Infant auditory capabilities

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Infants come into the world prepared to process and respond to sound. However, at birth their hearing is immature in several ways. Some aspects of hearing such as frequency and temporal resolution mature by 6 months postnatal age. Other aspects of hearing such as absolute sensitivity, intensity resolution, and complex sound processing continue to develop throughout infancy and well into childhood. Development during the early postnatal period likely results from maturation of relatively low-level neural processing. The final stages of auditory development depend on the maturation of higher-level processes such as selective attention. Curr Opin Otolaryngol Head Neck Surg 2002, 10:398–402 © 2002 Lippincott Williams & Wilkins, Inc.

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Abbreviations

ABR	auditory brainstem response
DPOAE	distortion product otoacoustic emissions
MMN	mismatch negativity
SPL	sound pressure level

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Tremendous strides in our understanding of infant perceptual development were made in the 1970s. The remarkable capabilities of even newborn infants to select stimuli for processing, to recognize complex visual patterns such as the human face, and to discriminate among speech sounds were among the most noteworthy findings of this period. It remained to subsequent research to demonstrate the limitations of these capabilities and their eventual maturation. Although progress has been made in this regard in the past 20 years, major questions about early human auditory development remain unanswered.

Audition can be described in terms of the processing of three acoustic dimensions: intensity, frequency, and temporal modulation. In the mature auditory system, these basic aspects of sound processing are largely determined by conductive transmission and cochlear processing, although processing at the level of brainstem and midbrain is also involved. We refer to these as "primary" processes. The processing of complex sounds, however, cannot be fully predicted on the basis of these fundamental aspects of sound processing. Additional 'central' processes must be invoked to account for complex perception. However, both primary and central processes have strong and direct influences on perception. It should come as no surprise that primary and central processes follow different developmental courses through infancy and childhood. It must be noted, in addition, that maturation proceeds differentially across the components of the primary processing system.

Primary auditory processing

Intensity processing

The most common way of describing hearing is in terms of absolute threshold, the intensity of sound just required for detection. Several studies have observed the course of threshold development during infancy [1,2]. Measured with similar behavioral methods across ages, frequency-specific thresholds improve from about 40 to 55 dB sound pressure level (SPL) in 1-month-old patients to 10 to 30 dB SPL in 6- to 12-month-old patients. Although behavioral thresholds have been estimated in newborns, the methods employed to obtain these thresholds are different from those used in older infants, and the pure-tone thresholds obtained, 70 to 80 dB SPL, seem unreasonably high [3]. Between 1 and 6 months, high-frequency thresholds improve considerably. A 6-month-old patient's threshold at 4 kHz is only about 10 dB higher than that of an adult. Low-frequency thresh-

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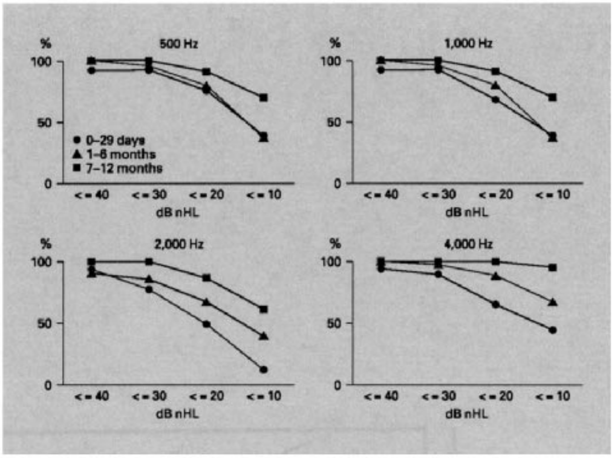
olds mature more slowly, and apparently do not reach adult values until 10 years of age. Tharpe and Ashmead [4•] recently tested infants longitudinally from birth to 12 months of age. Behavioral responses to speech-spectrum noise were recorded. Their findings essentially replicate those of previous cross-sectional studies in that threshold improved exponentially with age, leveling off at about 6 months.

Another interesting recent study examined steady state responses evoked by amplitude-modulated tonal complexes among infants 4 to 14 months old [5••]. Responses were analyzed to isolate the component at each frequency in the complex carrier, and the percent of detectable responses as a function of intensity at each frequency was estimated in three age ranges. To obtain equivalent response rates at 500 Hz, tone level had to be about 10 dB higher for 4- to 5-month-old patients than for older infants, but at 4000 Hz the tone level had to be more than 20 dB higher for the younger infants (Fig. 1). This pattern of development is very similar to that observed in behavioral responses of infants over the same age range.

Several of the mechanisms underlying early threshold development have been determined. Growth of the external ear and increases in the efficiency of middle ear transmission appear to be responsible for much of the improvement in threshold observed during early infancy [6]. Werner and Holmer [7] have recently demonstrated that improvements in middle ear conductance can account for about 8 dB of the improvement in threshold observed between 3 months and adulthood. Furthermore, about 40% of the variance in thresholds of adults and infants may be accounted for by differences in middle ear conductance.

Figure 1. Percent of multiple-frequency steady state responses detected in infants of 3 ages as a function of stimulus intensity



Percent of multiple-frequency steady state responses detected in infants of 3 ages as a function of stimulus intensity. Each panel shows the response at a different frequency. Published with permission [5••]

Every indication is that cochlear function is mature by the time of term birth. Otoacoustic emissions are sounds produced by the normal, mature ear in response to stimulation. The presence of otoacoustic emissions is a good indication of normal cochlear function, and emissions have been evaluated positively as a hearing-screening device for newborn infants. Abdala and her colleagues have completed a series of studies characterizing cochlear function of preterm and term infants using distortion product otoacoustic emissions (DPOAE). By term birth, the range of external tone frequencies that can suppress a DPOAE is equivalent for infants and adults, which suggests similar frequency tuning at the level of the cochlea [8•]. Furthermore, DPOAE amplitude has been shown to increase with stimulus amplitude in the same way for term infants and adults [9••]. Again, the implication is that sensitivity at the cochlear level is mature by term birth. Abdala has also reported in these articles that DPOAE of preterm infants tested at 31 to 33 weeks gestational age differ from those of adults. Essentially, DPOAE tuning appears to be maintained over a broader intensity range for preterm infants than it is for adults. However, it is not clear whether this age-related difference in DPOAE results from differences in cochlear processing or from immaturity of middle ear function.

Primary neural maturation is probably also involved in threshold maturation, at least before 6 months of age. Werner *et al.* [10] have shown a significant correlation between high-frequency behavioral detection threshold and auditory brainstem response (ABR) interpeak latency among 3-month-old patients, but not 6-month-old patients. Improvements in synaptic transmission efficiency within the brainstem may play an important role in maturation of both of these measures.

It is believed that threshold development after 7 months of age involves a small effect of conductive maturation. However, the processing of intensity of suprathreshold sounds also undergoes development during infancy. The just-noticeable difference (or change) in intensity is in the range of 1 to 2 dB for adults but can be as high as 8 dB among 7-month-old patients [11]. The maturation of absolute sensitivity and of suprathreshold intensity processing beyond infancy probably results from improvements in processing efficiency, a central phenomenon discussed in detail in the section on frequency processing.

Frequency processing

Frequency resolution refers to the ability to differentially process one component of a complex sound. The simplest, if least interpretable, measure of frequency resolution is the threshold for a frequency specific stimulus such as a tone or noise band masked by a broadband noise. Studies have examined the development of masked threshold in infants as young as 3 months [12,13]. Masked thresholds appear to be about 15 to 20 dB higher among 3-month-old patients than among adults. At 6 months, infants' thresholds for a tone are about 10 dB higher than adults' thresholds across the frequency range. Masked threshold continues to develop until around 5 to 6 years of age. It is probably no coincidence that masked threshold and intensity discrimination follow similar developmental courses because both involve the detection of an increment in sound energy.

Masked threshold depends on frequency resolution, but it also depends on processing efficiency. Processing efficiency is the signal-to-noise ratio required for detection or how much of an increase in energy is needed to indicate the presence of a signal. One study has shown that at 3 months, frequency resolution is immature, but only at frequencies above 4 kHz [13]. That similar immaturities are found in ABR measures of frequency resolution but not in cochlear measures suggests that the immaturity in early infancy results from a less refined innervation pattern at the brainstem level [14,15]. Several studies have now demonstrated that frequency resolution, as indicated for example by psychophysical tuning curves [13], is mature by 6 months of age. Thus, infants' immature masked thresholds generally cannot be accounted for by immaturity of frequency resolution, implying that efficiency is the culprit.

The difficulty is that efficiency is influenced by many factors including intensity resolution, attentiveness, motivation, memory, and selective attention. It is generally agreed that simple inattentiveness or being 'off-task' can account for only 2 to 3 dB of the difference between masked thresholds of infants and adults [16]. Similarly, memory and motivation appear to be of minor importance in threshold development [17,18]. Bargones and Werner [19], however, present evidence that infants do not selectively attend to a frequency-specific sound masked by broadband noise. Unlike adults, they appear to listen across the frequency range even when attempting to detect a pure tone. Therefore, noise in frequency bands away from the band containing the signal will contribute to the decision process, leading to a decrease in sensitivity. Because infants essentially listen in a 'broadband mode,' they are actually more sensitive, relative to adults, to broadband than to narrow band sounds. Werner and Boike argue that all but 2 to 3 dB of the infant–adult difference in masked threshold can be accounted for by a combination of inattention and broadband listening [20••].

Besides detecting sounds in noise, frequency resolution plays a role in frequency discrimination and pitch perception. However, because the auditory system represents frequency in terms of both a place code and a temporal code, immaturity of either code could influence infants' ability to perceive the pitch of simple and complex sounds. Early studies of infants' ability to discriminate between tones on the basis of frequency demonstrated changes during the first 6 months of postnatal life as well as continuing maturation beyond 6 months. For example, Olsho *et al.* [21] reported that 3-month-old infants were poorer than older infants and adults in pure-tone frequency discrimination, particularly at high frequencies. By 6 months, however, infants discriminated between high-frequency tones nearly as well as adults did; they remained immature in low-frequency discrimination. It appears that pure-tone frequency discrimination abilities are not completely mature until school age. At the same time, infants appear to process the pitch of harmonic complexes in an adult-like manner [22], and numerous studies have demonstrated that infants' perception of melodic sequences resembles that of adults in many respects: they prefer consonant musical intervals over dissonant ones and they appear to discriminate changes in musical intervals better when the interval is drawn from a typical musical scale [23••]. Recent studies on this topic by Saffran and her colleagues have garnered considerable attention. Saffran and Griepentrog [24••] showed that after 8-month-old patients were exposed to a repeating sequence of tones, they appeared to recognize the absolute pitch of the tones but not the relative pitch or intervals within the sequence. Adults exposed to the same sequences appeared to recognize the intervals in the sequences rather than the absolute pitch of the tones. This result is taken to mean that a reorganization of pitch representation takes place between infancy and adulthood.

Temporal processing

Temporal processing is the processing of rapid intensity and frequency changes in sound over time. The events of interest have durations of a few to hundreds of milliseconds and carry information such as the presence of voicing in speech and speech prosody. The ability to follow changes in intensity has been most extensively studied in adults who are able to follow intensity changes on the order of 2 to 3 milliseconds.

The question is whether infants too can follow such rapid changes in sound. Studies of infants' ability to detect interruptions, or "gaps," in sound suggest that they are quite poor in following rapid changes in sound, detecting gaps only as short as 25 to 40 milliseconds compared with 3 milliseconds for adults [25,26]. However, more recent work suggests that infants can in fact follow amplitude modulation at modulation frequencies comparable with those followed by adults [27]. Furthermore, Werner *et al.* [28•] have reported that infants' ABR to gaps in noise is quite adult-like, and Trainor *et al.* [29•]

have similarly reported adult-like cortical responses (*eg*, mismatch negativity and P2) to gaps between tone bursts in 6-month-old infants. These findings suggest that infants' apparent deficits in detecting gaps are not the result of immaturity of temporal resolution. Rather their poor gap detection is likely to result from poor processing efficiency, which has been demonstrated in sound detection tasks.

Higher-level auditory processing

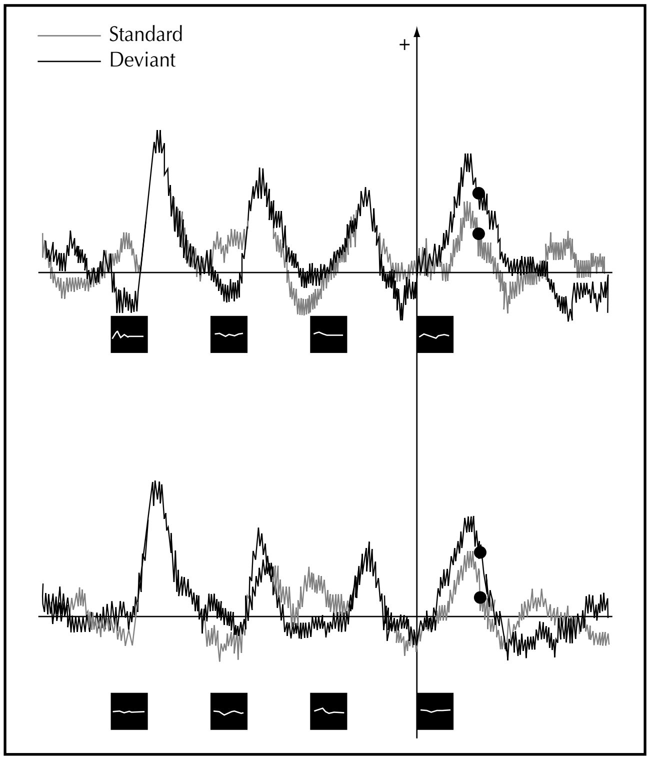
The impact of processes like selective attention on the detection of tones may seem of limited interest to all but audiologists and psychoacousticians. It is quite possible, however, that these observations of infants' perception of simple sounds are telling us something about what infants listen to in more common and important sounds such as speech. Although even young infants demonstrate an ability to discriminate among speech sounds, it is nonetheless clear that substantial changes in speech perception occur during infancy [30–32•]. Infants' perception of speech tends to become more specific to their native language during the first year of life [33•,34]. Furthermore, studies of older children demonstrate that the specific acoustic information within the speech signal used to make phonetic distinctions continues to change well into childhood [35]. The bottom line is that what infants hear when they listen to speech may well differ from what adults hear. It will be the goal of future research to extend observations of infants' specific listening strategies for nonspeech sound to those for speech sounds.

Although the speech discrimination abilities of newborn infants have been examined using behavioral responses [36], recent studies have focused on the event-related potential correlates of speech perception to assess the state of speech processing at birth. For example, several studies have shown that newborn infants demonstrate mismatch negativity (MMN) responses to a change in duration or spectrum of complex sounds [37–40•]. One study in particular has produced quite interesting results, demonstrating that the newborn's MMN to a change in syllable from /pa/ to /ta/ is the same whether the changed syllable is spoken by the same talker or not (Fig. 2) [41••]. This suggests that by birth the acoustic features that distinguish phonetic contrasts in the face of talker variability can readily be extracted by the auditory system and clearly do not require much exposure to speech.

Conclusions

The first 6 months of prenatal life represent the final stage of development for primary auditory processing. Many aspects of intensity, frequency, and temporal processing mature during that period. However, 6-month-old infants are still immature in some tasks: detecting sounds in noise, detecting intensity changes in sound, and discriminating between low-frequency tones. The bulk of recent evidence suggests that these immature auditory behaviors result from immaturity of the processes collectively known as efficiency, including selective attention. As experience with sound—and with speech in particular—is gained, infants and children only gradually learn to focus on the most informative. Such focus allows for the rapid and accurate identification of sound that is seen in adults.

Figure 2. Grand average event-related potentials in newborns to the syllables /pa/ and /ta/



The presentation of each syllable is represented in time by the inset time waveforms below the responses. In each panel, the response labeled 'standard' is the response when the same syllable was presented four times. The response labeled 'deviant' is the response when the fourth syllable differed from the first three. In the top panel, all syllables were spoken by different speakers. In the bottom panel, the fourth syllable was spoken by the same speaker used to produce the syllables in the top panel, but each of the four syllables in the sequence were spoken by different speakers. Published with permission [41••].

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