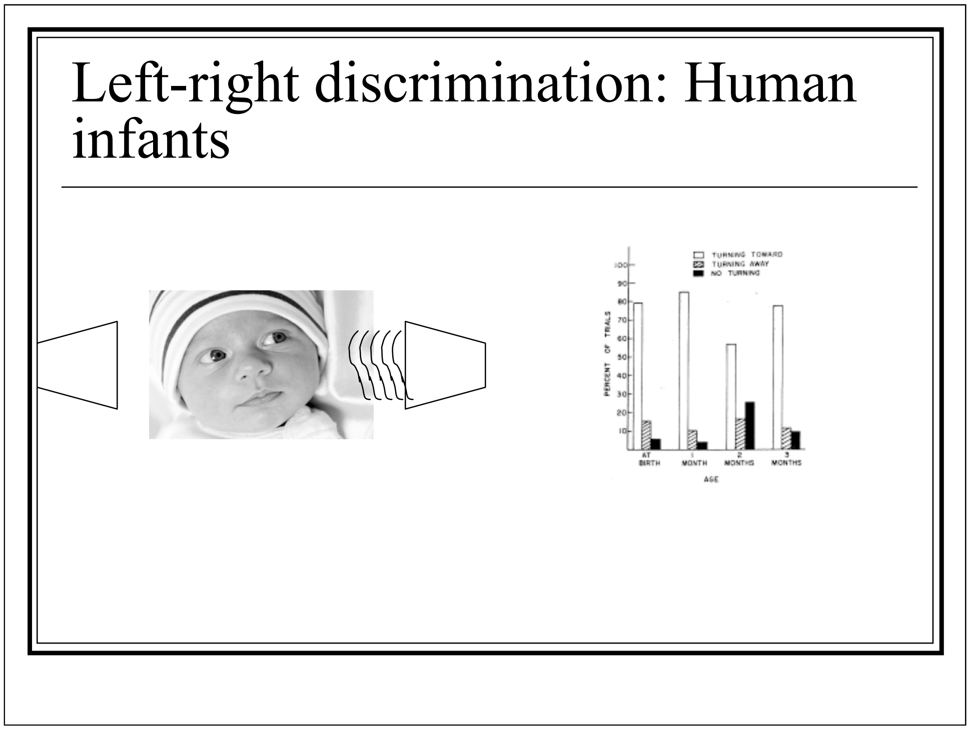
Kelly et al., (1987) determined whether rat pups would turn their head to a noise burst from a speaker on the left or right. Rats ears only start to work around 11 days. By 14 days, the rat pup is doing pretty well and by 20 days, he's approaching 100% correct.

1.Kelly, J.B., P.W. Judge, and I.H. Fraser, Development of the auditory orientation response in the albino rat (Rattus norvegicus). J Comp Psychol, 1987. **101**: p. 60-66.



Left-right discrimination: Frequency effects

In a second study of rat pups, Kelly et al compared two frequencies of sound, 16 kHz (squares) and 2 kHz (filled circles). The unfilled circles are no sound trials. You can see that at the first day tested here--right at the onset of hearing--the rat pup is turning toward the higher frequency a fair number of times. The response to 2k doesn't "catch up" for a few days. Because we believe that interaural time differences are used to localize sounds in azimuth at low frequencies, and interaural intensity differences at high frequencies, this suggests that IIDs may be usable before ITDs.



Left-right discrimination: Human infants

There was some controversy over whether human newborns turned to a sound source on the left or right. Wertheimer (1961) reported that he used a clicker held near a newborn infant's ear -- in the delivery room-- and that the baby turned his eyes toward the stimulated ear. However, later investigators had trouble replicating this effect, and some argued that Wertheimer had provided visual cues to the infant in addition to the auditory ones.. Muir and Field (1979) pretty much settled the matter in a series of carefully controlled studies using speakers instead of clickers, and carefully supporting the infant's head during the experiment. The stimulus was the sound of a rattle, rhythmically shaken.

Their results are shown here, the white bars show the percent of head turns toward the sound source, the striped bars show the number of head turns away from the sound source, and the black bars show the percent of trials on which the infant didn't turn at all. Newborns and 1 month olds turn toward the sound source 80% of the time. These head turns are long latency responses; sometimes it takes an infant 10 seconds to complete the response.

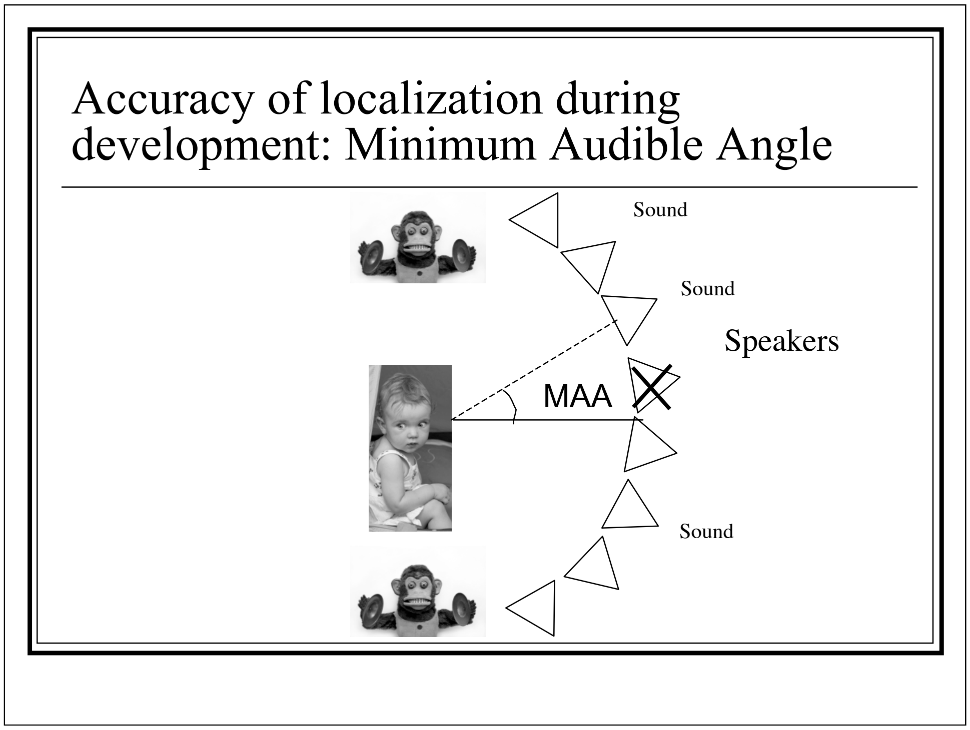
Note also that at 2 months, the percent of turns toward the source has decreased. This is a reliable phenomenon. Infants don't turn their heads toward sound sources so much-- it starts to come back at 3 months, by 5-6 months, infants are turning on a high proportion of trials again, and their responses are different-- now they are short latency responses.

It is believed that the sound localization system is re-organized in some way early in infancy, accounting for this pattern of change in the incidence of turns toward a sound source. It explains why VRA doesn't work well for infants younger than 5-6 months old.

Wertheimer, M., Psychomotor coordination of auditory and visual space at birth. Sci, 1961. **134**: p. 1692.

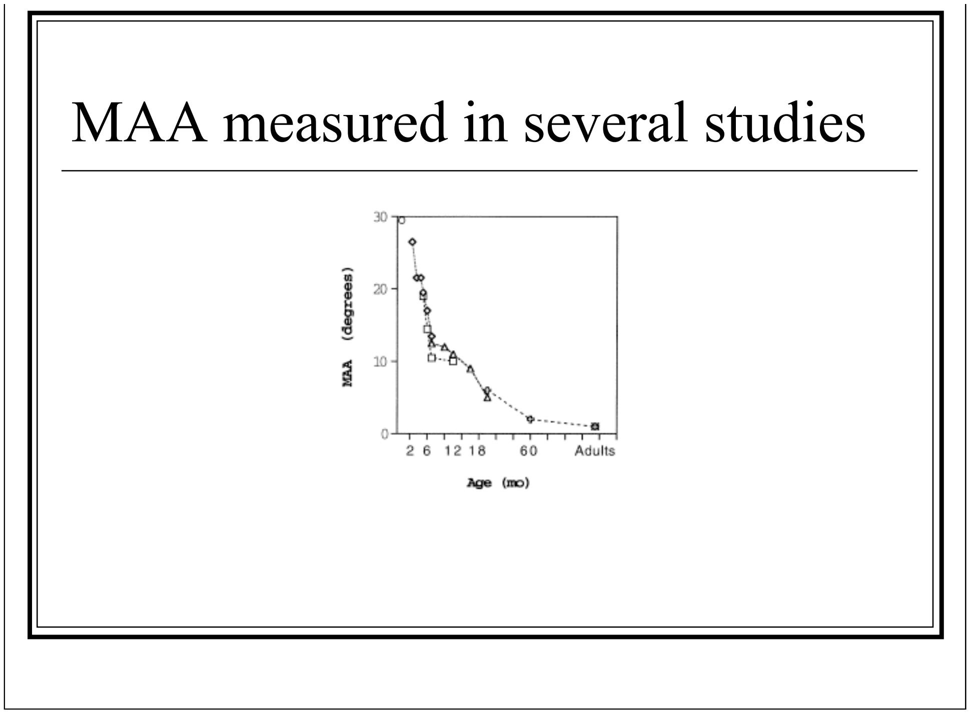
Field, T.J., D. Muir, R. Pilon, *et al.*, Infants' orientation to lateral sounds from birth to three months. Child Dev, 1980. **51**: p. 295-298.

Muir, D. and T. Field, Newborn infants orient to sounds. Child Dev, 1979. **50**: p. 431-436.



Accuracy of localization during development: Minimum Audible Angle

Studies in several labs estimated the minimum audible angle, the jnd for the spatial position of a sound source, in infants or children. The basic paradigm is that the infant sits in front of an array of speakers. A sound is presented from one of the speakers (or sometimes the sound shifts from the center speaker to one of the other speakers). The infant learns to look left if the sound is on the left and right if the sound is on the right. Reinforcers are positioned on either side of the array, and if the child turns the right way, the toy on that side is turned on. If the speaker is too close to the center (smaller than the minimum audible angle), the infant won't be able to tell which side it's on. So the MAA is the angular position of the speaker that the infant can tell is on the left or right, say 75% of the time.



MAA measured in several studies

This is a summary graph of the results of studies like these, which have tested newborns, older infants, and five year old children. The MAA is 30° at birth; It improves rapidly during infancy, and it is adultlike by ~5 yr. (It could be earlier; we don't have data at the intermediate ages.)

1.Ashmead, D.H., R.K. Clifton, and E.E. Perris, Precision of auditory localization in human infants. Dev Psychol, 1987. **23**: p. 641-7

3.Clifton, R.K., B. Morrongiello, J. Kulig*, et al.*, Auditory localization of the newborn infant: Its relevance for cortical development. Child Devel, 1981. **52**: p. 833-838.

4.Clifton, R.K., B.A. Morrongiello, J.W. Kulig*, et al.*, Developmental changes in auditory localization in infancy, *In* Development of perception, R. Aslin, J. Alberts, and M.R. Petersen, editors. 1981, Academic Press: New York. p. 141-160.

5.Litovsky, R.Y., Developmental changes in the precedence effect: Estimates of minimum audible angle. J Acoust Soc Am, 1997. **102**: p. 1739-1745.

6.Morrongiello, B.A., Infants' localization of sounds in the horizontal plane: Estimates of minimum audible angle. Dev Psychol, 1988. **24**: p. 8-13.7.Morrongiello, B.A., K. Fenwick, and G. Chance, Sound localization acuity in very young infants: An observer-based testing procedure. Dev Psychol, 1990. **26**: p. 75-84.

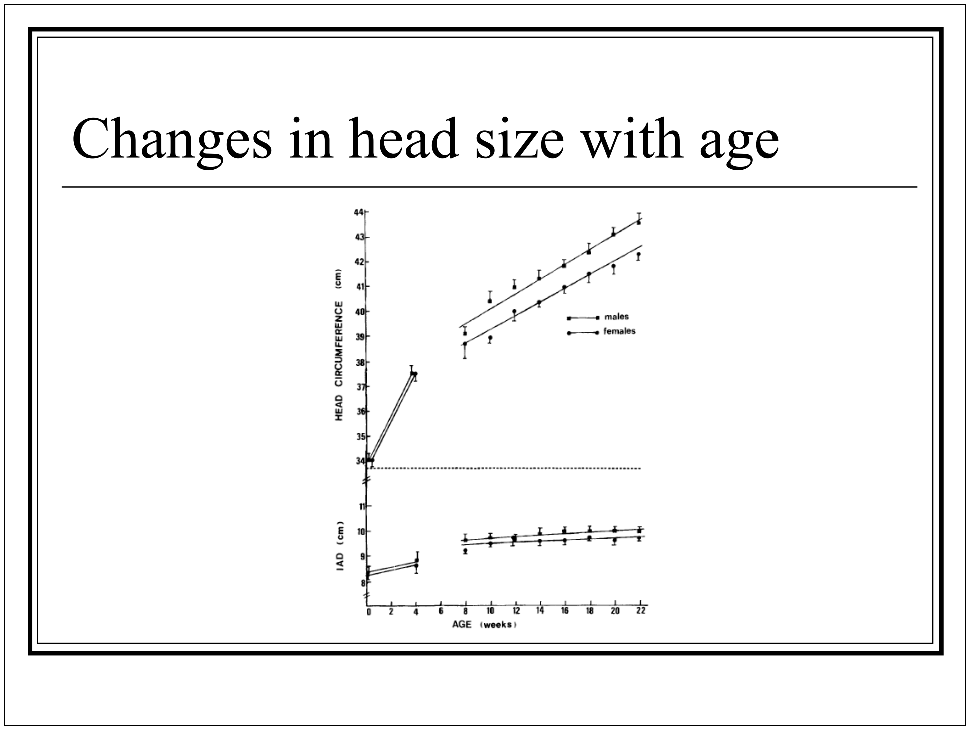
8.Morrongiello, B.A., K.D. Fenwick, L. Hillier*, et al.*, Sound localization in newborn human infants. Dev Psychobiol, 1994. **27**: p. 519-38.

9.Morrongiello, B.A. and P.T. Rocca, Infants' localization of sounds in the median sagittal plane: Effects of signal frequency. J Acoust Soc Am, 1987. **82**: p. 900-905.

10.Morrongiello, B.A. and P.T. Rocca, Infants' localization of sounds in the horizontal plane: Effects of auditory and visual cues. Child Dev, 1987. **58**: p. 918-927.

11.Morrongiello, B.A. and P.T. Rocca, Infants' localization of sounds in the median vertical plane: Estimates of minimal audible angle. J Exp Child Psychol, 1987. **43**: p. 181-193.

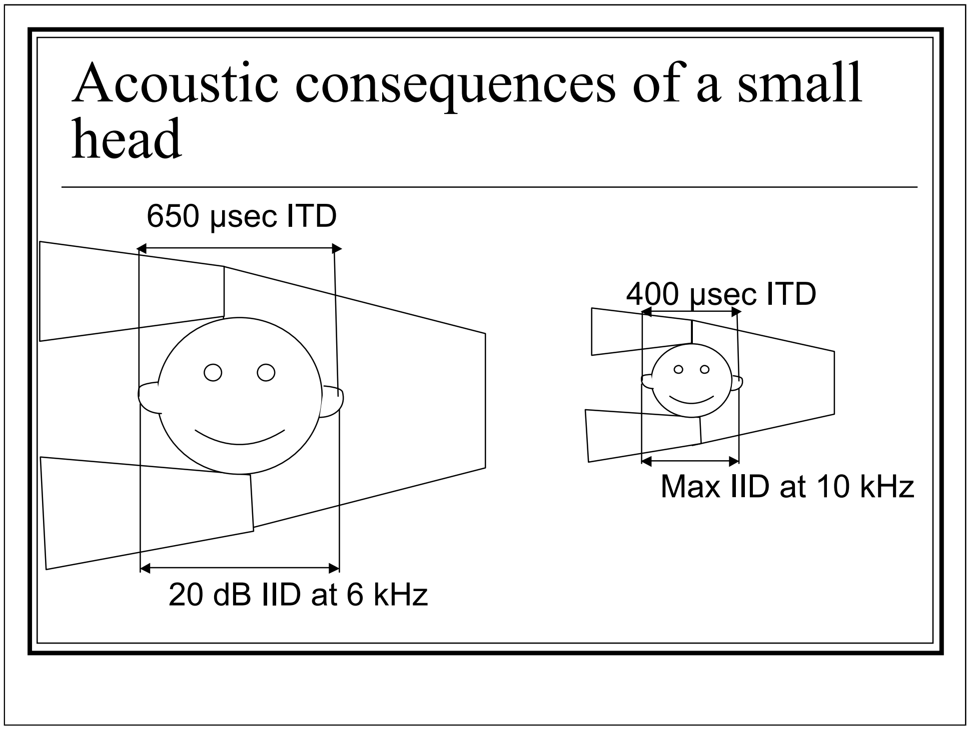
12.Morrongiello, B.A. and P.T. Rocca, Infants' localization of sounds within hemifields: Estimates of minimum audible angle. Child Dev, 1990. **61**: p. 1258-1270.



Changes in head size with age

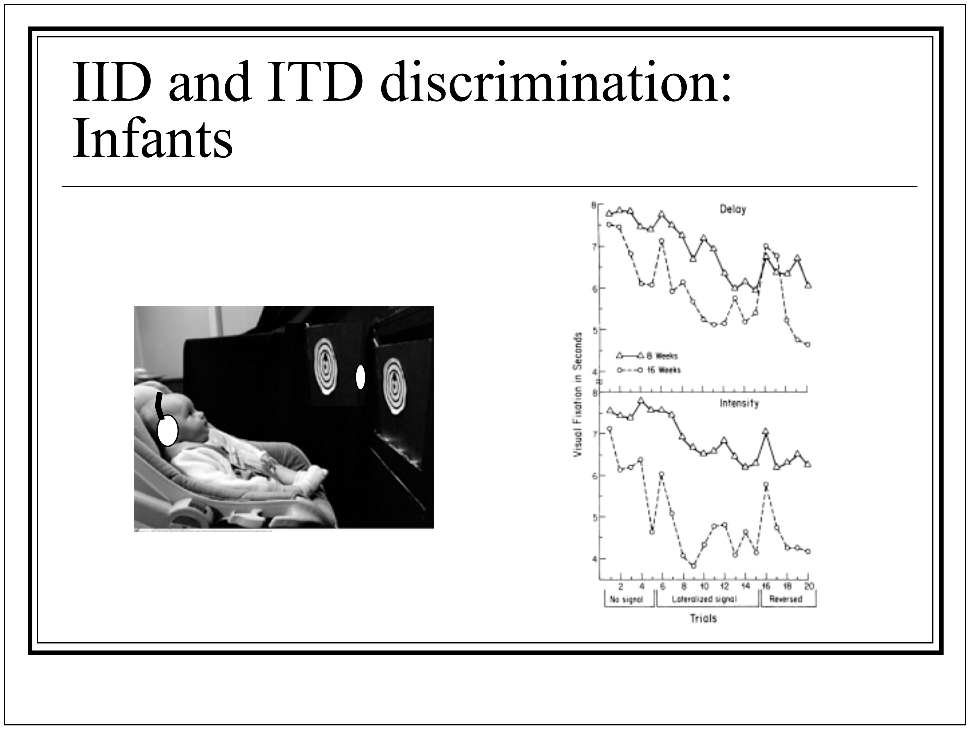
We know that head size increases between birth and adulthood. These are data Clifton et al (1988) collected on head circumference and interaural distance as a function of age.

1.Clifton, R.K., J. Gwiazda, J. Bauer*, et al.*, Growth in head size during infancy: Implications for sound localization*.* Dev Psychol, 1988. **24**: p. 477-483.



Acoustic consequences of a small head

Interaural acoustic cues will be smaller for a newborn than for an adult. However, if everything else about the infant’s auditory system were mature at birth, we wouldn’t expect the newborn’s MAA to be 30º when an adult’s is 2-3º. Perhaps it would be 5º. So interaural cues limit infants’ localization, but that can’t be the only thing going on.



IID and ITD discrimination: Infants

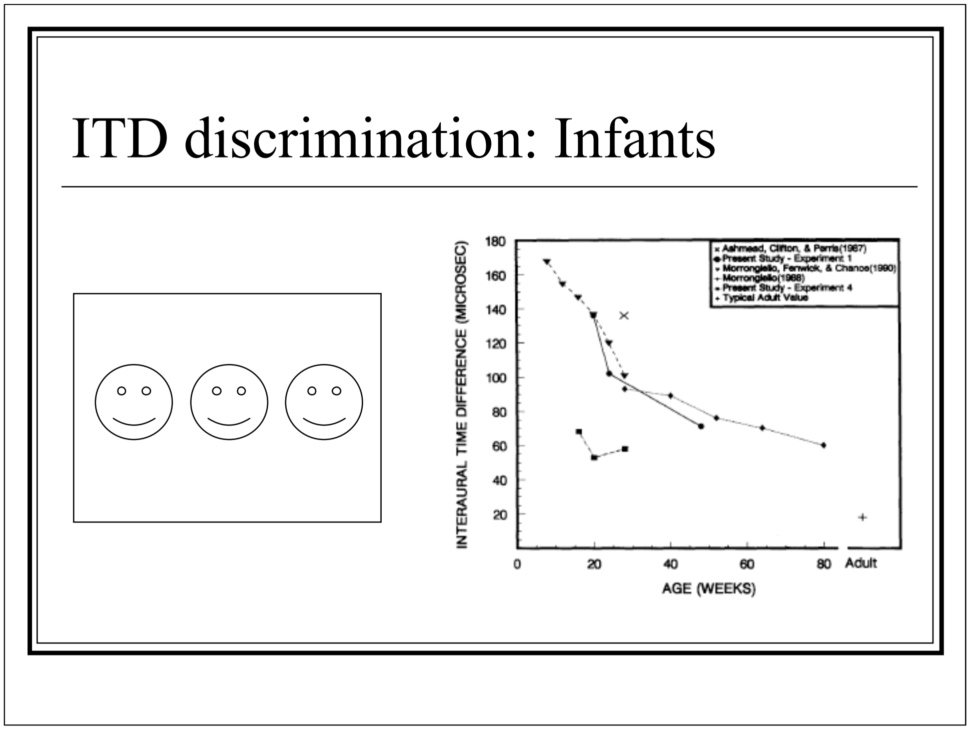
Bundy (1980) used a visual fixation paradigm to determine whether 8 and 16 week old infants responded to a change in ITD or a change in IID. Babies wore earphones. They were presented with 20 8-second trials. At the beginning of a trial, a light in the center of the display blinked. On the first 5 trials, an observer behind the screen just recorded which of the two visual patterns the infant looked at, without playing a sound. Then on Trial 6-15, a continuous tone came on after the light stopped blinking. Some infants heard a 400 Hz tone with a 300 microsecond delay between the ears. The other infants heard a 3000 Hz tone with a 6 dB difference between the ears. The observer recorded which pattern the infant looked at and for how long. Then on Trial 16-20, the interaural differences reversed. If the infant heard a delayed (or less intense) sound on the right, now he heard the delay (or less intense sound) on the left (and vice versa). Again the looking time was recorded. It turned out that the infants didn't particularly look to the left if the sound led or was more intense on the left or to the right if the reverse were true, but their looking times reflected something about what they heard.

The results are shown on the right. Let's look at the 16-week-olds first, because their results are pretty easy to interpret. Over the course of the first 5 trials, both the "delay" infants and the "intensity" infants decreased their looking time. When the sound comes on, they look more for a trial or two, but then their looking decreases. On trial 16, the direction of the interaural difference is reversed, and looking time goes up. Thus it is clear that the 16-week-olds heard a change, although it isn't certain that they heard an interaural change in the "intensity" condition: the sound level in each ear changed; infants could respond to an intensity change without hearing a change in the interaural intensity difference.

Now look at the data of the 8 week olds. The problem here is that the 8 week olds really liked to stare at those visual patterns! They don't particularly respond by looking more when they first hear the sound, but they do show an increase in looking when the interaural delay or intensity difference was reversed. It was statistically significant for the time delay, but not for the intensity difference.

So these results suggest that both 8 and 16 week olds can hear interaural time difference changes, but the evidence is weaker for interaural intensity differences, especially for the 8 week olds.

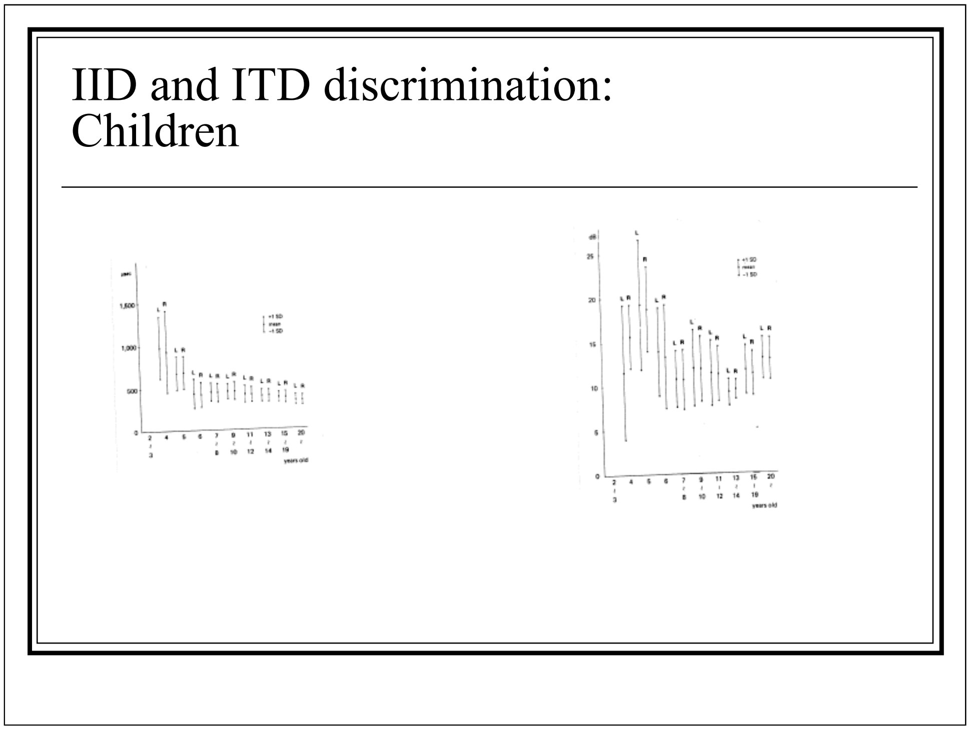
1.Bundy, R., Discrimination of sound localization cues in young infants. Child Dev, 1980. **51**: p. 292-294.



ITD discrimination: Infants

Ashmead et al. (1991) used an observer-based procedure to measure ITD discrimination thresholds in 16-28 week olds. This is an age when the minimum audible angle is still improving fairly rapidly. Ashmead et al reasoned that if immature ITD discrimination contributed to infants' immature MAA, they would see a similar trend in development of ITD discrimination, and the ITD discrimination thresholds would predict the MAA. During the experiment, infants watched a screen. A smiley face appeared in the center of the screen when the trial started, and the same time, a train of clicks was presented to the infant, with one ear leading by 50-400 μsec. A short time later the center smiley face would disappear, and a smiley face would appear on the side of the screen corresponding to the leading ear, right or left. So the idea was that the infants would learn to associate the sound in the right side of their head with the image on the right side of the screen, and look over to the right side of the screen in anticipation. An observer watched the infant from behind a screen and judged on each trial whether the clicks were leading in the right or the left ear. The ITD was varied to establish a threshold. Their results are shown in this figure, the filled square symbols lower down on the y-axis. The graph shows ITD at threshold as a function of age. You can see that the 16-week olds had a threshold of about 70 μsec, the 20 week olds had a threshold of around 52 μsec and the 24 week-olds had a threshold of 58 μsec. So there is some improvement in ITD discrimination threshold with age, if a little small and on the irregular side. Ashmead et al then took the MAA data shown on the graph I showed you a minute ago, as well as additional MAA data they collected in this study, and they converted the MAA to ITD. In other words, what would the ITD at the threshold angle for a person with the head size of an infant? You can see that The ITD at MAA decreased over this age range fairly dramatically, and more importantly, that the ITD at MAA is way higher than the thresholds measured in this study. Thus, while poor ITD processing might contribute to infants' immature MAAs, they can't account for them completely.

1.Ashmead, D.H., D. Davis, T. Whalen*, et al.*, Sound localization and sensitivity to interaural time differences in human infants*.* Child Dev, 1991. **62**: p. 1211-26.



IID and ITD discrimination: Children

There is just one study that has described the development of IID and ITD discrimination in children. Kaga (1992) had kids move a joystick to indicate where they heard a train of clicks under earphones coming from, with ITDs or IIDs. Remember that by about 5 years, the MAA is approaching adult values. The subjects in this study ranged from 4 to 20 years, so to the extent that the MAA depends on interaural cue processing, we wouldn't expect much change in ITD or IID discrimination over this age range.

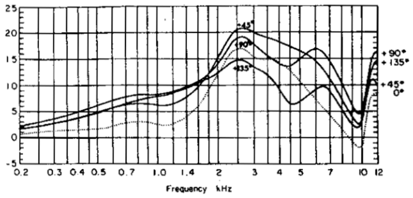
IID or ITD was varied to find threshold. The judgment on each trial was the final joystick position on that trial. The ITD results are shown on the left, with ITD discrimination threshold plotted for the left ear and for the right ear at 4 years to 20 years. Notice that the 4-year-olds' threshold is around 1000 µsec, a wee bit bigger than the 60 µsec thresholds reported by Ashmead et al for 4-6 month olds. But notice that the adults in this study had thresholds just under 500 µsec, so that may have more to do with the method used here than anything else. In any case, This is much worse than the MAA would suggest they should be able to do. ITD discrimination threshold decreases between 4 and 6 years, then improves very little after 6 years.

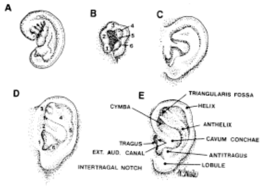
The IID discrimination thresholds are pretty much a mess. The adults have thresholds around maybe 13 dB--very high-- and there isn't much of a pattern for the kids, although you can imagine an age-related decrease between 4 and 6 years.

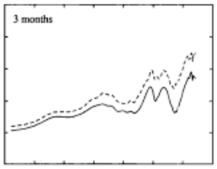
So it's not really clear role that cue discrimination plays a major role in the development of sound localization. Something else must be going on as well.

1.Kaga, M., Development of sound localization. Acta Paediatr Jpn, 1992. **34**: p. 134-138.

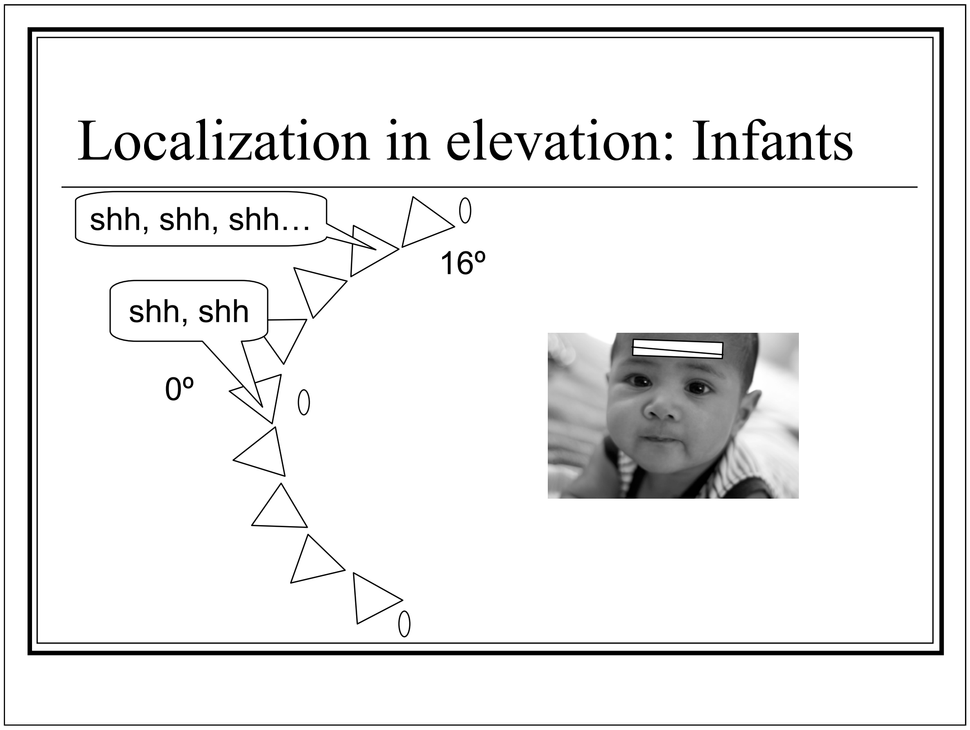
Localization in elevation depends on spectral cues







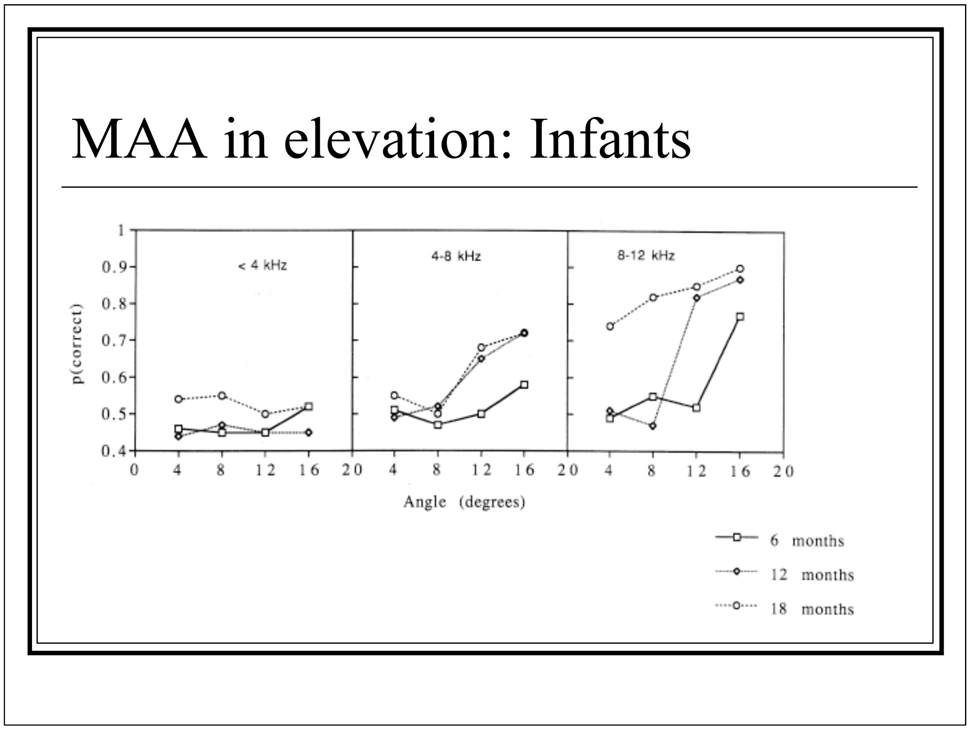
Remember that the acoustic cue to elevation is the shape of a sound’s spectrum. The transfer function of the external ear changes in shape as a sound’s position changes, and this is the only information available to us to determine elevation. The figure on the left shows the transfer function of an adult’s external ear for sounds in different locations. Notice that the changes in spectral shape are in the higher frequencies, around 4-5 kHz. That’s because the pinna is primarily responsible for these effects, and its resonant frequency is up around 5 kHz. Remember also that the pinna grows and changes shape considerable between birth and adulthood. A smaller ear will have higher resonant frequencies, as Keefe et al. (1994) showed (graph at bottom right is an example). So for an infant to localize sounds in elevation, we might guess that he’s got to have higher frequencies in the sound than the adult requires.



Localization in elevation: Infants

Morrongiello (1987) tested infants' ability to localize sounds in elevation. She had infants, aged 6 to 18 months looking toward a vertical array of speakers in a dimly lit room. The infant had a stripe taped to his head to help the observer behind the speakers tell if the infant looked up or down. When the infant was ready, two noise bursts were presented from the speaker at 0º elevation and a light flashed near that speaker. Then noise bursts were presented from one of the other speakers, and the observer recorded whether the infant looked up or down. If the infant looked the right way, the light at that end of the speaker array flashed as feedback. They presented 3 trials with shifts to each speaker, order randomized. Some infants were tested with a low pass noise with a high-frequency cutoff of 4 kHz; another group heard a 4-8 kHz noise band; a third group heard an 8-16 kHz noise band. (Infants were all trained to look up or down with a broadband noise.)

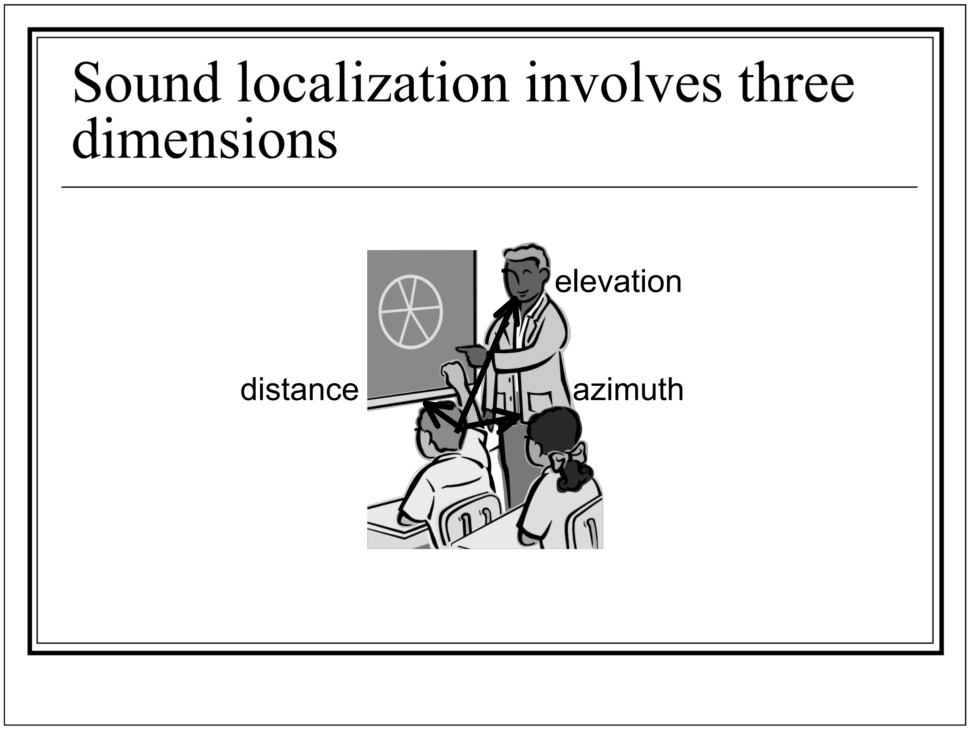
1. Morrongiello, B.A. and P.T. Rocca, Infants' localization of sounds in the median sagittal plane: Effects of signal frequency. J Acoust Soc Am, 1987. **82**: p. 900-905.
2. Morrongiello, B.A. and P.T. Rocca, Infants' localization of sounds in the median vertical plane: Estimates of minimal audible angle. J Exp Child Psychol, 1987. **43**: p. 181-193.



MAA in elevation: Infants

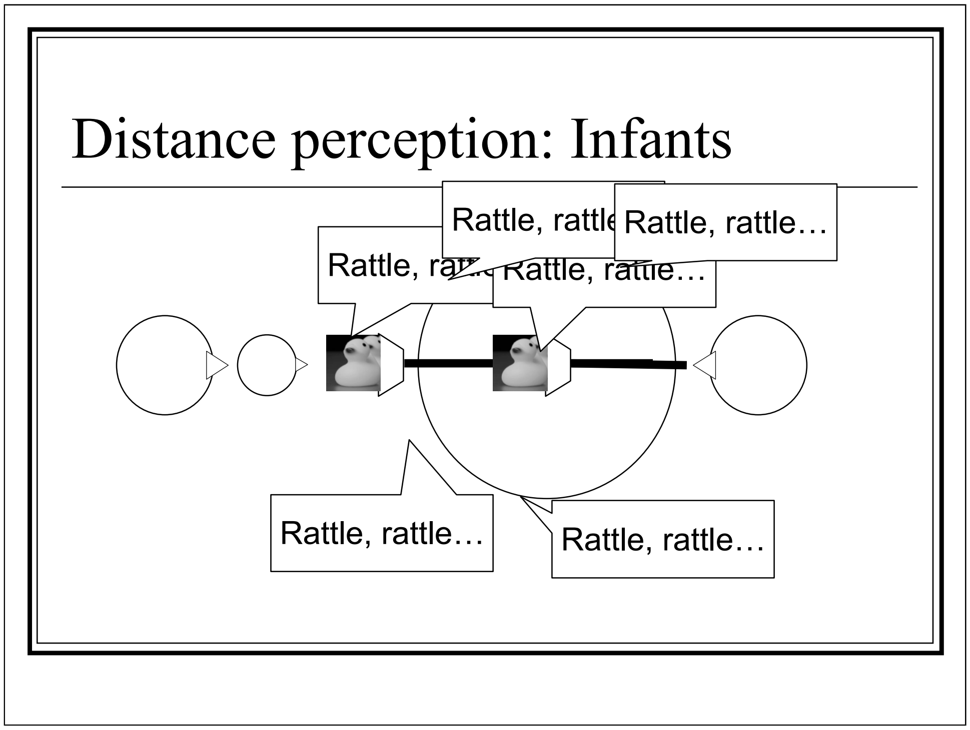
Morrongiello’s (1987) results are shown here. The graphs above show psychometric functions for detecting a change in a sound source’s elevation at the three different frequencies. The unfilled squares are for the 6-month-olds, the diamonds are for the 12 month olds and the circles are for the 18 month olds. If the noise band only included frequencies below 4000 Hz, none of the infants could get above chance performance at any angle. For the 4-8 kHz noise band, the 12 and 18 month olds show improvement as the angle is increased above 8 °; they get about 72% correct at 16°. The 6 month olds look like they are starting to be able to do the task at 16°. Adults should be able to localize this sound in elevation quite well. Now look what happens for the 8-12 kHz noise band. The 18 month olds are getting better than 70% correct at all angles; the 12 month olds pass 75% correct between 8 and 12°, and the 6 month olds are getting up there 16 degrees.

So discrimination of sound source elevation is improving between 6 and 18 months. It may even be adultlike in level of performance at 18 months. However, Infants can only perform the task at all if we give them very high frequencies of sound. This is, of course, consistent with their having little pinnas.



Sound localization involves three dimensions

Sound localization involves more than identifying a sound's position in azimuth. Places in space, and therefore sound source positions, also differ in elevation and in distance from the listener. A couple of studies have examined the ability to discriminate differences in elevation and distance, but we have far from a consistent picture of the development of these abilities.

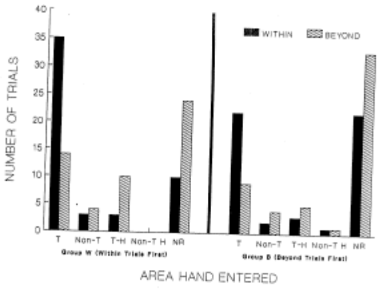


Distance perception: Infants

Perris and Clifton studied 7-month-olds' perception of the distance of a sound source by looking at their reaching for a sounding object in the dark. They reasoned that if the infant perceived the sound source as being within reach, they would reach for it, and if infants thought the sound source was out of reach, they would not reach for it. The sound source was a small speaker with a toy velcro'ed to the front of it. The speaker/toy were attached to the end of a stick. So the infant sits on the parent's lap at a table, and an infrared camera is used to record where the infant reaches. With the lights on, the assistant (on the right) presents the sounding object within the infant's reach and lets the infant take the toy off the speaker. Then she moves the toy out of the infant's reach, with the sound on. Then the lights go off. The speaker/toy are placed within the infant's reach or outside of the infant's reach. The toy might be placed to the left or right. The infrared camera records whether and where the infant reaches.

1.Perris, E.E. and R.K. Clifton, Reaching in the dark toward sound as a measure of auditory localization in infants. Infant Behav Dev, 1988. **11**: p. 473-491.

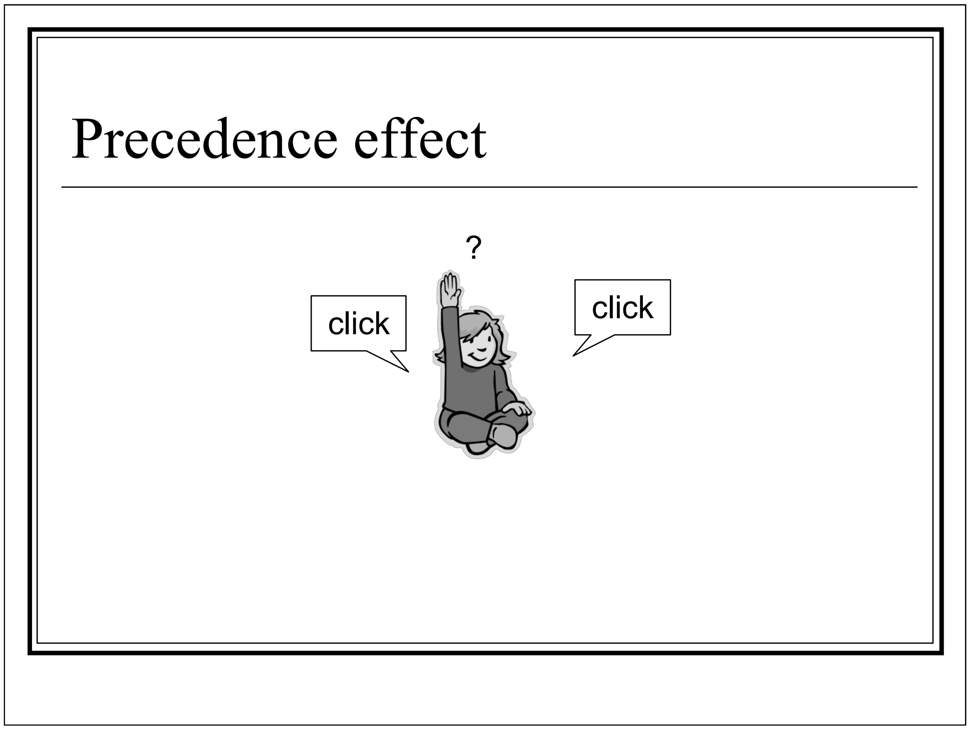
Distance perception: Infants



This graph shows the results of the experiment. Half of the infants got the toy within reach on the first trial in the dark (on the left); half got the toy beyond reach on the first trial (on the right). What is plotted is the number of trials on which the infant reached for the toy. The black bars show when the toy was within the infant's reach and the patterned bars show when the toy was beyond the infant's reach. "T"means the infant reached in the target area (e.g., on the left); "non-T" means the infant reached outside the target area; "T-H" means the infant reached in the correct hemifield (left or right) though not in the target area; "non-T H" means the infant reached in the wrong hemifield; and "NR" means "no reach".

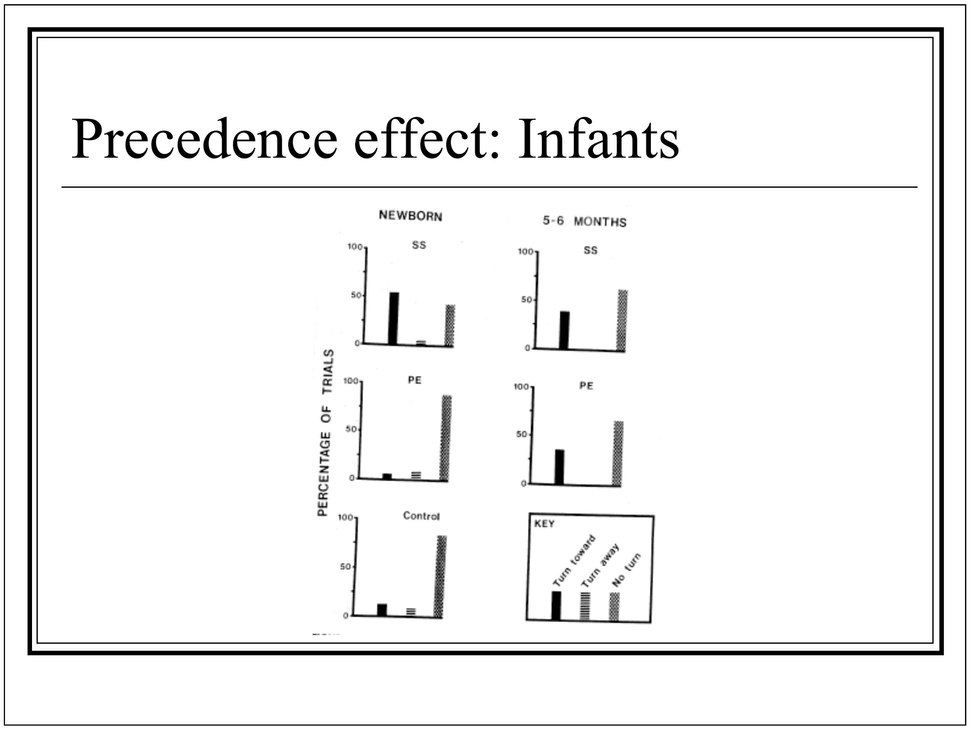
Both groups of infants reached toward the toy when it was within reach, but not when it was beyond reach. If they reached, they almost always reached into the target area. These results suggest that infants know when a sound they hear is within their reach; that is, they perceive the distance of the sound source.

In another experiment, Perris and Clifton didn't actually move the toy/speaker, but just made the intensity of the sound change-- high or low. The higher level would be associated with a within reach source, while the lower level would be associated with a beyond-reach source. The infants reached for the higher level, but not the lower level, again suggesting that they know something about sound and distance.



Precedence effect

The precedence effect is called the law of the first wavefront, or echo suppression. If I hear a sound coming from one direction, and the very same sound comes from some other direction within a matter of a few milliseconds, I hear the sound coming from the direction of the first sound. If the second sound is delayed more than about 7 milliseconds, I hear both sounds, so can’t pick a single direction. This mechanism might be useful if we are listening in a reverberant space, where the second sound would be the echo of the first. Clifton and her colleagues did a series of studies to determine whether infants demonstrate this effect. Basically, they looked at where the infant turned her head when she heard a single sound, and when she heard a single sound followed by an “echo”.



Precedence effect: Infants

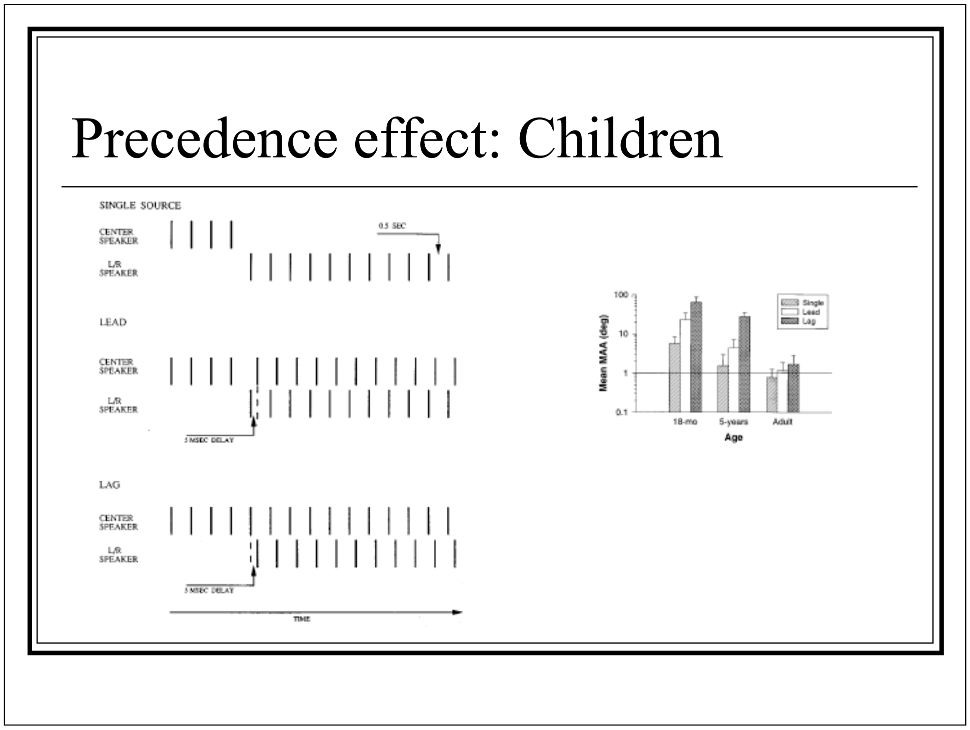
Clifton et al. (1984), tested 3 conditions. SS stand for single source-- one sound presented to the left or right of the infant's head. PE is for precedence effect. A sound would be presented from the left or right, followed very quickly by the same sound on the opposite side of the head. The control condition, is a trial with no sound presentation. Newborns are shown on the left of the figure and 5-6 month olds are shown on the right. Black bars are for turns toward the first or only sound; striped bars are for turns in the opposite direction and the patterned bars are for trials when no turn occurred. When newborns heard a single source sound, if they turned at all, they turned toward the side from which the single source sound came. On precedence trials and on control trials, newborns basically didn't turn. 5-6 month olds, on the other hand, turned toward the single source (again if they turned at all), and on precedence trials they turned toward the first sound if they turned at all. Clifton et al interpret their results to mean that the precedence effect is not heard by newborns, but develops between birth band 5-6 months of age.

1.Burnham, D., J. Taplin, D. Hendersonsmart, et al., Maturation of Precedence-Effect Thresholds - Full-Term and Preterm Infants. Infant Behav Dev, 1993. 16: p. 213-232.

2.Clifton, R.K., B.A. Morrongiello, and J.M. Dowd, A developmental look at an auditory illusion: The precedence effect. Dev Psychobiol, 1984. 17: p. 519-536.

3.Litovsky, R.Y., Developmental changes in the precedence effect: Estimates of minimum audible angle. J Acoust Soc Am, 1997. 102: p. 1739-1745.

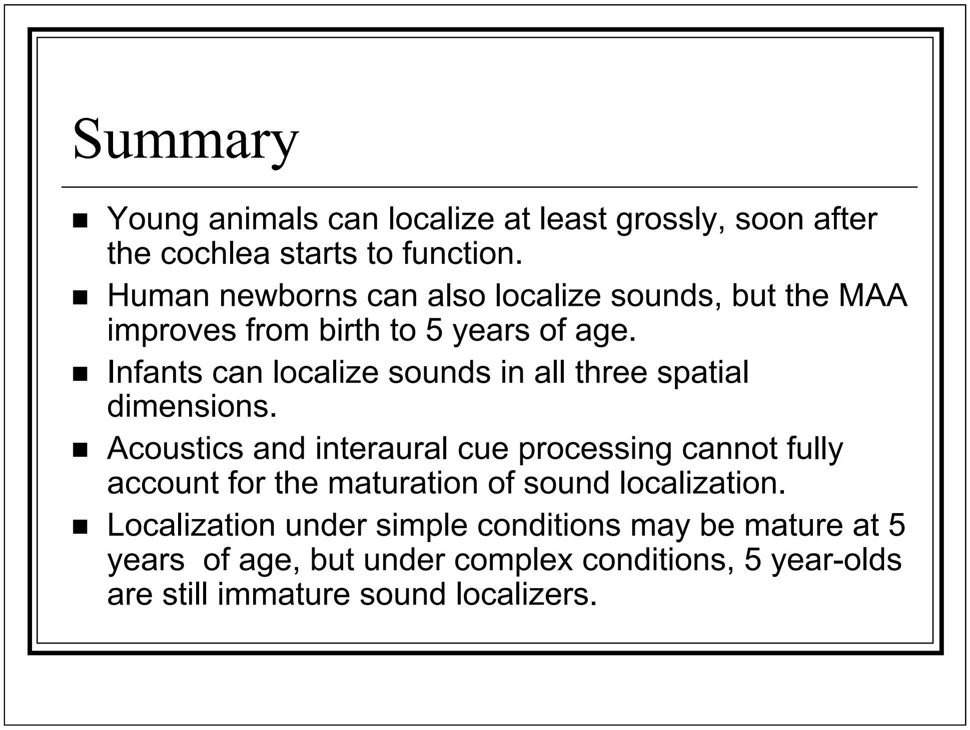
4.Morrongiello, B.A., R.K. Clifton, and J.W. Kulig, Newborn Cardiac and Behavioral Orienting Responses to Sound under Varying Precedence-Effect Conditions. Infant Behav Dev, 1982. 5: p. 249-259.



Precedence effect: Children

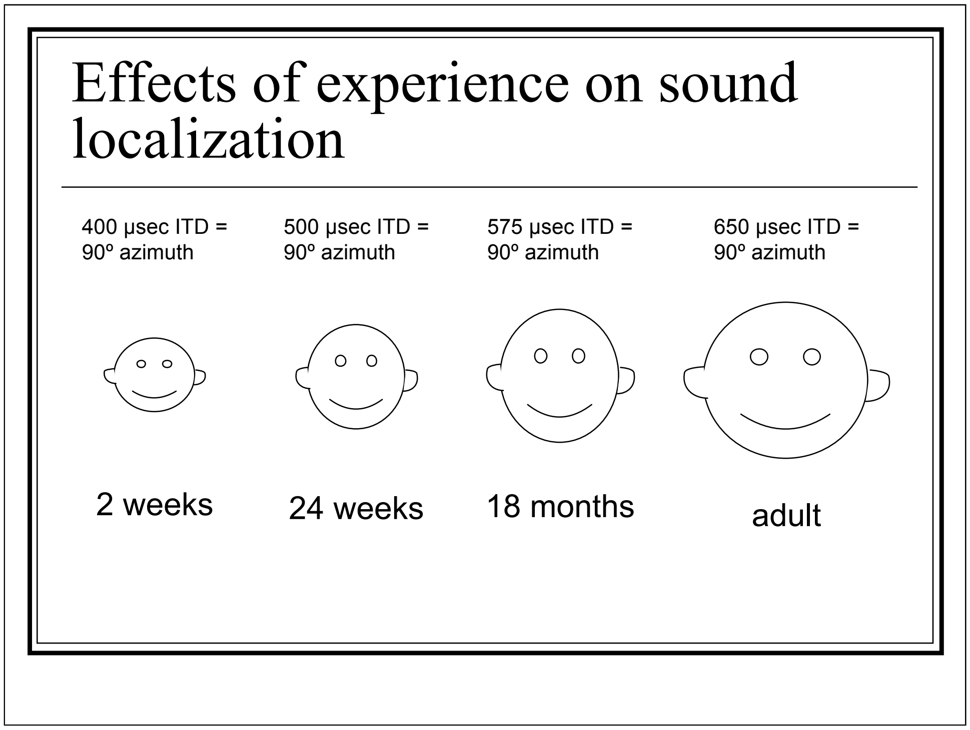
Litovsky (1997) measured the MAA in azimuth for 18 month olds and for 5 year olds under conditions that create the precedence effect for adults. The stimuli were click trains. The infants looked left or right and the 5 year olds pointed left or right to the speaker from which the click trains came. MAAs were measured in 3 conditions, illustrated in the drawing on the left. In the single source condition, the clicks start at the center speaker, then shift to a speaker on the left or right. The subject is supposed to hear the position of the click train shift and to look or point in that direction. In the Lead condition, the click train starts in the center, then a second click train is presented, leading the click train in the center by 5 ms. Subject should only hear the shifted click train (not the center), because the perceived direction is dominated by the leading click train. In the Lag condition, the shifted click train comes on lagging the center click train by 5 ms. All other things being equal, the subject shouldn't hear a shift, but Litovsky basically asked the subjects to tell which way they thought the sound had shifted.

The results of the experiment are shown on the right, the MAA as a function of age, in the single source condition (light gray bars), the Lead condition (white bars) and the lag condition (dark gray bars). Look at the adult results first. The MAA for a single source is around 1º and only a little worse when the shifted click train leads. The adults can tell where the lagging sound is coming from, but their MAA is a little bigger than in the other conditions. Now look at the kids. The infants have higher MAAs than the older listeners, and adding a leading or lagging sound makes them much worse. In the lag condition their threshold is 80º! That might be because of the precedence effect--they can't really hear the lagging sound. But the MAA in the Lead condition is also fairly bad--around 20º. So even though these kids hear the precedence effect, they can't localize as accurately under precedence conditions as they can when there is only one sound source. The 5 year olds are interesting in that their MAA for single source sounds is very close to adults', but again, they have difficulty in the precedence condition. So we might say that 5 year olds have mature localization in azimuth under simple conditions, but not under more complex conditions.



Summary

- Young animals can localize at least grossly, soon after the cochlea starts to function.
- Human newborns can also localize sounds, but the MAA improves from birth to 5 years of age.
- Infants can localize sounds in all three spatial dimensions.
- Acoustics and interaural cue processing cannot fully account for the maturation of sound localization.
- Localization under simple conditions may be mature at 5 years of age, but under complex conditions, 5 year-olds are still immature sound localizers.



Effects of experience on sound localization

400 µsec ITD = 90° azimuth

500 µsec ITD = 90° azimuth

575 µsec ITD = 90° azimuth

650 µsec ITD = 90° azimuth

2 weeks

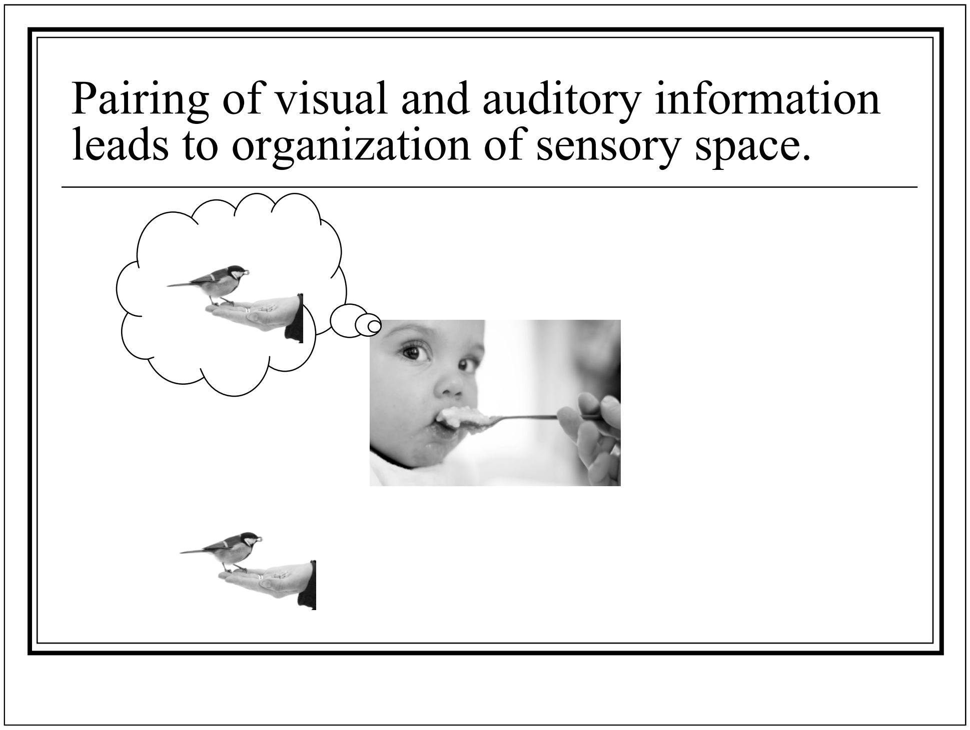
24 weeks

18 months

adult

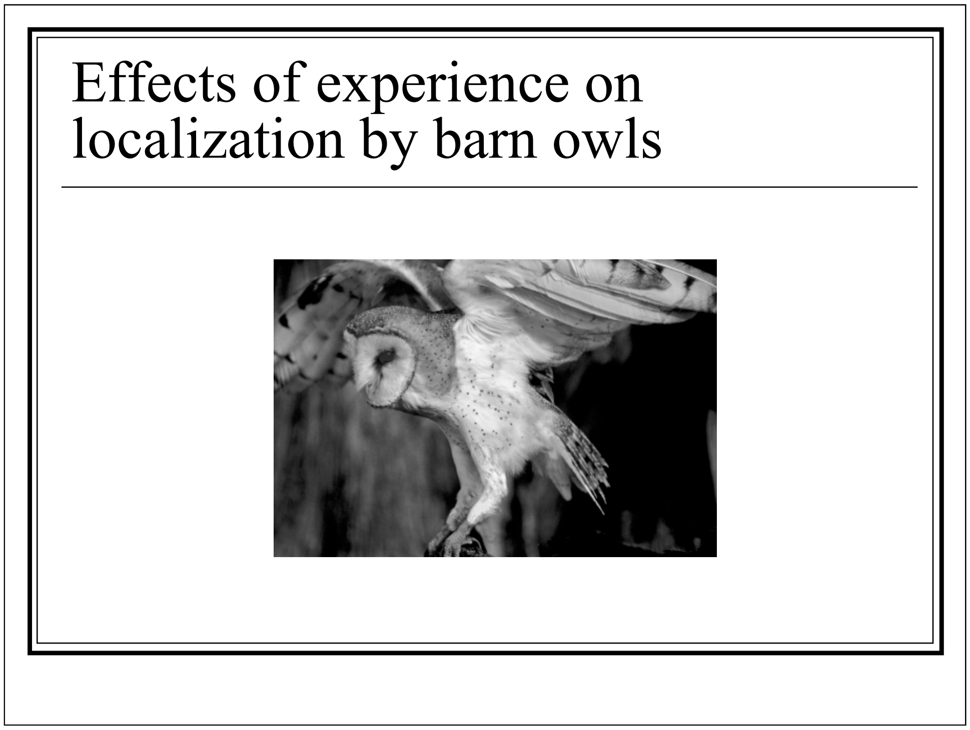
Effects of Experience

Why should experience be important in the development of sound localization? As the head grows, the interaural cues and spectral shape cues for a particular location in space are constantly changing. Basically, the localization system has to keep re-calibrating as the child grows.



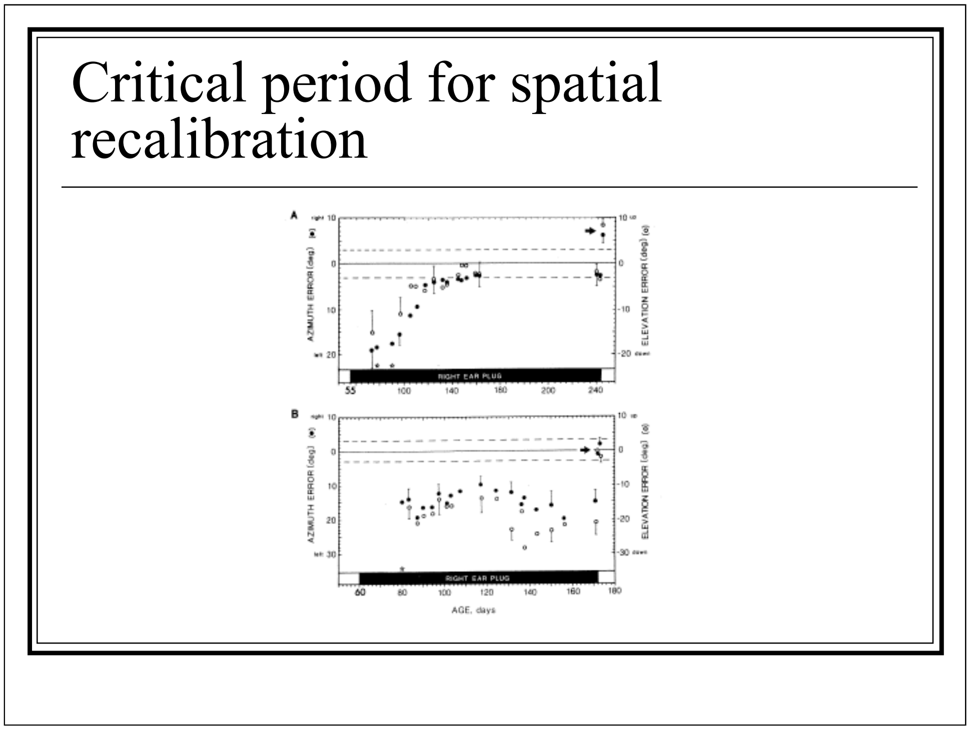
Pairing of visual and auditory information leads to organization of sensory space.

How does the infant know what the new cues for a particular location are? There has to be a coordination between the sensory systems, particularly auditory and vision, to make these corrections. The idea is that one day, the infant hears a sound that always meant that the family bird is to the right, but now is surprised to see the family bird in front of her. The pairing of the sight of the bird with a certain pattern of sound leads to recalibration of the sensory space.



Effects of experience on localization by barn owls

The classic studies on the effects of experience with sound on the development of sound localization were conducted by Eric Knudsen and his colleagues. Their subjects were barn owls. Barn owls are predators who use their hearing to find mice and other rodents dashing around on the ground in the grass and under leaves. Their sound localization abilities are very acute. Knudsen and his colleagues conducted a series of experiments with young owls in which one of the owl’s ears was plugged. They watched to see whether the owl would be able to adjust to the plug, like the re-calibration I talked about a minute ago. Then they would remove the plug, and see if the owl could re-adjust again. They performed the ear plugging and unplugging at different ages.



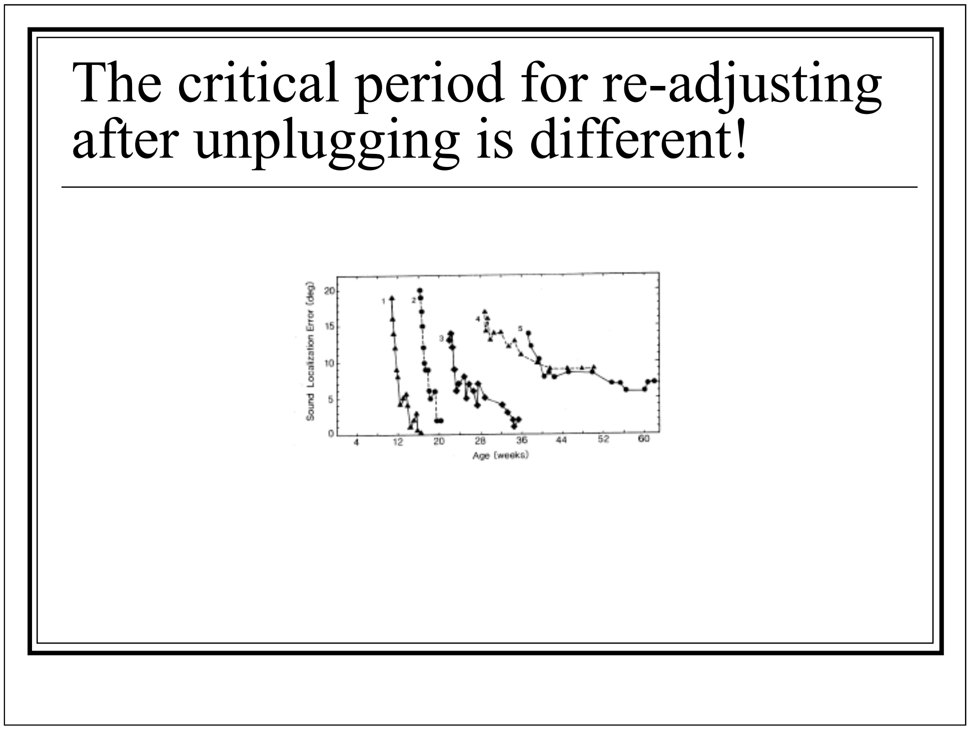
Critical period for spatial recalibration

These graphs show some of their results. Each graph shows the errors that owls made in localization as a function of the age. The top graph shows examples in which the owls had their ear plugged when they were 58 days old. The line is at 0° error (right on), and the dashed lines mark the normal range of performance. Each data point is for one owl. Between the time that the ear plug was put in and maybe 120 days, performance steadily improves, until the owl is finally localizing the sound as well as he did before the ear was plugged. The bottom panel shows the case of the owl whose ear wasn't plugged until 80 days of age. The owl never adjusts to the plug, and continues to make localization errors nearly 100 days later. When the ear plug is removed at 170 days, the owl's localization returns to normal. So there was no adjustment during the plugging, and no need for readjustment after unplugging.

So this suggests that owls are able to re-align their auditory and visual maps of space during development, but that the critical period during which the owl can re-align his auditory and visual maps of space is prior to 60 days.

1.Knudsen, E.I. and P.F. Knudsen, Vision guides the adjustment of auditory localization in young barn owls. Science, 1985. **230**: p. 545-8.

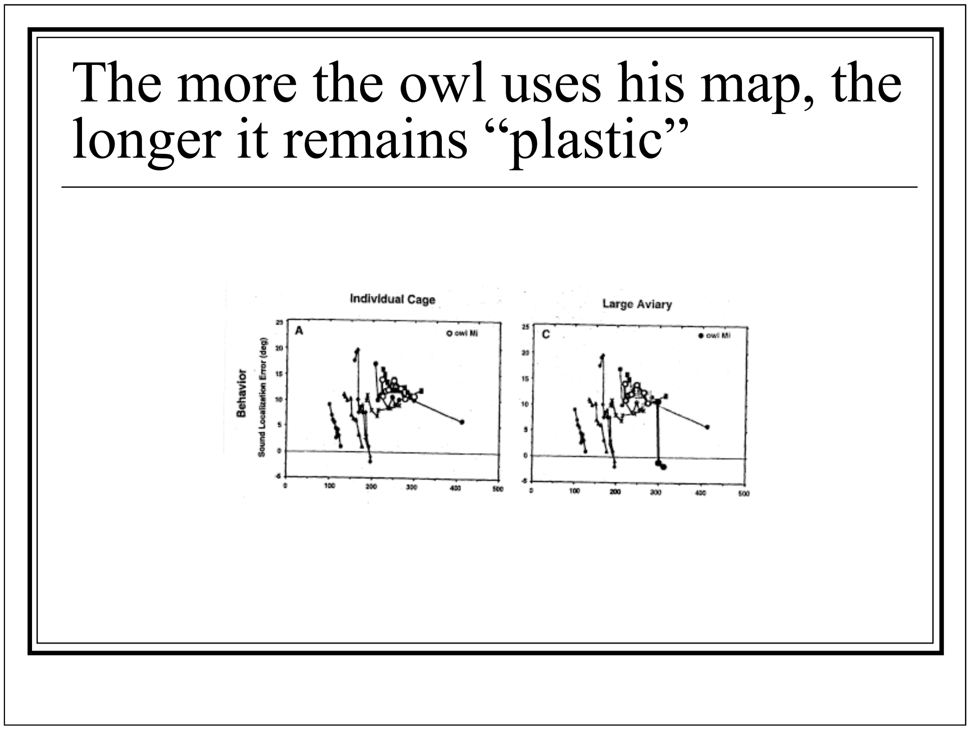
2.Knudsen, E.I., P.F. Knudsen, and S.D. Esterly, Early auditory experience modifies sound localization in barn owls. Nature, 1982. **295**: p. 238-240.



The critical period for re-adjusting after unplugging is different!

One interesting finding in this research is that while the owls can only adjust to ear plugging if they get the plug by 60 days, their capacity to re-adjust when the plug is removed is maintained for a longer time. This graph shows the reduction in localization error after the ear plug is removed for owls at different ages, here expressed in weeks. 60 days is less than 8 weeks. The youngest owl at unplugging shown here is unplugged at 12 weeks, and yet there is a rapid re-adjustment when the plug is removed. The owl whose data are at the right was unplugged at 36 weeks-- his localization improves slowly over a long period, but it never returns to normal.

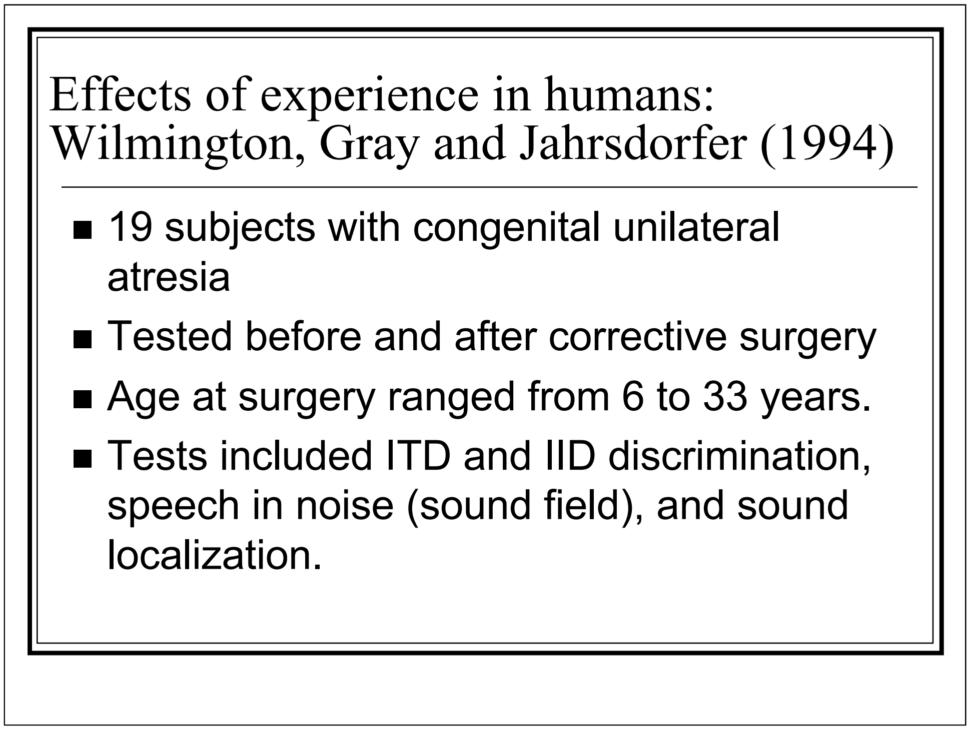
So the critical period for re-adjusting to unplugging (about 28-29 weeks) is longer than that for plugging. It is as if the system maintains the ability to adjust back to normal--equal inputs to the two ears for sound straight ahead--longer than it maintains the ability to adjust to an abnormal balance between the ears. Development tries to keep to the correct path, so to speak.



The more the owl uses his map, the longer it remains “plastic”

As it turns out, these critical periods are not carved in stone. They depend on how the owl is spending his time. The owls whose data are plotted on the left lived in individual cages. The graph plots their localization error as a function of age, after ear unplugging at different ages. These are like the data we just saw, where unplugging before 200 days (28-29 weeks) allows for re-adjustment, but later unplugging does not. One of these owls, labeled MI, was moved to a large aviary, where he could fly around all the time, when he was nearly 300 days old. Suddenly the owl’s localization performance improves back to normal.

So this result says that critical periods aren’t exactly “critical”; the right sort of experience beyond what we thought was the critical period can lead to normal development.

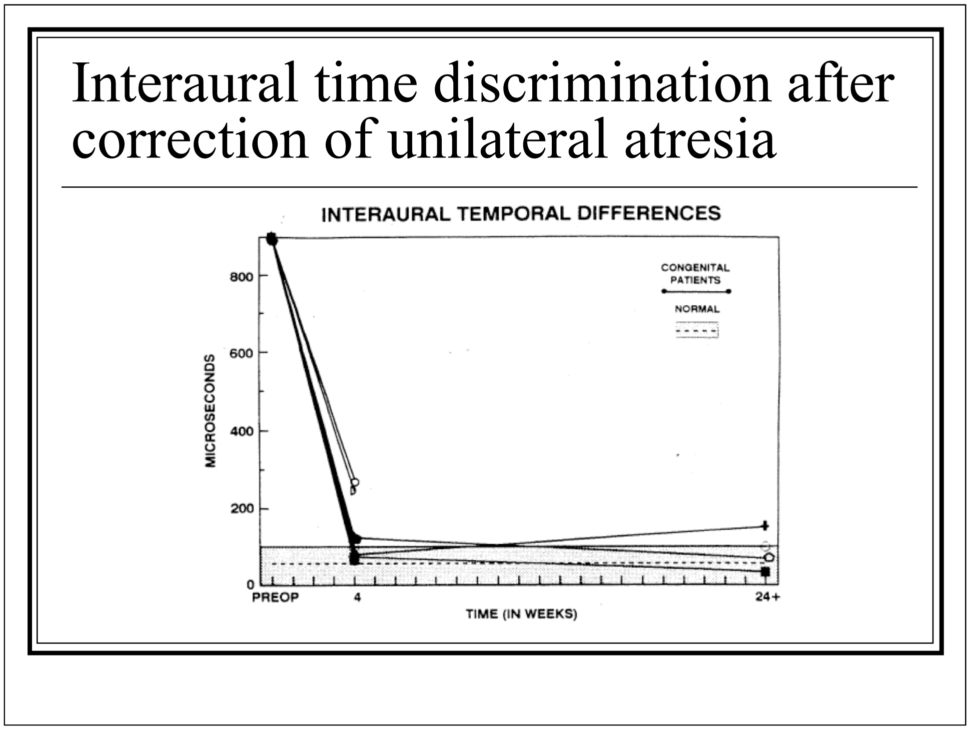


Effects of experience in humans: Wilmington, Gray and Jahrsdorfer (1994)

- 19 subjects with congenital unilateral atresia
- Tested before and after corrective surgery
- Age at surgery ranged from 6 to 33 years.
- Tests included ITD and IID discrimination, speech in noise (sound field), and sound localization.

Wilmington, Gray and Jarhsdorfer examined the binaural hearing and localization abilities of people who had corrected congenital unilateral atresia. In atresia, the external ear does not form, although the inner ear works fine. Thus, these listeners had a huge imbalance between their ears until the time of the surgery to correct the atresia. There were 19 subjects. Their ages at the time of the surgery ranged from 6 to 33 years. They were tested on a battery of binaural and localization tasks, including interaural time and intensity discrimination, speech perception in noise in sound field with the noise coming from the same speaker as the speech or from a different speaker, and sound localization, which involved pointing to the position from which a sound was coming.

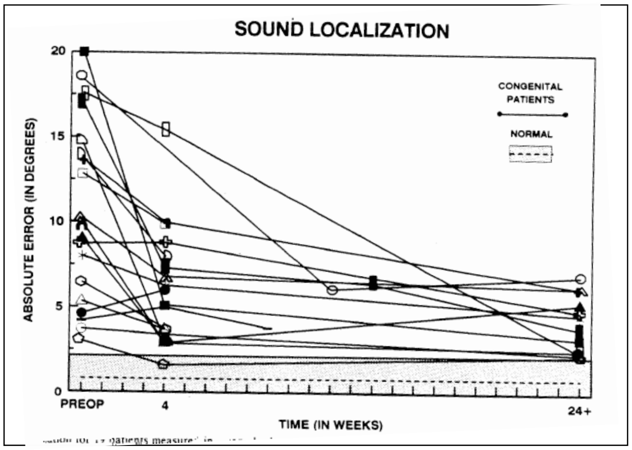
1.Wilmington, D., L. Gray, and R. Jahrsdorfer, Binaural processing after corrected congenital unilateral conductive hearing loss. Hear Res, 1994. **74**: p. 99-114.



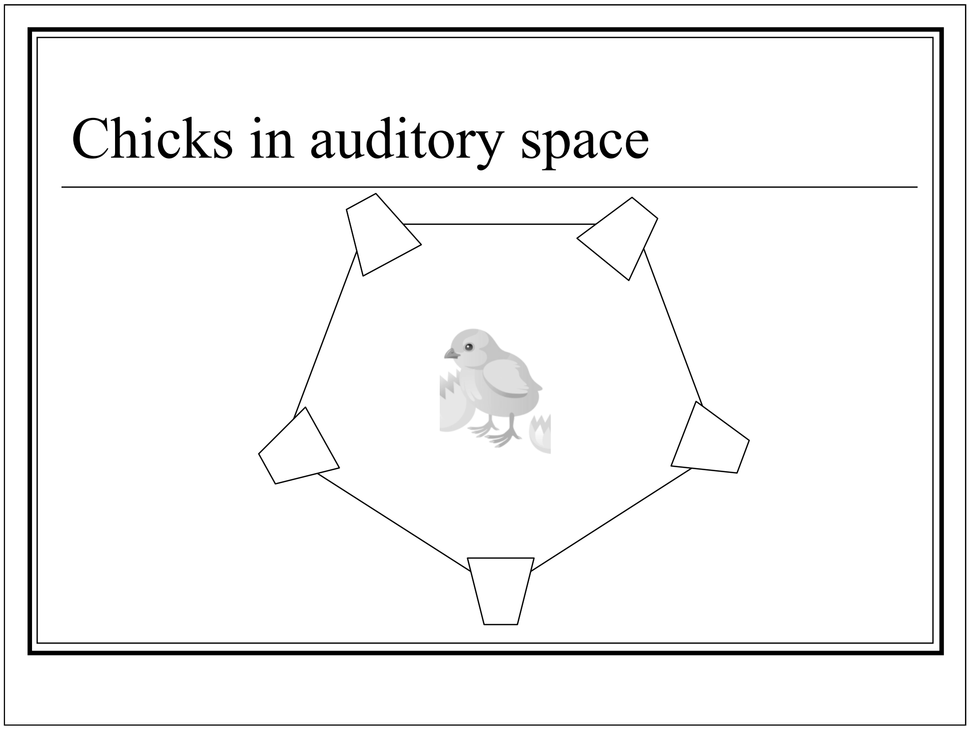
Interaural time discrimination after correction of unilateral atresia

These graphs show the ITD discrimination thresholds of the subjects as a function of time since surgery. Each curve is for one subject. The shaded area near the bottom of the slide represents the normal range of performance. Notice that in the weeks following surgery, thresholds improve, and by 4 weeks postsurgery, have reached the normal range.

Localization after correction of unilateral atresia



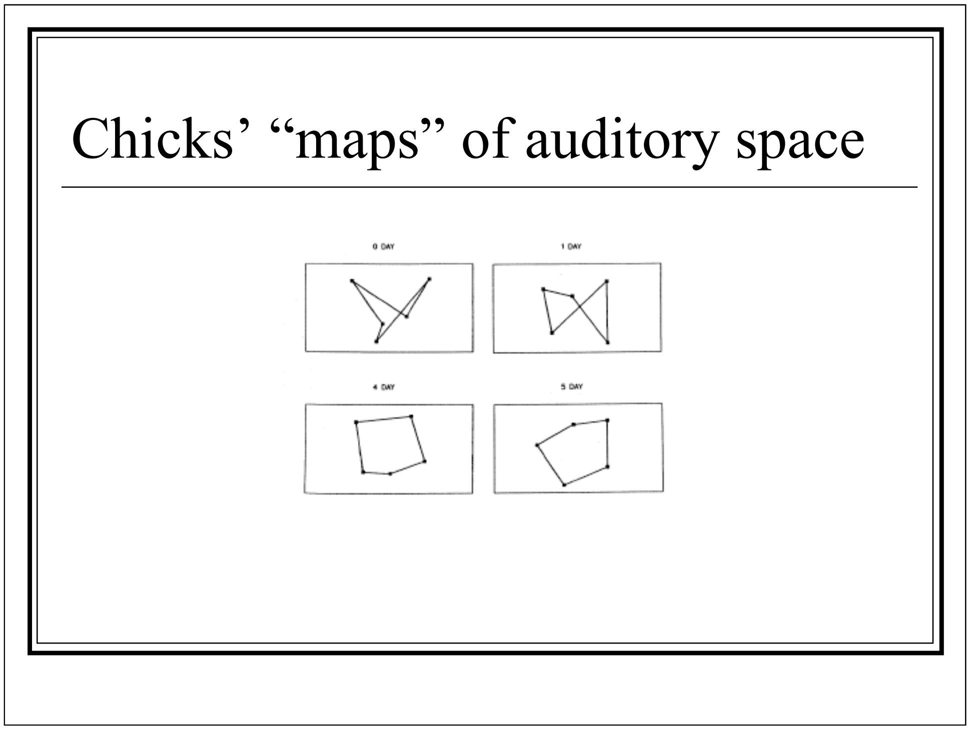
A very different pattern of performance was seen when subjects were asked to point to the location of a sound source. Few of them could do so after surgery; there was some improvement in the next several weeks, but after 24 weeks, few subjects were even close to the normal range.



Chicks in auditory space

A study of chicks may help us to understand what is going on with these human patients. Gray (1992) reported a study in which he measured newly hatched chicks’ response to sound. The chick was placed in an enclosure shaped like a pentagon, with a speaker at each corner. When a chick is left alone, it peeps incessantly. When it hears a sound, the chick stops peeping momentarily. Then it starts peeping again, even if the sound continues, but if the sound shifts from one speaker to another, the chick stops peeping again. The duration of peep suppression is related to how far the sound source shifted. If the sound shifted from one speaker to the speaker right next door, peep suppression was short. If it shifted to a speaker on the opposite side of the array, peep suppression was long. By looking at how long the chicks suppress peeping for all possible sound shifts (and applying a technique called multidimensional scaling) we can construct a “map” that represents the chick’s apparent perception of the locations of the speakers.

1.Gray, L., Interactions between sensory and nonsensory factors in the responses of newborn birds to sound, *In* Developmental psychoacoustics, L.A. Werner and E.W. Rubel, editors. 1992, American Psychological Association: Washington, D.C. p. 89-112.

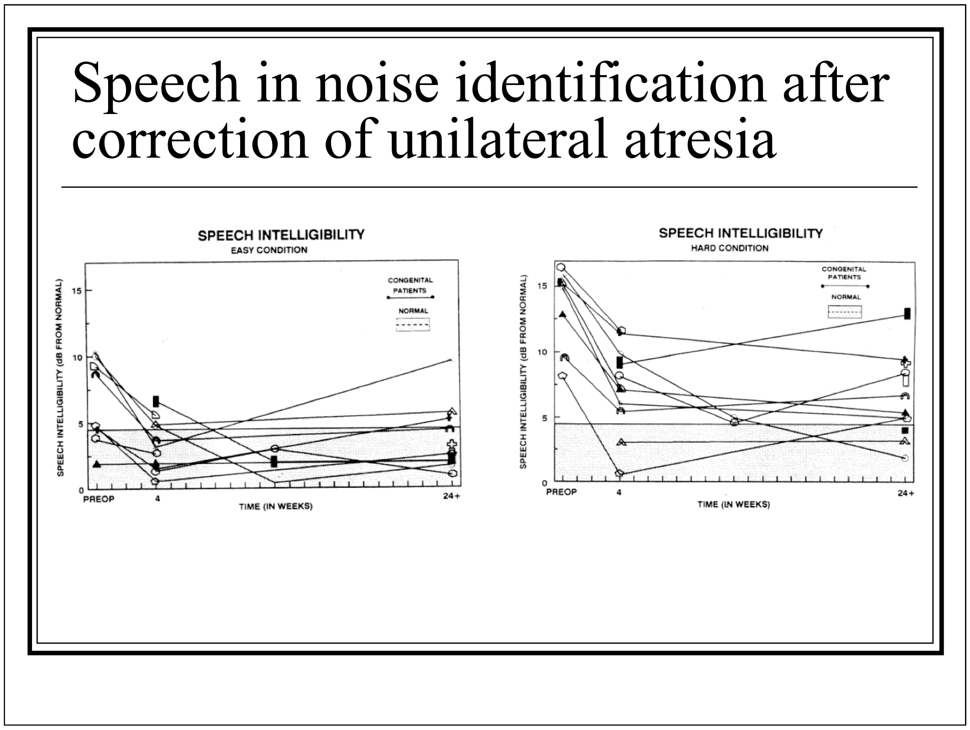


Chicks' "maps" of auditory space

These are the results of this experiment for chicks of different ages. The results for the 4 and especially the 5 day olds actually resemble the pentagonal arrangement of the speakers. The results for the 0 and 1 day olds are kind of a random mess-- they are not organized in a way that suggests that these young chicks really had an organized perceptual space, They heard the sounds, they responded to them, but their response does not vary systematically with sound source location like the older chicks' responses do.

The implication is that it takes some experience with sound outside the shell to form a map, or to assign particular patterns of sound to particular locations in space.

Wilmington et al.'s (1994) results with the people with corrected unilateral atresia suggest that while the people were able to differentiate the patterns that denote different spatial locations, they were unable to assign a spatial location to each pattern of sound. They are like the disorganized young chicks.



Speech in noise identification after correction of unilateral atresia

Speech in noise was another task that showed continued poor performance in some conditions following surgery in Wilmington et al (1994). If the noise was next to the congenitally normal ear, listeners had considerable difficulty understanding speech in their corrected ear, even taking into account differences in threshold between the ears. However, if the noise was next to the corrected ear, listeners had little difficulty identifying the speech.

This is an interesting result from the standpoint of selective attention: It seems that people can become so accustomed to attending to the input from just one ear, that they have difficulty ignoring any input from that ear. Selective attention is not always a conscious process.

Summary of effects of experience on sound localization

- Experience with sound is essential for the development of sound localization.
- Experience with sound is less essential for the development of the ability to process the acoustic cues to location.
- Although a critical period for the development of localization has been identified in some other species, a similar critical period has not yet been identified in humans.