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Issues in Human Auditory Development

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Abstract

The human auditory system is often portrayed as precocious in its development. In fact, many aspects of basic auditory processing appear to be adult-like by the middle of the first year of postnatal life. However, processes such as attention and sound source determination take much longer to develop. Immaturity of higher-level processes limits the processing of both simple and complex sounds by infants and children. Young listeners with impaired hearing may be at a particular disadvantage, in that they must make sense of sounds on the basis of a degraded representation using immature perceptual strategies.

Learning outcomes—(1) Readers will be able to describe three stages of human auditory development. (2) Readers will be able to describe how experience with sound is important in auditory development. (3) Readers will be able to describe the role of attention and other higher-level processes in early audition.

1. Introduction

Researchers in speech, language and hearing development have historically emphasized the idea that human infants typically come into the world prepared to process the sound around them, to learn speech and language through the auditory modality. Although that is undoubtedly true, infants' hearing is not yet like adults'. In fact, some aspects of auditory processing continue to develop well into childhood and adolescence. The purpose of this paper is to describe the major changes in auditory behavior that occur between birth and adulthood and to address the potential contributions of experience with sound to the maturation of auditory behavior.

Auditory experience begins during the third trimester of gestation, but we have only a little information about how this experience might affect postnatal development. For example, it appears that a newborn recognizes her mother's voice (DeCasper & Fifer, 1980) and some characteristics of her native language as well (Mehler et al., 1988). However, infants are only exposed to the full spectrum of sound after they are born, and it is clear that while prenatal experience may help infants "tune in" to certain sounds in the early weeks, environmental sounds become an overriding source of new information from birth on. The development of auditory behavior entails at least three postnatal stages. In the first stage, the neural encoding of the fundamental characteristics of sound matures. In the second stage, infants and children come to use the information in sound in a more specific way, allowing them to discover new information in the sound stream. In the third stage, children approach sound in a qualitatively adult-like manner, but continue to develop flexibility in sound processing.

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1.1. Maturation of the coding of sound

The first postnatal period of auditory development lasts less than 6 months. At birth, the newborn is less sensitive to sound than an adult, requires larger changes in the frequency or intensity of sound to notice a change, and likely has access to a fuzzier representation of sounds. All of these effects are most evident at higher frequencies, above about 2000 Hz. It has been estimated that a 1-month-old's behavioral response threshold at 4000 Hz is about 35 dB higher than an adults' (Tharpe & Ashmead, 2001;Werner & Gillenwater, 1990). By 3 months, the difference in threshold at 4000 Hz has improved to 30 dB re: adult threshold, and by 6 months of age, it is about 15 dB re: adult threshold. A 3-month-old only responds to a change in the frequency of a 4000 Hz tone if it is greater than 120 Hz or so, under conditions in which adults can hear a change less than 40 Hz (Olsho, Koch, & Halpin, 1987). Immature frequency discrimination is consistent with reports of immature frequency resolution, the ability to separate the frequency components of a complex sound (Spetner & Olsho, 1990). One implication of immature frequency resolution is that spectral details in complex sounds such as speech will not be as clearly represented in the auditory system, at least at high frequencies.

Some of the sources of immature auditory behavior in early infancy have been established. For example, immaturity of the middle ear is an important contributor to infants' poorer sensitivity to high-frequency sounds (Keefe & Levi, 1996). In addition, there is a relationship between an infant's sensitivity to a high-frequency tone and the speed with which information is transmitted through the auditory brainstem (Werner, Folsom, & Mancl, 1994), suggesting that information loss in the brainstem also contributes to infants' early lack of high-frequency sensitivity. Measures of frequency resolution at the level of the brainstem indicate the same immaturity of high-frequency resolution as seen in behavioral studies (Abdala & Folsom, 1995;Folsom & Wynne, 1987). Interestingly, all indications are that the inner ear is mature by term birth, making it unlikely to contribute to immature auditory behavior. One of the things we don't know is how auditory experience influences development in this early period. While experience probably isn't terribly important to the improvements in sound conduction through the middle ear, that early experience is necessary for improvements in neural coding of sound is a strong possibility. It is known, for example, that exposing animals to a constant broadband sound results in deficits in frequency resolution (Sanes & Constantine-Paton, 1985). The brain apparently needs exposure to sounds with peaks and troughs in their spectra, so that the neural elements that respond to the same frequency are simultaneously activated while other neural elements are not. Thus, it would seem that exposure to high-frequency sounds early in infancy is quite important to the normal development of the neural coding of high-frequency sounds. It is perhaps not coincidental that intervention prior to 6 months of age predicts better speech and language outcomes for hearing-impaired children (Yoshinaga-Itano & Apuzzo, 1998;Yoshinaga-Itano, Coulter, & Thomson, 2001).

2. Increasing specificity and discovering details in complex sounds

The second postnatal stage of auditory development begins at 6 months and extends into the early school years. It involves two sorts of age-related change. One is an increasing specificity in the acoustic cues that are used in making perceptual decisions. The other is the discovery of new, perhaps more subtle, cues that can be used to distinguish sounds.

Between birth and about 6 months of age, the processing of high-frequency sound improves to the point that a 6-month-old is generally as good as an adult at discriminating between two high-frequency tones (Olsho et al., 1987). Frequency resolution is like that in adults (Spetner & Olsho, 1990). Absolute sensitivity to sound is still somewhat poorer, but 6-month-olds' thresholds are only about 15 dB higher than adults' at frequencies above 2000 Hz (Olsho, Koch, Carter, Halpin, & Spetner, 1988;Trehub, Schneider, & Endman, 1980). Absolute sensitivity to low frequencies remains about 20 dB poorer than in adults and matures slowly during the remainder of infancy and into childhood. Maturation of the middle ear is probably responsible for this long slow developmental course for absolute sensitivity (Okabe, Tanaka, Hamada, Miura, & Funai, 1988).

2.1. Increasing specificity

An important observation is that while frequency resolution is mature by 6 months of age, infants remain immature in their ability to detect a tone in a broadband noise. Thus, even though the auditory system is able to filter out much of the noise surrounding the tone, the infant has difficulty extracting the tone from the noise that remains (Bargones, Werner, & Marean, 1995;Schneider, Trehub, Morrongiello, & Thorpe, 1989;Werner & Boike, 2001). As a matter of fact, 7-9-month-old infants have difficulty extracting a tone from an irrelevant sound, even when the irrelevant sound's spectrum does not overlap with the tone's spectrum (Leibold & Werner, 2006;Werner & Bargones, 1991). While this "distraction" effect is not well understood, there are at least three possible explanations for it.

First, it is possible that the infant auditory system is inconsistent in the way that it encodes the intensity of a sound. If that were the case, it would be difficult for an infant to tell when a tone has been added to a noise. In addition, variation in irrelevant sound has a distracting effect, even in adults (Durlach et al., 2003;Lutfi, Kistler, Oh, Wightman, & Callahan, 2003;Neff & Callaghan, 1988). Infants appear to demonstrate a similar effect when the experimenter varies the irrelevant sound, but if the infants' auditory system effectively varies a constant irrelevant sound, they may respond as if the sound itself had varied. There is not much evidence to support this explanation of infants' immature detection of tones in noise (although see Buss, Hall, & Grose, 2006).

Second, it is possible that infants have trouble perceptually separating the components of different simultaneous sounds. Adults are able to separate the sounds that come from one sound source (e.g., your spouse's voice) from those that come from another (e.g., the sound of a car moving down the street), because the sounds come from different locations, change over time in different ways, and are different in sound quality or timbre. This process is known as sound source determination, and even under simple conditions being able to separate sounds in this way improves the ability to detect or discriminate one of the sounds (e.g., Arbogast, Mason, & Kidd, 2005). It is known that infants are able to separate sounds in this way under some conditions (e.g., Fassbender, 1993), but that they need a better signal-to-noise ratio to do so (e.g., Newman & Jusczyk, 1996). Furthermore, other studies suggest that while children are able to take advantage of some cues to separate one sound from another (e.g., when the sounds come on, Leibold & Neff, under review), they are far less able than adults to take advantage of other cues (e.g., sound location, Hall, Buss, & Grose, 2005). The cues that infants and children use to separate sounds may be related to their ability to process the cues in isolated sounds. For example, infants seem to be similar to adults in their ability to judge whether or not two sounds began simultaneously (Jusczyk, Rosner, Cutting, Foard, & Smith, 1977), but 5-year-old children still have difficulties with sound localization in complex sound environments (Litovsky, 1997).

Third, it is possible that infants have stable representations of intensity and that they can separate the overlapping components of sound coming from different sources, but that they are unable to selectively attend to one sound while ignoring another (Gomes, Molholm, Christodoulou, Ritter, & Cowan, 2000). Bargones and Werner (1994) found that while adults expecting to hear a low-intensity tone at one frequency did not hear tones at other unexpected frequencies, infants detected expected and unexpected frequencies equally well. This suggests that the adults focused attention on the expected frequency, but that infants did not. However, infants do appear to form expectancies of when sounds will occur and to direct their attention toward sounds that occur at expected times. Parrish and Werner (2004) showed that if infants learned that a tone would come on 500 ms following another sound, they, like adults, detected the tone better when it came on 500 ms after the other sound than when it came on 200 or 800 ms after. Thus, it appears that even infants are capable of adult-like auditory attention under some conditions.

Preschool children continue to have difficulty in the separation of sounds under some circumstances. Four-year-olds are typically reported to have tone-in-noise thresholds perhaps 5 dB higher than adults', while 6-year-olds' tone-in-noise thresholds are no different from adults' (e.g., Hall & Grose, 1991). Distraction by irrelevant sounds may be worse than that seen in adults in children as old as 10-years of age, but by 7 or 8 years, children can overcome such distraction effects as well as adults can when they are given a cue like onset time to distinguish the target sound from the distracter (Leibold & Neff, under review). As late as 6-8 years, children generally perform more poorly than adults in dichotic listening tasks (Cherry, 1981;Pearson & Lane, 1991;Wightman & Kistler, 2005), suggesting that auditory selective attention continues to improve into this age range. The studies examining these age-related changes in behavior have all been cross-sectional studies, but there is little indication that these auditory skills develop very gradually. Rather, some children as young as 5 years of age may fall in the adult range, and the proportion of children falling in the adult range increases with increasing age (e.g., Allen & Wightman, 1994;Leibold & Neff, under review).

2.2. Discovering new details

At the same time that infants and children are becoming better at separating sounds and attending selectively to relevant sounds, they are learning to use new information to distinguish sounds. One example is low-frequency tone discrimination. As noted previously, frequency discrimination at high frequencies is nearly mature at 6 months of age. It was not mentioned, however, that low-frequency discrimination remains immature beyond 12 months of age. Adults are relatively better at discriminating between low frequencies than high, it is thought because they use periodicity rather than the cochlear excitation pattern to distinguish low-frequency tones (e.g., Moore, 1973). However, adults take longer to learn to discriminate between low-frequency tones reliably (Harris, 1952;Olsho, Koch, & Carter, 1988). It has been hypothesized that the same mechanism is involved in the development of low-frequency discrimination: Periodicity may not be the most obvious cue to differences in tone frequency, and it is only with experience with sound that we are able to use that information. Soderquist and Moore (1970) examined the ability to discriminate between low-frequency tones in 5-, 7- and 9-year-old children, before and after extensive training. Even after training, 5-year-olds were not as good as 7- and 9-year-olds in this task. However, all age groups, and particularly the 5-year-olds, improved with training. Nittrouer and her colleagues have published a series of studies that documents differences between preschool children and older listeners in the cues that they use in phonetic discriminations (e.g., Nittrouer, 2004,2005,2006). In general, the results of these studies support the view that children place greater weight on dynamic cues than on static cues in identifying and discriminating consonants when both types of cues are available, but that adults do just the opposite, weighting static cues more heavily than dynamic cues. Nittrouer argues that this difference reflects a tendency for children to attend to the global, slowly changing aspects of speech and that it is only with experience that they learn to use the finer details in sound to make discriminations. Other investigators have argued that it is not the dynamic nature of speech cues that leads to children's differentially weighting strategy, but a difference in the distinctiveness or informativeness of the cues (Sussman, 2001). A recent investigation has shown that while the distinctiveness of cues makes important contributions to the cues that children use in identifying speech, distinctiveness alone cannot account for the way that children weight cues in all situations (Mayo & Turk, 2004,2005). Whatever the variables that influence the cues that children use to identify speech sounds, the consensus is that the cues they use differ from those used by adults. It is clear that throughout the preschool and early school years, children continue to learn about the acoustic details in the sounds they hear and to extend their ability to distinguish sounds in a variety of listening conditions.

3. Flexibility in the use of acoustic information

By perhaps 8 or 9 years of age, children's auditory sensitivity and their ability to separate sounds even under quite complex listening conditions are similar to adults' (e.g., Hall, Buss, Grose, & Dev, 2004;Wightman & Kistler, 2005). Nonetheless, Hazan and Barrett (2000) have reported that children as old as 12 years of age are less consistent than adults in their identification of consonants. On average, children place their speech category boundaries in the same location as adults do, and changes in phonetic context have similar effects on the location of those boundaries. It is, however, as if the region of uncertainty between categories is broader for children than for adults.

Why children are less consistent in their identification of speech sounds is not well understood, but there are indications that although children now are able to use all the available acoustic cues in speech identification they are less able to choose the appropriate cue under less than optimal listening conditions. For example, Hazan and Barrett (2000) found that children were more consistent in identification when multiple cues were available compared to when only a single cue was available suggesting that children lack the flexibility to use whatever cue was available. Nittrouer et al. (2000) came to a similar conclusion in a study of 5- and 7-year-old children, and Johnson's (2000) observation that even 15-year-olds performed more poorly than adults in speech identification in the presence of noise or reverberation also is consistent with this idea.

4. Conclusions

Infants and children seem to go through three broad stages of auditory development. In the first stage, the neural mechanisms involved in coding sound mature. In the second stage, children become more specific in the way that they listen to sound and become able to use finer acoustic details in the identification of sounds. In the final stage, children become capable of flexibly choosing the acoustic information that they use to identify sounds. In all three stages, experience with sound is required, first to form the right neural connections to encode sound accurately, then to provide exposure to acoustic detail, and finally to provide opportunities for children to discover the cues that are most useful under different listening conditions.

The course of auditory development is prolonged. In some ways this should not come as a surprise to us. After all, communication is a complex but central process in human life that involves not only complex auditory but multimodal, cognitive and social processes. What is perhaps more surprising is that infants and children are very good at understanding speech, despite their apparent dependence on information that is much more limited than that available to mature listeners.

Appendix A. Continuing education

1. Auditory learning begins
    - **a.** At conception
    - **b.** In the third trimester of gestation
    - **c.** At birth
    - **d.** At 6 months of age
2. Which of the following is an attribute of hearing that is mature at birth?

a. Absolute sensitivity
b. Frequency resolution
c. Frequency discrimination
d. None of the above

3. Two important contributors to early postnatal immature auditory sensitivity are
   a. Middle ear and inner ear
   b. Inner ear and auditory brainstem
   c. Middle ear and auditory brainstem
   d. None of the above
4. Besides becoming more specific in the way they listen to sounds, between 6 months and 8 years of age, children
   a. Pick up more fine details of sound
   b. Become better able to relate sound to objects
   c. Become more flexible in their use of acoustic information
   d. Develop better coding of sound in the inner ear
5. The primary difference between school-aged children and adults in the way they process complex sounds is in
   a. The flexibility with which they can use different acoustic cues
   b. The extent to which noise interferes with their ability to detect sound
   c. The ability to pick up fine details in sound
   d. Basic capacity to distinguish between simple sounds

Appendix A. Continuing education (correct answers*)

1. Auditory learning begins
   a. At conception
   b. In the third trimester of gestation*
   c. At birth
   d. At 6 months of age
2. Which of the following is an attribute of hearing that is mature at birth?
   a. Absolute sensitivity
   b. Frequency resolution
   c. Frequency discrimination
   d. None of the above*
3. Two important contributors to early postnatal immature auditory sensitivity are
   a. Middle ear and inner ear
   b. Inner ear and auditory brainstem

c. Middle ear and auditory brainstem*

d. None of the above

4. Besides becoming more specific in the way they listen to sounds, between 6 months and 8 years of age, children

   a. Pick up more fine details of sound*

   b. Become better able to relate sound to objects

   c. Become more flexible in their use of acoustic information

   d. Develop better coding of sound in the inner ear

5. The primary difference between school-aged children and adults in the way they process complex sounds is in

   a. The flexibility with which they can use different acoustic cues*

   b. The extent to which noise interferes with their ability to detect sound

   c. The ability to pick up fine details in sound

   d. Basic capacity to distinguish between simple sounds

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