Human Auditory Development

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Synopsis:

The ability to detect, discriminate, and locate sounds improves throughout the course of infancy and childhood. This improvement stems from maturation of the conductive apparatus of the ear, of the primary auditory neural pathways, and of perceptual processes such as sound source segregation and selective attention.

GLOSSARY

auditory brainstem response: a scalp-recorded far-field evoked potential originating in the auditory nerve and auditory brainstem nuclei. Five peaks, labeled I through V, can be identified in the response. Wave I originates in the auditory nerve and has a latency of 1-2 ms in adults; Wave V originates in the inferior colliculus and has a latency of about 7 ms in adults.

auditory filter width: a psychophysical measure of frequency resolution obtained by measuring the threshold for a pure-tone masked by a band-reject noise. The “notch” in the noise spectrum is centered on the tone frequency, and the width of the notch is varied to determine the width of the auditory filter.

binaural masking level difference (BMLD): The reduction in masking that occurs when either the probe or the masker is presented dichotically. For example, threshold for a tone is reduced by as much as 15 dB when the tone is presented in opposite phase to the two ears, while the noise masker is the same in both ears. The condition in which the same masker and probe are presented to both ears is denoted N_0S_0, while the condition in which the probe is out of phase at the two ears is denoted N_0S_π.

conductive apparatus: the parts of the ear that conduct sound pressure to the inner ear; the external ear and the middle ear.

critical band: The band of frequencies in a broadband noise that is effective in masking a tone; conceptually equivalent to the auditory filter width.

cross-modality loudness matching: a method of measuring loudness in which the listener produces a stimulus in a nonauditory modality that matches the perceived magnitude of the sound. For example, the listener might draw a line that is as long as a sound is loud.

difference limen (DL): the threshold in a discrimination experiment; the difference between two stimuli in intensity, frequency or some other characteristic that the listener can just discriminate.

formant transition: Formants are peaks in the amplitude spectrum of speech sounds. As the articulators move from the position required to produce one sound (e.g., a consonant) to the position required to produce another (e.g., a vowel), the frequency of the formants gradually changes, creating a formant transition. The direction and extent of the formant transition provide information about the identity of speech sounds.

forward masking: masking that occurs when the masker precedes the probe by 0 to about 100 ms.

gap detection: a measure of temporal resolution in which the listener is asked to detect a temporal interruption in a sound.

interaural time difference: the difference between the arrival times of a sound at the two ears; a cue to sound source position in space.

minimum audible angle: the just noticeable difference in spatial position of a sound source, expressed as degrees of arc.

N_0S_0: see binaural masking level difference

N_0S_π: see binaural masking level difference

observer-based methods: A method for determining thresholds in infants in which an observer, blind to trial type, judges whether or not a signal was presented to the infant in a defined time period. The only information provided to the observer is the infant's behavior. Because the method does not require a particular response from the infant, it is useful in the testing of young infants who do not produce easily recorded head turns to sound sources. The method is described in detail by Werner, L.A. (1995).

otoacoustic emissions (OAE): sounds that are produced by the inner ear and that can be recorded in the ear canal with a sensitive microphone. The presence of OAE is a sign of normal hearing.

psychometric function: the function that describes the relationship between performance in a psychophysical task and the value of the stimulus. For example, the function that shows percent correct detections as a function of stimulus intensity is the psychometric function for detection.

psychophysical tuning curve: a measure of frequency resolution in which the masker level just required to detect a fixed-frequency probe is measured for different masker frequencies. A psychophysical tuning curve resembles the tuning curve of auditory nerve fibers.

release from masking: a reduction in masking resulting from a change in the probe, the masker or some other variable.

sound source determination: the process by which the components of sound emanating from a single source are grouped together as an auditory object.

visual reinforcement audiometry: A clinical procedure for determining thresholds in infants older than 6-7 months. The infant learns to turn her head toward a sound source; a mechanical toy or video is activated to reinforce the infant's head turn.

1. INTRODUCTION

The study of auditory development in human infants and children is relatively young. Studies of anatomical (Streeter, G. L., 1906, Streeter, G. L., 1917, McKinnis, M. E., 1936, Hall, J. G., 1964, Bredberg, G., 1968), physiological (Akiyama, Y. *et al.*, 1969, Engel, R. and Young, N. B., 1969, Lenard, H. G. *et al.*, 1969), and behavioral or psychophysiological (Bartoshuk, A. K., 1962, Steinschneider, A. *et al.*, 1966, Clifton, R. K. *et al.*, 1968, Jordan, R. E. and Eagles, E. L., 1963, Eisenberg, R. B. *et al.*, 1964, Leventhal, A. and Lipsitt, L. P., 1964) development had been published prior to 1970. It was, however, only in the 1970s that interest in assessing hearing in infants became serious, with the appearance of visual reinforcement audiometry (Moore, J. M. *et al.*, 1977, Liden, G. and Kankkonen, A., 1961)and the auditory brainstem response (Salamy, A. *et al.*, 1975). The first rigorous psychophysical studies of infants and children were published in 1979 (Schneider, B. A. *et al.*, 1979), and it is only in the last 15 years that attempts have been made to relate age-related changes in auditory behavior to the underlying physiological and anatomical processes (e.g., Ponton, C. W. *et al.*, 1996, Trainor, L. J. *et al.*, 2001, Werner, L. A., 1996, Werner, L. A. *et al.*, 1994b). The upshot is that while we have a fairly complete description of the development of the most basic aspects of audition, less is known about complex auditory perception and about the underlying causes of auditory development.

It is generally believed that the limits on the basic aspects of audition—frequency, intensity and temporal resolution—are established at the auditory periphery. Deficits in resolution in mature listeners generally result from peripheral damage or disease.

Observations of the human fetal and neonatal inner ear indicate that the cochlea is structurally and functionally adultlike by term birth (e.g., Bredberg, G., 1968, Lavigne-Rebillard, M. and Pujol, R., 1987, Lavigne-Rebillard, M. and Bagger-Sjoback, D., 1992, Pujol, R. and Lavigne-Rebillard, M., 1992, Lasky, R. *et al.*, 1992, Brown, A. M. *et al.*, 1994, Bargones, J. Y. and Burns, E. M., 1988, Abdala, C., 1996). These observations have led to the expectation that the basic aspects of hearing will likewise be adultlike at term birth, with any apparent immaturity in auditory behavior resulting from limitations in cognition or motor processes. However, just as we now understand that some types of purely auditory dysfunction can result from deficits in the neural encoding of sound (e.g., Zeng, F. *et al.*, 2005), we understand that immaturity of the primary auditory neural pathway may lead to immaturity of frequency, intensity or temporal resolution. Further, we must recognize that maturation of fundamentally auditory processes, such as sound source determination, may limit basic auditory sensitivities. Finally, immaturity of so-called higher level processes, such as attention or memory, may result in immaturity of auditory sensitivity that is functionally no different from that resulting from primary auditory immaturity. Thus, potential contributors to the development of auditory behavior include primary auditory processes at both peripheral and central levels, organizational and integrative auditory processes, and general perceptual, cognitive and motor processes.

In many ways, the methods available to describe and to understand human auditory development are limited. Few anatomical data are available and physiological indices are limited to acoustic measures, scalp-recorded far-field potentials, and recently neural imaging techniques. In addition, infants and children have limited capacities for carrying out psychophysical procedures. However, some 30 years of work honing developmental psychoacoustic procedures has resulted in what we believe to be valid and reliable measures of auditory sensitivity. The details of these procedures are beyond the scope of this chapter. The interested reader is referred to Werner, L. A. and Rubel, E. W (1992).

2. DEVELOPMENT OF PRIMARY AUDITORY CAPACITIES

2.1. Spectral Coding

2.1.1. Frequency resolution and discrimination

Schneider, B. A. *et al.* (1989) published the first comprehensive description of masked thresholds from infancy through adulthood. The beauty of this study is that very similar methods were used to obtain data from listeners in all age groups, 6 months to 20 years. Listeners in this study detected octave-bands of noise masked by a broadband noise by identifying the speaker—left or right—that was playing the octave-band signal on each trial. Infants indicated their choice with a head turn toward the correct speaker. Older listeners pushed a button on one of the arms of their chair. This two-alternative forced-choice method also has the advantage of controlling response bias. Thresholds were estimated from psychometric functions constructed from the data of all listeners in each group. The thresholds Schneider, B. A. *et al.* obtained are plotted in Figure 1 for several frequencies. Notice that masked thresholds improve with age at all frequencies. Between 6 months and adulthood the improvement is on the order of 10-12 dB, with all but a few dB of the improvement occurring prior to 8 years of age. This pattern of development was confirmed in many studies of infants or children (e.g., Bargones, J. Y.

et al., 1995, Berg, K. M., 1993, Berg, K. M. and Boswell, A. E., 1999, Maxon, A. B. and Hochberg, I., 1982, Nozza, R. J. and Wilson, W. R., 1984).

<figure 1 near here>

Schneider, B. A. *et al.*'s (1989) observations provided the starting point for much of the developmental psychoacoustic research that followed. The age-related improvement in masked threshold could result from maturation of several different processes. Of course, the most obvious explanation for threshold maturation to most people is that people get better at performing psychophysical tasks as they develop. For example, listeners are better able to remain "on-task" and to remember what they are listening for. The consensus is that while inattentiveness or forgetting are likely responsible for young listeners' imperfect psychoacoustic performance, such processes can only account for 2-3 dB of the observed age difference in masked threshold (discussed in greater detail in Section 3; see also Schneider, B. A. and Trehub, S. E., 1992, Viemeister, N. F. and Schlauch, R. S., 1992, Werner, L. A. and Bargones, J. Y., 1992, Wightman, F. and Allen, P., 1992).

Another obvious process affecting detection in noise is frequency resolution, the precision with which the auditory system can analyze the frequency content of a complex sound. Frequency resolution improves dramatically in the period following the onset of cochlear function in mammals, and there is evidence that some neural responses continue to become more frequency selective even after cochlear tuning is well established (Sanes, D. H. and Walsh, E. J., 1998). In humans, the cochlea begins to function in the prenatal period, probably around 22 weeks of gestation (Pujol, R. *et al.*, 1990, , 1991). Both behavioral and brainstem evoked potentials can be recorded around 28 weeks of gestation (e.g., Birnholz, J. C. and Benacerraf, B. R., 1983, Lary, S. *et al.*, 1985). By term birth, acoustic and electrophysiological measures of cochlear function are generally reported to be adultlike (Teas, D. C. *et al.*, 1982, Abdala, C. and Chatterjee, M., 2003), save for the potential effects of conductive immaturity (discussed below). Frequency resolution has been examined at the level of the brainstem using the auditory brainstem response (ABR) and masking paradigms by Folsom, R. C. and his colleagues (Folsom, R. C., 1985, Folsom, R. C. and Wynne, M. K., 1987, Abdala, C. and Folsom, R. C., 1995). Their results consistently indicate mature frequency resolution at 6 months postnatal age. At 3 months, however, they report immaturity of frequency tuning, but only at frequencies above 4000 Hz.

The results of psychoacoustic studies of the development of frequency resolution are consistent with ABR results. For example, critical bandwidth (Schneider, B. A. *et al.*, 1990) and psychophysical tuning curve width (Olsho, L. W., 1985) have been reported to be adultlike in 6-month-old listeners. Spetner, N. B. and Olsho, L. W. (1990) conducted the only psychophysical examination of frequency resolution in infants younger than 6 months of age. These investigators reported that psychophysical tuning curve width was mature by 3 months of age at 500 and 1000 Hz, but remained immature at 4000 Hz. They also found that tuning was mature at 4000 Hz by 6 months. Several studies have examined frequency resolution in older children. While initial results indicated immature frequency resolution in 3-4-year-olds (Allen, P. *et al.*, 1989, Irwin, R. J. *et al.*, 1986), Hall, J. W. and Grose, J. H. (1991) showed that the apparent immaturity in frequency resolution in young children could be accounted for by age-related changes in perceptual decision processes. Thus, there is now general agreement that frequency resolution matures relatively early in postnatal life, and that age-related differences in masked threshold must stem from other causes. The nature of these "other causes" is discussed in detail below.

One would expect that the development of frequency discrimination would follow that of frequency resolution. The available data suggest that, in fact, high-frequency pure tone discrimination develops along a course similar to that of frequency resolution at high frequencies: 3-month-old infants are immature in frequency discrimination from 500 to 4000 Hz, while 6- and 12-month-old infants remain immature at 500 and 1000 Hz but are close to adultlike at 4000 Hz (Olsho, L. W. *et al.*, 1987). Studies of children support this pattern of development, showing low-frequency pure-tone discrimination only reaching adult levels of performance around 10-11 years (Fischer, B. and Hartnegg, K., 2004, Maxon, A. B. and Hochberg, I., 1982). One explanation for this developmental gradient begins with the observation that low-frequency tones are discriminated on the basis of periodicity, while high-frequency tones are discriminated on the basis of excitation pattern (e.g., Moore, B. C. *et al.*, 1999). Frequency resolution and high-frequency discrimination are mature by around 6 months of age, as noted above. Immature low-frequency discrimination is consistent with immaturity of periodicity processing, either the primary representation of periodicity (i.e., phase-locking) or the ability to use that representation in the case of pure-tone frequency discrimination. Several lines of evidence point toward the latter possibility. First, the development of evoked potentials, at least at the brainstem level (e.g., ABR), is generally complete before a child is 5 or 6 years old (Hall, J. W. I., 1992). Because evoked potential amplitude depends heavily on the existence of phase locking, this finding implies that phase locking is also mature by that age. Further, it is generally believed that more training is required to learn low-frequency discrimination, even among adults, and several studies support this belief (Olsho, L. W. *et al.*, 1988a, Harris, J. D., 1952). Soderquist, D. R. and Moore, M. (1970) have shown that young children can achieve adult levels of performance in low frequency discrimination with training. Thus it appears that the periodicity information may be available even to infants, but that in the context of pure-tone frequency discrimination, listeners do not readily access that information.

2.1.2. Pitch and timbre

Complex pitch perception requires not only an adequate representation of the spectrum and periodicity of the stimulus, but some integration of temporal and spectral information across frequency regions, making it an interesting phenomenon from a developmental standpoint. Clarkson, M. G. and her colleagues have conducted a series of studies examining the perception of complex pitch in 7-month-old infants. The phenomenon that defines complex pitch psychophysically is the pitch of the missing fundamental: people will assign a harmonic complex the pitch associated with its fundamental frequency, even when the fundamental frequency is not part of the complex. The perception of the pitch of the missing fundamental clearly depends on integration of the information carried by the harmonics, and Clarkson, M. G. and Clifton, R. K. (1985) first demonstrated that infants can learn to respond when the missing fundamental frequency of a complex changes, while ignoring other spectral changes. In many respects, infants' and adults' ability to perform this task depends on the same stimulus parameters. For example, both infants and adults continue to hear the pitch of the missing fundamental when a noise band "masks" the fundamental frequency, but fail to hear that pitch if the higher frequency harmonics are masked (Montgomery, C. R. and Clarkson, M. G., 1997). Both age groups have greater difficulty categorizing the pitch of inharmonic complexes (Clarkson, M. G. and Clifton, R. K., 1995), but while adults can hear the pitch of the missing fundamental, albeit weakly, when only high-frequency harmonics are present, infants appear unable to hear this less salient pitch (Clarkson, M. G. and Rogers, E. C., 1995). Because the perception of the pitch of the missing fundamental on the basis of only high-frequency harmonics is believed to depend on the periodicity that results from unresolved harmonics, the latter observation provides additional evidence that infants may have greater problems in tasks that require the use of periodicity.

Finally, infants ability to categorize spectrally dissimilar sounds on the basis of their common fundamental frequency would mean little if infants are unable to discriminate the spectral dissimilarity. Adults perceive these spectral changes as changes in timbre. One of the difficulties in ensuring that the listener is responding on the basis of the timbre of a complex is that the listener could listen to only a restricted frequency region of the complex and respond when the energy in that frequency region changes, regardless of the spectral shape of the complex as a whole. To prevent that from happening, studies of timbre generally vary, or “rove”, the overall intensity of the complex from presentation to presentation, so that the amount of energy in any frequency region is not a reliable indicator of a change in spectral shape. Several studies have reported that infants can learn to categorize sounds on the basis of spectral shape (Clarkson, M. G. *et al.*, 1988, Clarkson, M. G., 1996, Trehub, S. E. *et al.*, 1990), but infants have difficulty ignoring random changes in overall intensity (Clarkson, M. G., 1996). None of the existing studies have been able to get infants to respond to timbre changes in tonal complexes when the intensity is roved sufficiently to prevent the listener from responding on the basis of local intensity changes. Because infants are consistently able to discriminate between sounds that adults distinguish on the basis of spectral shape (e.g., vowels, Marean, G. C. *et al.*, 1992, Kuhl, P. K. and Miller, J. L., 1982) and because infants appear to have difficulty listening to a restricted frequency region (discussed below, Bargones, J. Y. and Werner, L. A., 1994), it is likely that they do perceive timbre in some fashion. A definitive demonstration remains elusive, however.

2.2. Intensity Coding

A difficulty in studying the development of intensity processing is that it is difficult to separate the perception of intensity from other variables that influence the efficiency with which the listener performs the task. There is no measure, like critical bandwidth or auditory filter width, that allows intensity coding to be distinguished from factors like attentiveness or memory. To date, the most fruitful approach has been to examine the effects of stimulus variables (e.g., frequency, duration) on intensity processing: the more adultlike these effects, the more likely it is that intensity processing is adultlike. A goal of future developmental research in this area, however, should be to find more definitive procedures for solving this dilemma.

2.2.1. Absolute sensitivity

To many, and certainly to audiologists, absolute sensitivity represents the most basic characterization of the auditory system. Threshold sensitivity improves dramatically in the period following the onset of cochlear function in the species that have been tested (e.g., Ehret, G., 1976, Zimmermann, E., 1993, Ehret, G. and Romand, R., 1981, Gray, L.

and Rubel, E. W., 1985, Kenyon, T. N., 1996), but to date, no species has been followed systematically from the onset of hearing to adulthood in a single study. Because different methods are generally used to test the behavioral thresholds of young and adult animals, it is difficult to know how much of an age difference in threshold is due to differences in test methodology. In no case have thresholds of the oldest developing animal been found to approach adult thresholds in that species. The usual conclusion drawn from these studies, nonetheless, is that the development of threshold sensitivity is primarily due to maturation of the inner ear, although middle ear function is also known to undergo developmental improvements early in life (e.g., Ehret, G., 1976). Neural contributions to threshold development are rarely if ever considered.

The human fetus moves in response to sound by 28 weeks of gestation. While a few attempts to measure behavioral response thresholds *in utero* have been made (reviewed by Lecanuet, J. P., 1996), the technical difficulties involved in estimating the sound pressure level *in utero*, not to mention the myriad other methodological difficulties involved in this experiment, make interpretation of the results problematic. Moreover, it is clear that whatever sound makes it to the fetus is at least partially masked by noise produced by the mother's body (e.g., Querleu, D. *et al.*, 1988, Gerhardt, K. J. *et al.*, 1990). A few studies have examined the behavioral response of preterm infants to sound. The percentage of behavioral responses to a broadband noise centered at 3000 Hz with a peak intensity of 90 dB SPL A has been reported to increase more or less systematically from about 20% to about 45% of trials between 34 and 41 weeks conceptional age (Gerber, S. E., Mencher, G. T. *et al.*, 1985), but it is of course, difficult to know what is responsible for the increase in responsiveness to sound. If spontaneous responses to octave-band noises are considered, even in a rigorous psychophysical procedure, behavioral response thresholds in full-term newborns are on the order of 75 dB HL over the frequency range from 125 to 4000 Hz (Weir, C., 1976, 1979).

By 1 month of age, human infants are awake and alert long enough that a few attempts have been made to establish their behavioral thresholds using the observer-based approach[1]. For example, Werner, L. A. and Gillenwater, J. (1990) estimated that 2- to 4-week-old infants' behavioral thresholds to pure tones were about 45 dB higher than adults' at 500 Hz and about 35 dB higher than adults' at 4000 Hz. Trehub, S. E. et al (1991) found that thresholds for a 4000 Hz octave-band noise were about 30 dB higher in 1-month-olds than in adults, and Tharpe. A. M. and Ashmead, D. H. (2001) reported that infants between 0 and 3 months of age had thresholds for a speech filtered noise that were about 40 dB higher than adults'. None of these studies reinforced the infants' responses to sound; Werner, L. A. and Mancl, L. R. (1993) reported that 1-month-olds' thresholds for pure tones were improved by about 5 dB if responses to the tones were reinforced by an audio recording of a woman reading from a children's book.

By 3 months of age, infants' behavioral thresholds improve to about 40 dB SPL at 500 Hz and to 24 dB SPL at 4000 Hz (Olsho, L. W. *et al.*, 1988b, Tharpe, A. M. and Ashmead, D. H., 2001, Trehub, S. E. *et al.*, 1991). Between 3 and 6 months, little improvement occurs in low-frequency thresholds, but thresholds are about 15 dB higher than adults' at higher frequencies (Bargones, J. Y. *et al.*, 1995, Berg, K. M. and Smith, M. C., 1983, Nozza, R. J. and Wilson, W. R., 1984, Sinnott, J. M. *et al.*, 1983, Trehub, S. E. *et al.*, 1980). Trehub, S. E. *et al.* followed the development of thresholds for octave

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[1] .

noise bands from 6 months through the school years to adulthood. They found that mature sensitivity was achieved earlier at higher frequencies, before age 5 years at 4000 and 10000 Hz, but after 10 years of age at 1000 Hz. Thus, the development of absolute sensitivity is a prolonged process, summarized in Figure 2.

<figure 2 near here>

The nature of these age-related changes in sensitivity have been a matter of debate. Certainly similar improvements in physiological indices of sensitivity are observed in preterm and young infants. Improvements in click-evoked auditory brainstem thresholds from 40 to 10 dB nHL have been documented from about 28 to 38 weeks conceptional age on (Lary, S. *et al.*, 1985). In general, thresholds for responses generated in the inner ear or auditory nerve at term birth have been reported to be no more than 15 dB higher than those observed in adults (Engel, R. and Young, N. B., 1969, Stuart, A. *et al.*, 1993, Stevens, J. C. *et al.*, 1990, Abdala, C. *et al.*, 2006). Sininger and her colleagues (Sininger, Y. and Abdala, C., 1996, Sininger, Y. S. *et al.*, 1997) have reported that for stimuli calibrated in the ear canal, thresholds for click-evoked ABR Wave V are about 20 dB higher in term neonates than in adults. This laboratory also reported that while neonates' thresholds for tone-pip-evoked ABR Wave V are adultlike at 500 Hz, they are about 20 dB higher than adults' at 4000 and 8000 Hz.

One of the factors known to contribute to the improvements in absolute sensitivity with age is maturation of the conductive apparatus. Keefe, D. H. and his colleagues (Keefe, D. H. *et al.*, 1993, Keefe, D. H. and Levi, E. C., 1996) have shown that the efficiency of transmission through the middle ear improves throughout infancy, and it is believed that this process continues well into childhood (Okabe, K. S. *et al.*, 1988). In 1-

month-olds, as much as 20 dB less sound energy is transmitted through the middle ear at high frequencies, compared to adults. At lower frequencies, the difference in sound transmission is only 5-10 dB at 1 month. Transmission at high frequencies improves by 10 dB by 6 months of age; low-frequency transmission improves at a slower rate. Thus, it is likely that age-related threshold differences in otoacoustic emissions (OAE), ABR and other measures of peripheral function early in infancy can be accounted for by immaturity of the conductive apparatus. Further, improvement in conductive efficiency can account for at least a portion of the improvement in behavioral thresholds observed between 1 month and 6 months of age, especially at higher frequencies. Werner, L. A. and Holmer, N. M. (2002), in fact, have shown that behavioral threshold at 4000 Hz is significantly correlated with middle ear admittance at that frequency among 3-month-old infants and among adults.

One of the factors unlikely to contribute to improvements in absolute sensitivity with age, at least beyond the conceptional age of 38 weeks or so, is maturation of the inner ear. On the basis of anatomical benchmarks, as well as physiological and behavioral responses, the human inner ear apparently begins to respond to sound around 22 weeks gestational age (Birnholz, J. C. and Benacerraf, B. R., 1983, Pujol, R. *et al.*, 1991). By term birth, the consensus is that the cochlea is anatomically and functionally mature (Fujimoto, S. *et al.*, 1981, Igarashi, Y. and Ishii, T., 1979a, b, Igarashi, Y. *et al.*, 1978; Lavigne-Rebillard, M. and Pujol, R., 1987, , 1988, Lavigne-Rebillard, M. and Bagger-Sjoback, D., 1992, Bredberg, G., 1968, Igarashi, Y. and Ishii, T., 1980, Streeter, G. L., 1917, Streeter, G. L., 1906, Lavigne-Rebillard, M. and Pujol, R., 1990, Isaacson, G. *et al.*, 1986, Shimizu, T. *et al.*, 1991, Hoshino, T., 1990, Nakai, Y., 1970, Bargones, J. Y.

and Burns, E. M., 1988, Leiberman, A. *et al.*, 1973, Plinkert, P. K. *et al.*, 1990, Abdala, C., 1998, Chuang, S. W. *et al.*, 1993, Morlet, T. *et al.*, 1996, Eggermont, J. J. *et al.*, 1996, Collet, L. *et al.*, 1993).

Maturation of the primary auditory neural pathways, however, may well be involved in threshold improvements during early infancy. Werner, L. A. and her colleagues (Werner, L. A. *et al.*, 1994b, , 1993) have shown that behavioral threshold at 4000 and at 8000 Hz is significantly correlated with ABR threshold in the same infants, but even more strongly correlated with Wave I-V interpeak latency. Improvement in ABR latencies during infancy is thought to result from changes in the length of the neural pathway, from myelination of nerve fibers, and in great part, from improvement in synaptic efficiency (Ponton, C. W. *et al.*, 1996, Moore, J. K. *et al.*, 1995, Moore, J. K. *et al.*, 1997, Moore, J. K. *et al.*, 1996, Ponton, C. W. *et al.*, 2000). It is likely that the improvement in synaptic efficiency, at least, also leads to improvements in auditory sensitivity.

2.2.2. Intensity discrimination

A notable property of immature auditory neurons is their limited dynamic range (Kotak, V. and Sanes, D., 1995). Thus, it would not be surprising to find that intensity discrimination undergoes postnatal development in humans. Because detection in noise is immature in infants and young children and because frequency resolution is apparently mature early in infancy, the development of masked thresholds must reflect changes in the signal-to-noise ratio required for detection. We refer to the signal-to-noise ratio required for detection as “efficiency”. One of the variables that determines efficiency is intensity resolution. Of course, many other factors, such as attentiveness, selective attention, motivation and memory, also determine efficiency. Nonetheless, one would predict that the ability to detect changes in the intensity of a suprathreshold sound follows a developmental course similar to that for masked thresholds.

A summary of the development of intensity discrimination taken from several studies of infants and children is shown in Figure 3. In general, intensity discrimination has been found to be relatively immature in infants. For pure tone intensity discrimination, 6-9-month-old infants have been reported to have intensity difference limens (DL) on the order of 6-9 dB, compared to a DL of 1-2 dB in adults (Sinnott, J. M. and Aslin, R. N., 1985, Berg, K. M. and Boswell, A. E., 1998, Kopyar, B. A., 1997). Infants are more adultlike in intensity discrimination of broadband than narrow band sounds (Bull, D. *et al.*, 1984, Kopyar, B. A., 1997). Although there is considerable variability in the intensity DL reported for children in different studies, there is a general trend for intensity discrimination to improve through the preschool period and to approach adult levels at 5-6 years of age (Jensen, J. K. and Neff, D. L., 1993, Maxon, A. B. and Hochberg, I., 1982, Berg, K. M. and Boswell, A. E., 2000), mirroring the age-related improvement in detection-in-noise (Schneider, B. A. *et al.*, 1989).

<figure 3 near here>

If the immature auditory system exhibits a sluggish growth of response with increases in intensity or if the response at a given intensity is variable, detection and discrimination will be poor. Schneider, B. A. *et al.* (1989, Schneider, B. A. and Trehub, S. E., 1992) discuss the role of intensity coding in the development of detection in noise, but there is little direct evidence for immaturity of intensity coding in infancy or childhood. Cochlear responses tend to grow with intensity in a similar way in neonates and adults (Abdala, C., 2000). There are few studies that have compared infants and adults in the growth of neural evoked response amplitude with intensity, although response latency appears to change with increasing intensity in an adultlike fashion even in preterm infants (Gorga, M. P. *et al.*, 1989). Several studies (Durieux-Smith, A. *et al.*, 1985, Cornacchia, L. *et al.*, 1983, Rickard, L. K., 1988) have shown that ABR Wave V amplitude grows with increasing intensity more slowly in young infants, but the age difference did not persist beyond 10 months of age. Although auditory cortical evoked potentials development clearly continues throughout childhood (e.g., Huttenlocher, P. R., 1979, Kraus, N. *et al.*, 1985, Sharma, A. *et al.*, 1997), the effects of age on the growth of cortical potentials with stimulus intensity has not been addressed. In fact, that infants are more mature in their detection of broadband than of narrow-band sounds, in the absence of any obvious bandwidth-dependent differences in attentiveness, suggests that intensity coding is not responsible for infants' immature detection in noise (Werner, L. A. and Boike, K., 2001).

2.2.3. *Loudness*

Given the relatively prolonged development of intensity discrimination performance, it is surprising that direct measures of loudness growth show few developmental effects beyond infancy (Bond, B. and Stevens, S. S., 1969, Collins, A. A. and Gescheider, G. A., 1989, Dorfman, D. D. and Megling, R., 1966). For example, Collins, A. A. and Gescheider, G. A. found that preschool children could not only perform a cross-modality loudness matching procedure, but that their results were quite similar to those of adults. It should be noted that this observation argues against immaturity of intensity processing in general, at least during the preschool period.

Interestingly, there is limited evidence for immaturity of loudness perception among infants. Leibold, L. J. and Werner, L. A. (2002) showed that infants, like adults, respond more quickly to a more intense tone. They found, further, that the rate at which response latency decreased with increasing tone intensity was greater in infants than it was in adults. In other words, loudness growth appeared to be more rapid in infants than in adults. This finding is difficult to reconcile with the idea that the neural response is growing more slowly with increasing intensity in young listeners. It is consistent with the idea that infants listen in a high level of internal noise: Loudness grows more rapidly in external noise among adult listeners.

2.3. Temporal Resolution

Again, several observations of early auditory development in nonhuman species suggest that age-related changes in temporal resolution occur in the course of human development. Immature auditory neurons, for example, do not sustain response to continuous stimulation and demonstrate prolonged recovery from prior stimulation (e.g., Brugge, J. F. *et al.*, 1978). Whether the corresponding developmental period in humans occurs in the postnatal period is not clear.

Estimates of temporal resolution in infancy are heavily dependent on the measure used to assess temporal resolution. A popular measure has been the gap detection threshold, the shortest interruption in ongoing sound that can just be detected by the listener. Werner, L. A. *et al.* (1992) measured gap detection thresholds in 3-, 6-, and 12-month-old infants and in adults for broadband noise and for low-pass noises with varying high-frequency cutoffs. Infants' gap detection thresholds were quite poor, on the order of 40-50 ms in the broadband noise condition. Gap detection threshold did not improve between 3 and 12 months of age, but changed with the frequency of the stimulus in a manner similar to that seen in adults. In subsequent experiments, Werner, L. A. and her colleagues reported the same poor gap detection thresholds using a different method to estimate thresholds (Werner, L. A. *et al.*, 1994a) and showed that the effect of changing the stimulus frequency from gap onset to gap offset had similar effects on infants and adults (Werner, L. A. *et al.*, 1994a). Trehub, S. E. *et al.* (1995) found that infants were better at detecting a gap between two Gaussian shaped tone bursts than gaps in noise, but their gap thresholds were still far from adultlike. Studies of preschool children, on the other hand, generally indicated mature gap detection thresholds by 4 or 5 years of age (Wightman, F. *et al.*, 1989, Trehub, S. E. *et al.*, 1995).

Studies employing other measures of temporal resolution suggest a quite different pattern of development. Duration discrimination, for example, has been shown to be immature in infants and to remain immature in young children (Morrongiello, B. A. and Trehub, S. E., 1987, Elfenbein, J. L. *et al.*, 1993). Werner, L. A. (1999), in contrast, reported that forward masking was adultlike by 6 months of age. While Buss, E. *et al.* (1999) reported improvements in forward masked thresholds between 5 and 11 years, the improvement in masked threshold just paralleled the improvement seen in threshold in quiet. Thus, the amount of forward masking demonstrated at each age was about the same as that seen in adults. Finally, two developmental studies of the temporal modulation transfer function (TMTF) have been conducted. The TMTF shows the depth of modulation required to detect amplitude modulation as a function of the modulation frequency. The TMTF has a low-pass characteristic and its cutoff frequency is a measure of temporal resolution (Viemeister, N. F., 1979). Both 3-month-old infants and 4-5-year-old children (Figure 4) appear to have adultlike TMTF (Hall, J. W. and Grose, J. H., 1994, Werner, L. A., 2006).

<figure 4 near here>

What conclusion can be drawn about the development of temporal resolution? On the basis of the TMTF, the gold standard of measures of temporal resolution, one would conclude that temporal resolution is mature quite early in life. This conclusion is consistent with several developmental physiological studies of temporal resolution: forward masking and gap detection in the ABR (Lasky, R. E., 1991, , 1993, Werner, L. A. *et al.*, 2001) and in the mismatch negativity, a cortical evoked potential, (Trainor, L. J. *et al.*, 2001) appear to be adultlike by 3 months postnatal age. An unanswered question is why infants and children have greater difficulty dealing with other temporally-based tasks.

2.4. Spatial Resolution and Perception

2.4.1. Sound localization

Of all auditory capacities, spatial resolution would seem to be the most likely to undergo clear improvements with age because it depends on the size of the external ear and the head. Infants will certainly have a smaller range of interaural differences to work with, even if peripheral coding and the central circuits that calculate interaural differences are adult-like. In addition, the resonance of the small external ear will limit the frequencies that infants can use to localize sounds in elevation or to make front-back distinctions.

In fact, spatial resolution has been found to improve systematically with age, but to an extent that cannot be accounted for by peripheral immaturity alone. Newborn infants turn toward a sound source on their left or right (Clifton, R. K. *et al.*, 1981, Muir, D. and Field, T., 1979), but the minimum audible angle (MAA) at birth has been estimated at around 30º in azimuth (Morrongiello, B. A. *et al.*, 1994). The MAA in azimuth has been examined in infants and children in several laboratories; it has been reported to decrease from 30º at birth to about 14º at 7 months to adult levels at 5 years (Morrongiello, B. A. and Rocca, P. T., 1990, Morrongiello, B. A. and Rocca, P. T., 1987a, Morrongiello, B. A. *et al.*, 1994, Litovsky, R. Y. and Ashmead, D. H., 1997, Clifton, R. K., 1992, Clarkson, M. G., 1995, Ashmead, D. H. *et al.*, 1987). However, sound localization probably continues to develop beyond the preschool period; for example, 5-year-olds' sound localization may be disrupted by the presence of sound reflections more than adults' (Litovsky, R., 1993).

Sound localization in elevation has been less well studied, although one laboratory has reported that the MAA in elevation for an 8-12 kHz noise band improved from nearly 16º at 6 months to about 6º at 18 months (Morrongiello, B. A. and Rocca, P. T., 1987c, b). An interesting observation in these studies is that infants never achieve 75% correct in detecting a change in the position of a 4-8 kHz noise band or a 4 kHz lowpass noise. Adults also perform better in elevation discrimination if the stimulus contains frequencies above 4-5 kHz, but it appears that infants are more heavily dependent on frequencies above 8 kHz, which would be consistent with their smaller pinnas.

By 7 months of age, infants appear to discriminate differences in the distance to a sound source. Clifton, R. K. and her colleagues (1991) developed a clever procedure to allow infants to demonstrate their ability to judge the distance of a sounding object. After allowing the infant to play with a sounding object in the light, these researchers presented the same sounding object to infants at varying distances in the dark. Infants were found to reach more often for the object when it was within their reach than when it was beyond their reach. Litovsky, R. and Clifton, R. K. (1992) subsequently showed that infants did not depend solely on the sound pressure level arriving at their head to perform this discrimination; they continued to reach more to within-reach than to beyond-reach objects even when the intensity of sound was varied randomly. Interestingly, adult subjects tested in a similar situation appeared to be more heavily dependent on sound pressure level in making distance judgments.

Several attempts have been made to explicate the mechanisms responsible for age-related improvements in sound localization. Potential candidates include acoustic cues, peripheral coding, neural calculation of interaural differences and spectral shape, and the central mapping of acoustic cues onto positions in space. Clifton, R. K. *et al.* (1988) addressed the issue of changes in the acoustic cues available for localization by directly measuring interaural distance and head circumference in neonates and 22-week-olds. From these measurements, they estimated that the maximum interaural time difference (ITD) available to infants would increase from 400 to 500 μs over this age period. If infants depended only on interaural time differences to locate sounds in azimuth, they should be able to achieve an MAA less than 10° at this age, compared to the 20° observed (Ashmead, D. H. *et al.*, 1987). Ashmead, D. H. *et al.* (1991) followed the development of ITD discrimination from 16 to 28 weeks of age. ITD discrimination thresholds were on the order of 50-75 μs, were never poor enough to account for the infant's immature MAA, and did not improve with age as the MAA does. This suggests that maturation of neither the precision of temporal information provided by the ear nor the function of the neural circuits involved in ITD calculation can entirely account for the maturation of spatial resolution in azimuth. Gray, L. (1992) has argued that changes in chicks' responses to changes in the location of a sound source in the first few days after hatching reflect the acquisition of an organized representation of auditory space. Observations of humans who are congenitally deprived of binaural input support the idea that this mapping process is an important aspect of the development of sound localization. These individuals achieve respectable performance in ITD discrimination when surgical intervention makes binaural hearing possible for them, but they continue to have quite poor abilities to identify the location of a sound source in space (Wilmington, D. *et al.*, 1994). These observations in humans are consistent with many studies of the effects of abnormal binaural experience on the development of spatial hearing in other species (e.g., Moore, D. R., 1983, Knudsen, E. I., 1988, Binns, K. E. *et al.*, 1995).

2.4.2. *Binaural masking level difference and spatial release from masking*

One advantage of binaural hearing is the improvement in sensitivity to target sounds that results when target and competing sounds are perceived as coming from different spatial locations. In the laboratory, one form of this advantage, the binaural masking level difference (BMLD), has been extensively studied. Compared to the condition in which the same masker and tone are presented under earphones to both ears (designated N_0S_0), threshold for a tone presented in a broadband masker is as much as 15 dB lower when the same masker is presented to both ears, while the tone is presented 180° out of phase at one ear relative the other (designated N_0S_π). The BMLD is the threshold improvement observed under such dichotic conditions.

Given the dramatic improvement in auditory spatial resolution during infancy and early childhood, it is of some interest whether similar improvements are evident in the BMLD. To the extent that the same mechanism are involved in calculating the interaural time difference that underlies both sound localization and the BMLD, one might predict that the two follow similar developmental courses. At first blush, this appears to be the case Nozza, R. J. (1987) and Nozza, R. J. *et al.* (1988) have reported that under conditions that produce a BMLD of about 11 dB for adults, 7-month-old infants have a BMLD of only 5 dB. Nozza, R. J. *et al.* concluded that preschool children were probably adultlike in BMLD, but Hall, J.W. and Grose, J. H. (1990) subsequently found that while 6-year-old children had adultlike BMLD, 4-5-year-old children still had somewhat smaller BMLD than adults. In all cases, the reduced BMLD resulted from a relatively higher threshold in the N_0S_π condition, suggesting immaturity of binaural processing.

In several studies, however, Hall, J.W., Grose, J. H. and colleagues (Grose, J. H. *et al.*, 1997, Hall, J. W. and Grose, J. H., 1990, Hall, J. W. *et al.*, 2004) have found that while school-age children have adultlike BMLD for a broadband masker, they have significantly smaller BMLD for narrow-band maskers. Adults seem to be able to take advantage of low-energy segments of the fluctuating envelope of a narrow-band masker in binaural detection (i.e., by "listening in the dips"). One explanation for the developmental trend observed in the BMLD for narrow-band maskers is that children are less able than adults to use this additional information. This idea is consistent with an observation by Litovsky, R. Y. (2005) that school age children were unable to take advantage of spatial separation of speech target and masker in free field when the masker is the voice of a single speaker, although they did show spatial release from masking in other masking conditions. In the single-speaker masking condition, listeners have a particular opportunity to use gaps in the masker to hear the target, Thus, infants appear to have immature binaural processing. Given little evidence that intensity or temporal coding is immature at 7 months, this finding is consistent with a central processing immaturity. By age 5 or 6 years, children appear capable of using binaural information under many conditions, but under more difficult listening conditions, adults are able to access additional cues that children do not.

3. DEVELOPMENT OF COMPLEX PERCEPTUAL CAPACITIES

Mature processing of complex sounds in real environments requires more than a simple representation of the spectral and temporal characteristics of the acoustic stimulus.

Because sound from multiple sources is generally present, the listener is required to group the components of each complex sound according to its source and to select the sound from the appropriate source for further processing. Furthermore, within the complex arising from any one source, some frequency bands or temporal segments may be more informative than others, and thus be more heavily weighted in the process of recognition or identification. An important point is that immaturity of processes such as sound source determination, selective attention and listening to relevant sound features is likely to manifest itself in many ways, including apparent immaturity of intensity resolution or listening efficiency. Because primary auditory processes appear to be relatively mature during infancy, we tend to believe that it is these complex, higher-level auditory processes that limit the performance of infants and children, even in simple listening tasks.

The idea that infants and children are just not as good as adults in performing psychophysical tasks is one that occurs to even the casual student of sensory development. In psychophysical terms, infants and children are inefficient listeners. Efficiency is influenced by primary auditory processes, but also by a variety of factors such as memory, attention and motivation. Both resolution and efficiency influence sensitivity. An inefficient listener is less sensitive to a tone in noise, and one would expect that inefficiency to carry over into the perception of any sound in a noisy background. Many investigators have suggested that infants and children are inefficient listeners compared to adults (Allen, P. and Wightman, F., 1994, Bargones, J. Y. *et al.*, 1995, Hartley, D. E. H. *et al.*, 2000, Werner, L. A. and Boike, K., 2001). The sources of early immature efficiency, however, are not well understood. In this section, possible contributions of higher-level perceptual processes to the development of auditory sensitivity are considered.

3.1. Sound Source Determination

By sound source determination is meant the process by which a listener segregates the components of complex sound into different auditory objects. For example, listeners are able to take sound emanating simultaneously from the voice of a conversant, a barking dog, and a passing car and to parse the complex into three different sound sources despite the fact that there is spectral and temporal overlap among the three sounds. Listeners use many types of information to accomplish this task, considering common temporal modulation, location, and harmonicity among others. In the lab, a common approach to studying sound source determination is auditory streaming, in which a listener is asked to report the number of separate sound sources heard in a complex sound and sometimes to describe each source. Because infants and young children have difficulty understanding such procedures, researchers have had to develop more indirect measures of sound source determination in young listeners.

It is clear that infants can segregate sound sources under some conditions. Newman, R. S. and Jusczyk, P. W. (1996) exposed 7-8-month-old infants to two superimposed voices, one male and one female. The female voice spoke a series of words with exaggerated intonation, while the male voice recited text from the methods section of a journal article. Following 30 seconds exposure, infants were presented with a list of words spoken by the same female voice whenever they looked at a flashing light. On some trials, the words were the same words spoken in the initial exposure; on others, the words were novel. If infants looked longer for one list of words than the other, it was concluded that the infants recognized the words they had heard in competition with the male voice. If the female voice was presented at a level 5 or 10 dB greater than that of the male voice, infants looked longer for the word list previously presented, but if the levels of the two voices were equal, they showed no evidence of recognizing the words. This study certainly indicates that under some circumstances, infants are capable of segregating two competing voices. However, it suggests that even when the two voices differ in fundamental frequency, timing, and intonation, infants have difficulty segregating the two voices without an additional intensity difference. Because adult's speech reception thresholds under similar conditions would be well below 0 dB signal-to-noise-ratio (e.g., Litovsky, R. Y., 2005), the acoustic components of the target words were presumably audible to both infants and adults. Beyond that, infants' failure to respond differentially to the familiar words at 0 dB signal-to-noise ratio could result from a failure of sound source determination, a failure of selective attention, or both. Although it does not resolve this issue, a recent study by Hollich, G. *et al* (2005) showed that infants did recognize the words in the target voice when the competing voice was of equal intensity, if presentation of the voices was accompanied by a video of the talker's face.

Several investigators have attempted to study auditory streaming in infants using other approaches. Adult listeners have difficulty judging the relative order of elements of sound that are perceived in separate auditory streams. Thus, if the order of sounds in a sequence is reversed, the listener's ability to discriminate the change in order will depend on whether or not the sounds are heard in the same auditory stream (Figure 5). Demany, L. (1982), Fassbender, C. (1993) and McAdams, S. and Bertoncini, J. (1997) have all demonstrated that infants' ability to discriminate a change in the order of a sound sequence changes in a way that is consistent with adults' stream segregation. However, the limits of the infants' ability to form auditory streams and the relative importance of different acoustic cues in determining how infants form streams remain unexplored.

<figure 5 near here>

It is curious that auditory streaming experiments with older children have not been reported, because it is quite possible that even preschool children would be able to perform some version of the auditory streaming task. The question of sound source determination in children has been addressed indirectly in studies of comodulation masking release (CMR). Adults detect a tone at a lower intensity if intensity fluctuations in sounds in frequency bands away from the tone frequency match the fluctuations in the intensity of a masker centered on the signal frequency. Adults' thresholds for the tone are actually higher if no sounds other than the masker centered on its frequency are present. This phenomenon is referred to as CMR (Hall, J. W., 1987). CMR is thought to reflect processes important to sound source determination: The signal tone may be more audible if the on-signal masker is perceptually grouped with the other flanking noise bands. Grose, J. H. *et al.* (1993) reported that 4-year-old children showed the same threshold improvement from adding off-frequency, comodulated frequency bands as adults do. Hall, J.W. *et al.* (1997) found that slightly older children also exhibited adultlike CMR, but reported that when the masker band centered on the signal frequency and the off-frequency comodulated bands were slightly asynchronous, adults' CMR was reduced while children's CMR was eliminated or became negative. One possible explanation for this result is that temporal synchrony is a more important grouping factor for children than it is for adults.

3.2. Auditory Attention

The development of two varieties of attention is considered here. The first is attentiveness, often referred to as sustained attention. By attentiveness is meant the ability to remain “on task” and to acquire information about the stimulus. The other, probably more important sort of attention will be referred to as selective attention. Once incoming sound has been parsed into separate auditory objects, a listener must frequently choose the sound from one source for further processing while ignoring others. Further, some features of sound from a single source may be processed while others are not. These processes require auditory selective attention. It should be noted that any complex listening task involves the basic analytic processes that underlie all hearing. Then the components belonging to a single source must be identified and integrated, and finally, one source selected for processing. Failure to selectively process a sound, then, will occur if any of these processes—analysis, sound source determination, selective attention—is immature. On the basis of the studies reviewed above, we conclude that the basic analytic processes are mature by 6 or 7 months of age, but while several studies have attempted to study selective auditory attention, immature sound source determination could well have influenced children’s performance in these studies.

3.2.1. Attentiveness

An obvious reason that infants and children perform rather poorly in some psychophysical tasks is that they have difficulty sustaining attention to the task. Inattentiveness may prevent them from having any idea whether or not a tone was presented on some trials, for example. Several investigators have argued that while infants and children are undoubtedly inattentive at some points during testing, the effects of inattentiveness would not be expected to be large enough to account for the observed age differences in auditory sensitivity (Schneider, B. A. and Trehub, S. E., 1992, Viemeister, N. F. and Schlauch, R. S., 1992, Werner, L. A. and Bargones, J. Y., 1992, Wightman, F. and Allen, P., 1992). In studies that have examined the psychometric function for detection, the upper asymptote of the function has been reported to be less than 1 for many infants and children (Allen, P. and Wightman, F., 1994, Bargones, J. Y. *et al.*, 1995, Werner, L. A. and Boike, K., 2001). This is consistent with inattentive listening: Even when the sound is audible, young listeners respond incorrectly on some trials. If one assumes that the listener has no information about the stimulus on inattentive trials and that on such trials the listener guesses whether or not a signal occurred, then the rate of inattention would be twice the difference between 1 and the observed upper asymptote. In infants, the inattention rate is estimated at about 30% in a variety of conditions (Bargones, J. Y. *et al.*, 1995, Werner, L. A. and Boike, K., 2001), and in children, it appears to range from 0 to 25% (Allen, P. and Wightman, F., 1994). Further analyses show, however, that even an inattention rate of 30% would shift the observed threshold for detecting a tone by only 2-3 dB. Similarly small effects would be expected in other tasks. In no case is the effect of inattentiveness sufficient to account for the observed difference between adults and infants and children.

3.2.2. *Selective listening to relevant sound features*

Another explanation for early immature psychoacoustic performance is immature listening strategies. Adults tend to listen at expected frequencies and at times when a sound could be presented. Adults quickly discover and focus on the most informative cues in a complex stimulus. Infants, on the other hand, may listen in a less selective fashion. Werner, L. A. and Bargones, J. Y. (1991), for example, showed that 7-month-old infants' threshold for a tone were elevated by the presence of a higher frequency "masker" well removed from the frequency region of the tone. Adults tested under the same condition demonstrated little or no masking. Bargones, J. Y. and Werner, L. A. (1994) subsequently showed that while adults were more sensitive to a frequency they expected to hear than to other unexpected frequencies, infants were equally sensitive to expected and unexpected frequencies. Thus, adults appear to restrict listening to the frequency band around the signal they are trying to detect, while infants listen broadly across frequencies regardless of the signal to be detected. It has been estimated that failure to monitor the frequency band around the to-be-detected signal would increase threshold by about 7 dB (Dai, H. *et al.*, 1991), which would account for a large protion of the difference between infants' and adults' thresholds for a tone in noise (Werner, L. A. and Boike, K., 2001).

Preschool children have not yet become consistently selective listeners. Stellmack, M. A. *et al.* (1997) asked 5-year-olds and adults to discriminate changes in intensity in one component of a three-component complex. If the level of the "distractor" components was lower than that of the target, both children and adults were able to listen selectively to the target component. In contrast, if the target and distractors were equal in level, only the adults were able to continue to listen selectively to the target. It should be noted, however, that even when the task was to discriminate overall intensity differences between three-component complexes, 5-year-olds needed larger intensity differences to perform the task than adults did, despite the fact that selective listening was not the optimal strategy (Willihnganz, M. S. *et al.*, 1997).

Even infants may be able to listen selectively in time, however. Parrish and Werner, L. A. (2004) tested infants' ability to detect a tone that occurred following a short noise burst that indicated the beginning of a trial. On most trials, the tone occurred 500 ms after the noise burst, but on a small proportion of trials, the tone occurred 200 or 800 ms after the noise burst. Under these conditions, both infants and adults detected the tone at 500 ms better than the tone at 200 or at 800 ms, and the effect of presentation time was no different for the two age groups. Thus it would appear that listening broadly over time does not contribute to infant-adult threshold differences.

Another developmental effect that may be important in somewhat more complex listening situations is a shift in the cues used to detect or discriminate sounds. One example is the observation of Hall, J.W. and Grose, J. H. (2004) discussed above, that children do not take advantage of temporal fluctuations in the level of a masker to detect a signal. Similarly, infants and children may focus on salient aspects of a sound, but ignore additional cues that may allow them to discriminate between sounds under more difficult listening conditions. For example, Lacerda, F. (1992) found that infants younger than 5 months of age were more likely to respond to a change in a formant transition in a CV syllable, while adults labeled the syllables primarily on the basis of vowel quality. Nittrouer, S. and her colleagues (Nittrouer, S., 1996, Nittrouer, S. and Boothroyd, A., 1990, Nittrouer, S. and Crowther, C. S., 1998, , 2001, Nittrouer, S. *et al.*, 1998, Nittrouer, S. and Miller, M. E., 1997, Nittrouer, S. and Studdert-Kennedy, M., 1987) have completed a series of studies of preschool and school-age children that demonstrate that they, too, are more influenced by formant transitions than by static cues in identifying consonants. Recently, Nittrouer, S. (2005) has suggested that young children's differential attention to dynamic cues in speech may make it more difficult for them to identify speech in noise.

3.2.3. *Ignoring irrelevant sound features*

Informational masking is defined here as a reduction in the audibility or discriminability of one sound that results from the presence of another sound, beyond that accounted for by overlap of the excitation patterns of the two sounds in the auditory periphery. Although there is currently some controversy over the meaning of informational masking (e.g., Durlach, N. I. *et al.*, 2003), this definition captures the generally agreed upon features of the phenomenon. In a paradigm that has been used in many subsequent studies, Neff, D. L. and Green, D. M. (1987) showed that detection threshold for a tone was elevated over quiet threshold when the frequencies of a competing multicomponent complex varied randomly from trial to trial, even though the frequencies in the competing complex were well outside the auditory filter centered on the target frequency. Essentially, informational masking results from a failure to ignore the resolvable competing components (Lutfi, R. A. *et al.*, 2003).There are large individual differences among adults in the amount of informational masking demonstrated, but in general, the greatest amount of masking is seen with 10-component competing complexes (e.g., Neff, D. L. and Callaghan, B. P., 1988). Allen, P. and Wightman, F. (1995) first demonstrated that preschool children's threshold for a pure tone in noise was increased by more than 24 dB if one other random frequency tone was presented simultaneously, compared to 11 dB for adults. Moreover, half of the children Allen, P. and Wightman, F. tested were unable to detect the target tone at an intensity less than 90 dB.

Oh, E. L. *et al.* (2001) obtained thresholds for a 1000-Hz tone from preschoolers and adults in broadband noise and in the presence of tonal complexes with 2-1000 randomly drawn components. Children demonstrated somewhat more masking than adults in the broadband noise masker, but 25-35 dB more masking than adults when the masker components varied randomly. Children were qualitatively similar to adults in that they demonstrated the most informational masking in the 10-component masker condition, but were more likely than adults to exhibit significant masking in the presence of a 2-component masker. The results were well described by a model (Lutfi, R. A., 1993) in which children monitor a greater number of auditory filters than adults do, consistent with previous studies of infants and children (Allen, P. and Wightman, F., 1994, Bargones, J. Y. and Werner, L. A., 1994, Bargones, J. Y. *et al.*, 1995, Werner, L. A. and Boike, K., 2001).

Leibold, L. J. and Werner, L. A. (in press) compared 7-9-month-olds' and adults' detection of a 1000-Hz tone in the presence of three different maskers, a broadband noise, a random-frequency two-tone complex and a fixed-frequency two-tone complex. Neither of the two-tone complexes had energy around 1000 Hz. Adults' thresholds were 15 dB higher, while infants' thresholds were 23 dB higher, with the random frequency masker than with the broadband noise masker, suggesting more informational masking with the random frequency masker. It is not clear why children appear to perform more poorly than infants, relative to adults, in informational masking (compare to Oh, E. L. *et al.*, 2001 described above). Interestingly, adults' thresholds were 37 dB higher, while infants' threshold were just 33 dB higher, with the fixed-frequency two-tone masker than with the random-frequency two-tone masker. On this basis, it is not clear at all that infants are more susceptible to random-frequency masking effects than adults are.

A related question is whether manipulations that reduce informational masking in adults have similar effects on children. For example, gating a random-frequency masker prior to the onset of the target tone tends to reduce the amount of informational masking, as does repeating the target several times while the random frequency masker varies (Hall, J. W. *et al.*, 2005, Kidd, G. *et al.*, 1994). Hall, J.W. *et al.* reported that children tended to derive less benefit in detection from such manipulations than adults do, but it was not clear whether the ability to do so improved between 5 and 9 years of age. Another manipulation that reduces informational masking in adults is a spatial difference between the random frequency masker and the target tone, for example, by presenting the masker and target to different ears or to speakers located in different spatial positions (Arbogast, T. L. *et al.*, 2002, Kidd, J., G. *et al.*, 1998, Neff, D. L., 1995). Two different laboratories have now demonstrated that 4-9-year-old children do not show a spatial release from informational masking and may even show increased masking when the masker and target are presented dichotically (Hall, J. W. *et al.*, 2005, Wightman, F. *et al.*, 2003).

3.2.4. Listening to competing messages

Dichotic listening is the classic paradigm for the study of selective auditory attention (Cherry, E. C., 1953): A listener is presented with two sound sequences. In one condition, the sequences are presented simultaneously to the same ear(s). In the other, one sound sequence is presented to one ear and a different sound sequence to the other. The sound sequences are typically speech. The listener is asked to report the sound presented to one sequence, while ignoring the other. Maccoby, E. E. and Konrad, K. W. (1966) tested kindergarten, second-grade, and fourth-grade children in such a selective listening task. In the dichotic condition, a male voice spoke words in one ear, while a female voice spoke words in the other. In the diotic condition, both voices were presented to both ears. Children were instructed to report the word spoken by either the male or female voice. Performance in the diotic condition was rather poor overall, but improved from 18 to 33 percent correct between kindergarten and fourth grade. In the dichotic condition, performance was uniformly better at all ages, but still improved from 35 to 52 percent correct over the age range tested. Doyle, A.-B. (1973) reported that the improvement in performance in the diotic competing message condition continued to a lesser extent between 8 and 14 years of age. The results of more recent studies are consistent with this pattern, and indicate that differences between event-related potentials evoked by attended and unattended stimuli increase in parallel with performance in dichotic listening tasks (Bartgis, J. *et al.*, 2003, Berman, S. and Friedman, D., 1995, Coch, D. *et al.*, 2005).

Recent studies of children disentangling competing messages have produced a wide range of results. For example, Litovsky, R. Y. (2005) asked 4-7-year-olds and adults to identify spondees in the presence of 1- or 2-talker speech or of speech-shaped noise modulated with the 1- or 2-talker speech envelope. Children's thresholds were higher than adults' in all conditions, but 1) the amount of masking exhibited by children and adults was similar in all conditions, 2) both children and adults had higher speech reception thresholds in modulated speech-shaped noise than in speech, and 3) children and adults showed equivalent release from masking when the spondee was presented from the speaker in front of the listener and the competing sound was presented to a speaker on the listener's right. Fallon, M. *et al.* (2000) reported that 5-year-olds were as good as adults in identifying words in a background of multi-talker babble, as long as age differences in masked thresholds were taken into account. Hall, J.W. *et al.* (2002), in contrast, found that while adults' spondee identification was about the same with two-talker and noise maskers, 5-9-year-old children's spondee identification was worse with a two-talker masker than with a noise masker, particularly when the speech masker was presented continuously throughout the session. Finally, Wightman, F. and Kistler, D. (2005) asked children and adults to identify speech in a paradigm developed by Brungart, D.S. and his colleagues (Brungart, D. S., 2001) . Listeners heard a target sentence along with a competing sentence in one ear, and in one condition, an additional competing sentence or a modulated speech-shaped noise was presented in the other ear. Listeners ranging in age from 4.6 to 30 years were tested with a female-talker distracter. The youngest children, 4.6-5.7 years old, needed a 23 dB greater signal-to-distracter ratio than 20-30-year-olds to identify a word in the target sentence when no contralateral distracter was presented. Adding noise to the contralateral ear had little effect at any age, but adding speech to the contralateral ear had a greater effect on the youngest children than on other age groups. Older children seemed to be affected by the presence of contralateral speech to about the same extent as adults.

It is difficult to draw conclusions about the development of selective attention from these studies. Several variables seem to be important in determining whether children will be able to attend selectively to one of several competing messages. One of these is the extent to which the target and distracters are synchronized in time. In the Wightman, F. and Kistler, D. (2005) experiment, for example, the words in the target and distracter stimuli were precisely aligned. Temporal synchrony is one variable that makes it difficult for listeners to segregate sound sources (Yost, W. A., 1991).

It is interesting that in the speech studies in which the words in the target and distracter sentences were not precisely aligned, children are generally able to take advantage of differences in spatial location to improve performance, while in informational masking studies where target and distracter are temporally aligned, they are not. This suggests a problem with sound source segregation rather than with selective attention. The precise characteristics of the distracter also seem to be important. For example, if children are less able than adults to take advantage of periods of low distracter energy to process the target, then more modulated distracters (e.g., single talk versus multi-talker) will put children at a relative disadvantage compared to adults. Finally, it does appear that children may less easily ignore the semantic content of the distracter than adults. Hall, J.W. *et al.* (2002) reported that children's spondee identification was more disrupted by continuous speech (in which the listener might follow the meaning) than by gated speech (in which the semantic content would be disrupted by gating), while gating the distracter made little difference to adult performance. A similar result was reported by Cherry (1981). Considerably more research will obviously be needed to understand the development of auditory attention.

4. SUMMARY AND CONCLUSION

Postnatal auditory development in humans appears to occur in two stages. In the first six months of life, maturation of the conductive apparatus and of the primary neural pathways results in substantial improvement in absolute sensitivity and frequency resolution, especially at high frequencies. The challenge for future research in this area is to develop approaches that allow us to understand the nature of these early changes and their impact on early perceptual learning.

After six months of age, perceptual performance remains immature, however, despite the fact that intensity, frequency and temporal processing are nearly adultlike. Auditory perception continues to improve into childhood and adolescence. Development over this prolonged period involves maturation of perceptual organization and attentional processes, but also learning about the important features of sound through experience. The challenge in understanding development in this later period is to develop approaches that will allow us to disentangle the effects of the many perceptual processes involved.

REFERENCES

Abdala, C. 1996. Distortion product otoacoustic emission (2f1-f2) amplitude as a function of f2/f1 frequency ratio and primary tone level separation in human adults and neonates. J. Acoust. Soc. Am. 100, 3726-40.

Abdala, C. 1998. A developmental study of distortion product otoacoustic emission (2f1-f2) suppression in humans. Hear. Res. 121, 125-38.

Abdala, C. 2000. Distortion product otoacoustic emission (2f1-f2) amplitude growth in human adults and neonates. J. Acoust. Soc. Am. 107, 446-56.

Abdala, C. and Chatterjee, M. 2003. Maturation of cochlear nonlinearity as measured by distortion product otoacoustic emission suppression growth in humans. J. Acoust. Soc. Am. 114, 932-943.

Abdala, C. and Folsom, R. C. 1995. The development of frequency resolution in humans as revealed by the auditory brain-stem response recorded with notched-noise masking. J. Acoust. Soc. Am. 98, 921-30.

Abdala, C., Oba, S. and Keefe, D. H. 2006. DPOAE ipsilateral suppression from birth through six months of age. Paper presented at the meeting of the American Auditory Society, Scottsdale, AZ.

Akiyama, Y., Schulte, F. J., Schultz, M. A. and Parmelee, A. H. 1969. Acoustically evoked responses in premature and full term newborn infants. Electroencephalogr. Clin. Neurophysiol. 26, 371-80.

Allen, P. and Wightman, F. 1994. Psychometric functions for children's detection of tones in noise. J. Speech Hear. Res. 37, 205-15.

Allen, P. and Wightman, F. 1995. Effects of signal and masker uncertainty on children's detection. J. Speech Hear. Res. 38, 503-11.

Allen, P., Wightman, F., Kistler, D. and Dolan, T. 1989. Frequency resolution in children. J. Speech Hear. Res. 32, 317-322.

Arbogast, T. L., Mason, C. R. and Kidd, G. 2002. The effect of spatial separation on informational and energetic masking of speech. J. Acoust. Soc. Am. 112, 2086-2098.

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

Ashmead, D. H., Davis, D., Whalen, T. and Odom, R. 1991. Sound localization and sensitivity to interaural time differences in human infants. Child Dev. 62, 1211-26.

Bargones, J. Y. and Burns, E. M. 1988. Suppression tuning curves for spontaneous otoacoustic emissions in infants and adults. J. Acoust. Soc. Am. 83, 1809-16.

Bargones, J. Y. and Werner, L. A. 1994. Adults listen selectively; Infants do not. Psychol. Sci. 5, 170-4.

Bargones, J. Y., Werner, L. A. and Marean, G. C. 1995. Infant psychometric functions for detection: Mechanisms of immature sensitivity. J. Acoust. Soc. Am. 98, 99-111.

Bartgis, J., Lilly, A. R. and Thomas, D. G. 2003. Event-related potential and behavioral measures of attention in 5-, 7-, and 9-year-olds. J. Gen. Psychol. 130, 311-335.

Bartoshuk, A. K. 1962. Human neonatal cardiac acceleration to sound: Habituation and dishabituation. Percept. Mot. Skills 15, 15-27.

Berg, K. M. 1993. A comparison of thresholds for 1/3-octave filtered clicks and noise bursts in infants and adults. Percept. Psychphys. 54, 365-9.

Berg, K. M. and Boswell, A. E. 1998. Infants' detection of increments in low- and high-frequency noise. Percept. Psychophys. 60, 1044-1051.

Berg, K. M. and Boswell, A. E. 1999. Effect of masker level on infants' detection of tones in noise. Percept. Psychophys. 61, 80-86.

Berg, K. M. and Boswell, A. E. 2000. Noise increment detection in children 1 to 3 years of age. Percept. Psychophys. 62, 868-873.

Berg, K. M. and Smith, M. C. 1983. Behavioral thresholds for tones during infancy. J. Exp. Child Psychol. 35, 409-25.

Berman, S. and Friedman, D. 1995. The development of selective attention as reflected by event-related brain potentials. J. Exp. Child Psychol. 59, 31-Jan.

Binns, K. E., Withington, D. J. and Keating, M. J. 1995. The developmental emergence of the representation of auditory azimuth in the external nucleus of the inferior colliculus of the guinea-pig: The effects of visual and auditory deprivation. Brain Res. Dev. Brain Res. 85, 14-24.

Birnholz, J. C. and Benacerraf, B. R. 1983. The development of human fetal hearing. Science 222, 516-8.

Bond, B. and Stevens, S. S. 1969. Cross-modality matching of brightness to loudness by 5-year-olds. Percept. Psychophys. 6, 337-9.

Bredberg, G. 1968. Cellular pattern and nerve supply of the human organ of Corti. Acta Otolaryngol. Suppl. (Stockh) 236.

Brown, A. M., Sheppard, S. L. and Russell, P. 1994. Acoustic distortion products (ADP) from the ears of term infants and young adults using low stimulus levels. Br. J. Audiol. 28, 273-280.

Brugge, J. F., Javel, E. and Kitzes, L. M. 1978. Signs of functional maturation of peripheral auditory system in discharge patterns in anteroventral cochlear nucleus of kittens. J. Neurophysiol. 41, 1557-1579.

Brungart, D. S. 2001. Evaluation of speech intelligibility with the coordinate response measure. J. Acoust. Soc. Am. 109, 2276-2279.

Bull, D., Eilers, R. E. and Oller, D. K. 1984. Infants' discrimination of intensity variation in mulitsyllabic stimuli. J. Acoust. Soc. Am. 76, 13-17.

Buss, E., Hall, J. W., Grose, J. H. and Dev, M. B. 1999. Development of adult-like performance in backward, simultaneous, and forward masking. J. Speech Lang. Hear. Res. 42, 844-849.

Cherry, E. C. 1953. Some experiments on the recogntion of speech, with one ear and with two ears. J. Acoust. Soc. Am. 25, 975-979.

Cherry, R. S. 1981. Development of selective auditory attention skills in children. Percept. Mot. Skills 52, 379-385.

Chuang, S. W., Gerber, S. E. and Thornton, A. R. 1993. Evoked otoacoustic emissions in preterm infants. Int. J. Pediatr. Otorhinolaryngol. 26, 39-45.

Clarkson, M. G. 1995. Psychophysical measures of auditory localization in human infants. Abstracts of the Association for Research in Otolaryngology 18, 57.

Clarkson, M. G. 1996. Infants' intensity discrimination; Spectral profiles. Infant Beh. Dev. 19, 181-190.

Clarkson, M. G. and Clifton, R. K. 1985. Infant pitch perception: Evidence for responding to pitch categories and the missing fundamental. J. Acoust. Soc. Am. 77, 1521-1528.

Clarkson, M. G. and Clifton, R. K. 1995. Infants' pitch perception: inharmonic tonal complexes. J. Acoust. Soc. Am. 98, 1372-9.

Clarkson, M. G., Clifton, R. K. and Perris, E. E. 1988. Infant timbre perception: Discrimination of spectral envelopes. Percept. Psychophys. 43, 15-20.

Clarkson, M. G. and Rogers, E. C. 1995. Infants require low-frequency energy to hear the pitch of the missing fundamental. J. Acoust. Soc. Am. 98, 148-54.

Clifton, R. K. 1992. The development of spatial hearing in human infants. In: Developmental psychoacoustics (eds. L. A. Werner and E. W. Rubel), p. 135-157. Washington, D.C., American Psychological Association.

Clifton, R. K., Graham, F. K. and Hatton, H. M. 1968. Newborn heart-rate response and response habituation as a function of stimulus duration. J. Exp. Child Psychol. 6, 265-278.

Clifton, R. K., Gwiazda, J., Bauer, J., Clarkson, M. and Held, R. 1988. Growth in head size during infancy: Implications for sound localization. Dev. Psychol. 24, 477-483.

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

Clifton, R. K., Perris, E. E. and Bullinger, A. 1991. Infants' perception of auditory space. Dev. Psychol. 27, 187-197.

Coch, D., Sanders, L. and Neville, H. 2005. An event-related potential study of selective auditory attention in childrenand adults. J. Cogn. Neurosci. 17, 605-22.

Collet, L., Garner, M., Veuillet, E., Moulin, A. and Morgon, A. 1993. Evoked and spontaneous otoacoustic emissions: A comparison of neonates and adults. Brain Dev. 15, 249-252.

Collins, A. A. and Gescheider, G. A. 1989. The measurement of loudness in individual children and adults by absolute magnitude estimation and cross-modality matching. J. Acoust. Soc. Am. 85, 2012-2021.

Cornacchia, L., Martini, A. and Morra, B. 1983. Air and bone conduction brain stem responses in adults and infants. Audiol. 22, 430-437.

Dai, H., Scharf, B. and Buus, S. 1991. Effective attenuation of signals in noise under focused attention. J. Acoust. Soc. Am. 89, 2837-2842.

Demany, L. 1982. Auditory stream segregation in infancy. Infant Beh. Dev. 5, 261-276.

Dorfman, D. D. and Megling, R. 1966. Comparison of magnitude estimation of loudness in children and adults. Percept. Psychophys. 1, 239-241.

Doyle, A.-B. 1973. Listening to distraction: A developmental study of selective attention. J. Exp. Child Psychol. 15, 100-115.

Durieux-Smith, A., Edwards, C. G., Picton, T. W. and Mcmurray, B. 1985. Auditory brainstem responses to clicks in neonates. J. Otolaryngol. 14, 12-18.

Durlach, N. I., Mason, C. R., Kidd, G., Arbogast, T. L., Colburn, H. S. and Shinn-Cunningham, B. G. 2003. Note on informational masking (L). J. Acoust. Soc. Am. 113, 2984-2987.

Eggermont, J. J., Brown, D. K., Ponton, C. W. and Kimberley, B. P. 1996. Comparison of distortion product otoacoustic emission (DPOAE) and auditory brainstem response

(ABR) traveling wave delay measurements suggests frequency-specific synapse maturation. Ear Hear. 17, 386-394.

Ehret, G. 1976. Development of absolute auditory thresholds in the house mouse (mus musculus). J. Am. Audiol. Soc. 1, 179-184.

Ehret, G. and Romand, R. 1981. Postnatal development of absolute auditory thresholds in kittens. J. Comp. Physiol. Psychol. 95, 304-311.

Eisenberg, R. B., Griffin, E. J., Coursin, D. B. and Hunter, M. A. 1964. Auditory behavior in the human neonate: A preliminary report. J. Speech Hear. Res. 7, 233-244.

Elfenbein, J. L., Small, A. M. and Davis, M. 1993. Developmental patterns of duration discrimination. J. Speech Hear. Res. 36, 842-849.

Engel, R. and Young, N. B. 1969. Calibrated pure tones audiograms in normal neonates based on evoked electroencephalographics responses. Orig. Articles 1, 149-160.

Fallon, M., Trehub, S. E. and Schneider, B. A. 2000. Children's perception of speech in multitalker babble. J. Acoust. Soc. Am. 108, 3023-3029.

Fassbender, C. (1993) Auditory grouping and segregation processes in infancy, Norderstedt, Germany, Kaste Verlag.

Fischer, B. and , H., K. 2004. On the development of low-level auditory discrimination and deficits indyslexia. Dyslexia. 10, 105-18.

Folsom, R. C. 1985. Auditory brain stem responses from human infants: Pure tone masking profiles for clicks and filtered clicks. J. Acoust. Soc. Am. 78, 555-562.

Folsom, R. C. and Wynne, M. K. 1987. Auditory brain stem responses from human adults and infants: Wave V tuning curves. J. Acoust. Soc. Am. 81, 412-417.

Fujimoto, S., Yamamoto, K., Hayabuchi, I. and Yoshizuka, M. 1981. Scanning and transmission electron microscope studies on the organ of corti and stria vascularis in human fetal cochlear ducts. Arch. Histol. Jap. 44, 223-235.

Gerber, S. E. 1985. Stimulus, Response, and State Variables in the Testing of Neonates. Ear Hear. 6, 15-19.

Gerhardt, K. J., Abrams, R. M. and Oliver, C. C. 1990. Sound environment of the fetal sheep. Am. J. Obstet. Gynecol. 162, 282-287.

Gorga, M. P., Kaminski, J. R., Beauchaine, K. L., Jesteadt, W. and Neely, S. T. 1989. Auditory brainstem responses from children three months to three years of age: Normal patterns of response II. J. Speech Hear. Res. 32, 281-288.

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

Gray, L. and Rubel, E. W. 1985. Development of absolute thresholds in chickens. J. Acoust. Soc. Am. 77, 1162-1172.

Grose, J. H., Hall, J. W. and Dev, M. B. 1997. MLD in children: Effects of signal and masker bandwidths. J. Speech Lang. Hear. Res. 40, 955-959.

Grose, J. H., Hall, J. W. and Gibbs, C. 1993. Temporal analysis in children. J. Speech Hear. Res. 36, 351-356.

Hall, J. G. 1964. The cochlea and the cochlear nuclei in neonatal asphyxia. Acta Otolaryngol. Suppl. (Stockh) 194, 8-93.

Hall, J. W. 1987. Experiments on comodulation masking release. In: Auditory processing of complex sounds (eds. W. A. Yost and C. S. Watson), p. 57-66. Hillsdale, NJ, Erlbaum.

Hall, J. W., Buss, E. and Grose, J. H. 2005. Informational masking release in children and adults. J. Acoust. Soc. Am. 118, 1605-1613.

Hall, J. W., Buss, E., Grose, J. H. and Dev, M. B. 2004. Developmental effects in the masking-level difference. J. Speech Lang. Hear. Res. 47, 13-20.

Hall, J. W. and Grose, J. H. 1990. The masking level difference in children. J. Am. Acad. Audiol. 1, 81-88.

Hall, J. W. and Grose, J. H. 1991. Notched-noise measures of frequency selectivity in adults and children using fixed-masker-level and fixed-signal-level presentation. J. Speech Hear. Res. 34, 651-660.

Hall, J. W. and Grose, J. H. 1994. Development of temporal resolution in children as measured by the temporal modulation transfer function. J. Acoust. Soc. Am. 96, 150-154.

Hall, J. W., Grose, J. H., Buss, E. and Dev, M. B. 2002. Spondee recognition in a two-talker masker and a speech-shaped noise masker in adults and children. Ear Hear. 23, 159-165.

Hall, J. W., Grose, J. H. and Dev, M. B. 1997. Auditory development in complex tasks of comodulation masking release. J. Speech Lang. Hear. Res. 40, 946-954.

Hall, J. W. III. (1992) Handbook of auditory evoked responses, Boston, Allyn and Bacon.

Harris, J. D. 1952. Pitch discrimination. J. Acoust. Soc. Am. 24, 750-755.

Hartley, D. E. H., Wright, B. A., Hogan, S. C. and Moore, D. R. 2000. Age-related improvements in auditory backward and simultaneous masking in 6-to 10-year-old children. J. Speech Lang. Hear. Res. 43, 1402-1415.

Hoshino, T. 1990. Scanning electron microscopy of nerve fibers in human fetal cochlea. J. Electron Microsc. 15, 104-114.

Hollich, G., Newman, R.S., and Jusczyk, P.W. 2005. Infants' use of synchronized visual information to separate streams of speech. Child Dev. 76, 598-613.

Huttenlocher, P. R. 1979. Synaptic density in human frontal cortex—developmental changes and effects of aging. Brain Res. 163, 195–205.

Igarashi, Y. and Ishii, T. 1979a. Development of organ of corti and stria vascularis in human fetus. Audiol. (Jap.) 22, 459-460.

Igarashi, Y. and Ishii, T. 1979b. Development of the cochlear and the blood-vessel-network in the fetus: A transmission electrographic observation. Audiol. (Jap.) 22, 459-460.

Igarashi, Y. and Ishii, T. 1980. Embryonic development of the human organ of Corti: Electron microscopic study. Int. J. Ped. Otorhinolaryngol. 2, 51-62.

Igarashi, Y., Yamazaki, H. and Mitsui, T. 1978. An electronographic study of inner/outer haircells of human fetuses. Audiol. (Jap.) 21, 375-377.

Irwin, R. J., Stillman, J. A. and Schade, A. 1986. The width of the auditory filter in children. J. Exp. Child Psychol. 41, 429-442.

Isaacson, G., Mintz, M. C. and Sasaki, C. T. 1986. Magnetic resonance imaging of the fetal temporal bone. Laryngoscope 96, 1343-1346.

Jensen, J. K. and Neff, D. L. 1993. Development of basic auditory discrimination in preschool children. Psychol. Sci. 4, 104-107.

Jordan, R. E. and Eagles, E. L. 1963. Hearing sensitivity and related factors in children. Monogr. Laryngoscope 143.

Keefe, D. H., Bulen, J. C., Arehart, K. H. and Burns, E. M. 1993. Ear-canal impedance and reflection coefficient in human infants and adults. J. Acoust. Soc. Am. 94, 2617-2638.

Keefe, D. H. and Levi, E. C. 1996. Maturation of the middle and external ears: Acoustic power-based responses and reflectance typmanometry. Ear Hear. 17, 1-13.

Kenyon, T. N. 1996. Ontogenetic changes in the auditory sensitivity of damselfishes (pomacentridae). J. Comp. Physiol. A 179, 553-561.

Kidd, G., Mason, C. R., Deliwala, P. S., Woods, W. S. and Colburn, H. S. 1994. Reducing informational masking by sound segregation. J. Acoust. Soc. Am. 95, 3475-80.

Kidd, J., G., Mason, C. R., Rohtla, T. L. and Deliwala, P. S. 1998. Release from masking due to spatial separation of sources in the identification of nonspeech auditory patterns. J. Acoust. Soc. Am. 104, 422-431.

Knudsen, E. I. 1988. Experience shapes sound localization and auditory unit properties during development in the barn owl. In: Auditory function: Neurobiological bases of hearing (eds. G. M. Edelman, W. E. Gall and W. M. Cowan), p. 137-149. New York, John Wiley & Sons.

Kopyar, B. A. 1997. Intensity discrimination abilities of infants and adults: Implications for underlying processes. Doctoral dissertation, University of Washington, Seattle, Washington.

Kotak, V. and Sanes, D. 1995. Synaptically evoked prolonged depolarizations in the developing auditory system. J. Neurophsyiol. 74, 1611-1620.

Kraus, N., Smith, D., Reed, N. L., Stein, L. K. and Cartee, C. 1985. Auditory middle latency responses in children: effects of age and diagnostic category. Electroencephal. Clin. Neurophysiol. 62, 343-351.

Kuhl, P. K. and Miller, J. L. 1982. Discrimination of auditory target dimensions in the presence or absence of variation in a second dimension by infants. Percept. Psychophys. 31, 279-292.

Lacerda, F. 1992. Young infants' discrimination of confusable speech signals. In: The auditory processing of speech: From sound to words (ed. M. E. H. Schouten), p. 229-238. New York, Mouton de Gruyter.

Lary, S., Briassoulis, G., De Vries, L., Dubowitz, L. M. S. and Dubowitz, V. 1985. Hearing threshold in preterm and term infants by auditory brainstem response. J. Pediatr. 107, 593-599.

Lasky, R., Perlman, J. and Hecox, K. 1992. Distortion-product otoacoustic emissions in human newborns and adults. Ear Hear. 103, 430-441.

Lasky, R. E. 1991. The effects of rate and forward masking on human adult and newborn auditory evoked response thresholds. Dev. Psychobiol. 24, 21-64.

Lasky, R. E. 1993. The effect of forward masker duration, rise/fall time, and integrated pressure on auditory brain stem evoked responses in human newborns and adults. Ear Hear. 14, 95-103.

Lavigne-Rebillard, M. and Bagger-Sjoback, D. 1992. Development of the human stria vascularis. Hear. Res. 64, 39-51.

Lavigne-Rebillard, M. and Pujol, R. 1987. Surface aspects of the developing human organ of corti. Acta Otolaryngol. (Stockh.) 436, 43-50.

Lavigne-Rebillard, M. and Pujol, R. 1988. Hair cell innervation in the fetal human cochlea. Acta Otolaryngol. (Stockh.) 105, 398-402.

Lavigne-Rebillard, M. and Pujol, R. 1990. Auditory hair cells in human fetuses: Synaptogenesis and ciliogenesis. J. Electron. Microsc. Tech. 15, 115-122.

Lecanuet, J. P. 1996. Fetal sensory competencies. Eur. J. Obstet. Gynecol. 68, 1-23.

Leiberman, A., Sohmer, H. and Szabo, G. 1973. Cochlear audiometry (Electro-cochleography) during the neonatal period. Dev. Med. Child Neurol. 15, 8-13.

Leibold, L. and Werner, W. A. 2002. Relationship between intensity and reaction time in normal hearing infants and adults. Ear Hear. 23, 92-97.

Leibold, L. J. and Werner, L. A. in press. The effect of masker-frequency variability on the detection performance of infants and adults. J. Acoust. Soc. Am.

Lenard, H. G., Bernuth, H. V. and Hutt, S. J. 1969. Acoustic evoked responses in newborn infants: The influence of pitch and complexity of the stimulus. Electroencephal. Clin. Neurophsyiol. 27, 121-127.

Leventhal, A. and Lipsitt, L. P. 1964. Adaptation, pitch discrimination and sound localization in the neonate. Child Dev. 35, 759-767.

Liden, G. and Kankkonen, A. 1961. Visual reinforcement audiometry. Acta Otolaryngol. (Stockh.) 67, 281-292.

Litovsky, R. 1993. The influence of the precedence effect on developmental changes in sound localization precision. J. Acoust. Soc. Am., 1-31.

Litovsky, R. Y. 2005. Speech intelligibility and spatial release from masking in young children. J. Acoust. Soc. Am. 117, 3091-9.

Litovsky, R. Y. and Ashmead, D. H. 1997. Development of binaural and spatial hearing in infants and children. In: Binarual and Spatial Hearing in Real and Virtual Environments (eds. R. H. Gilkey and T. R. Anderson), p. 571-592. Manwah, N.J., Lawrence Erlbaum Associates.

Litovsky, R. Y. and Clifton, R. K. 1992. Use of sound-pressure level in auditory distance discrimination by 6-month-old infants and adults. J. Acoust. Soc. Am. 92, 794-802.

Lutfi, R. A. 1993. A model of auditory pattern analysis based on component-relative-entropy. J. Acoust. Soc. Am. 94, 748-758.

Lutfi, R. A., Kistler, D. J., Oh, E. L., Wightman, F. L. and Callahan, M. R. 2003. One factor underlies individual differences in auditory informational masking within and across age groups. Percept. Psychophys. 65, 396-406.

Maccoby, E. E. and Konrad, K. W. 1966. Age trends in selective listening. J. Exp. Child Psychol. 3, 113-122.

Marean, G. C., Werner, L. A. and Kuhl, P. K. 1992. Vowel categorization by very young infants. Dev. Psychol. 28, 396-405.

Maxon, A. B. and Hochberg, I. 1982. Development of psychoacoustic behavior: Sensitivity and discrimination. Ear Hear. 3, 301-308.

Mcadams, S. and Bertoncini, J. 1997. Organization and discrimination of repeating sound sequences by newborn infants. J. Acoust. Soc. Am. 102, 2945-53.

Mckinnis, M. E. 1936. The number of ganglion cells in dorsal root ganglia of the second and third cervical nerves in human fetuses of various ages. Anat. Rec. 65, 255-259.

Mencher, G. T., Mencher, L. S. and Rohland, S. L. 1985. Maturation of behavioral response. Ear Hear. 6, 10-14.

Montgomery, C. R. and Clarkson, M. G. 1997. Infants' pitch perception: Masking by low- and high-frequency noises. J. Acoust. Soc. Am. 102, 3665-3672.

Moore, B. C., Peters, R. W. and Glasberg, B. R. 1999. Effects of frequency and duration on psychometric functions for detection of increments and decrements in sinusoids in noise. J. Acoust. Soc. Am. 106, 3539-3552.

Moore, D. R. 1983. Development of inferior colliculus and binaural audition. In: Development of auditory and vestibular systems (ed. R. Romand), p. 121-166. New York, Academic Press.

Moore, J. K., Guan, Y. L. and Shi, S. R. 1997. Axogenesis in the human fetal auditory system, demonstrated by neurofilament immunohistochemistry. Anat. Embryol. (Berl.) 195, 15-30.

Moore, J. K., Perazzo, L. M. and Braun, A. 1995. Time course of axonal myelination in human brainstem auditory pathway. Hear. Res. 87, 21-31.

Moore, J. K., Ponton, C. W., Eggermont, J. J., Wu, B. J. and Huang, J. Q. 1996. Perinatal maturation of the auditory brain stem response: changes in path length and conduction velocity. Ear Hear. 17, 411-8.

Moore, J. M., Wilson, W. R. and Thompson, G. 1977. Visual reinforcement of head-turn responses in infants under 12 months of age. J. Speech Hear. Disord. 42, 328-334.

Morlet, T., Perrin, E., Durrant, J. D., Lapillonne, A., Ferber, C., Duclaux, R., Putet, G. and Collet, L. 1996. Development of cochlear active mechanisms in humans differs between gender. Neurosci. Lett. 220, 49-52.

Morrongiello, B. A., Fenwick, K. D., Hillier, L. and Chance, G. 1994. Sound localization in newborn human infants. Dev. Psychobiol. 27, 519-38.

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

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

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

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

Morrongiello, B. A. and Trehub, S. E. 1987. Age-related changes in auditory temporal perception. J. Exp. Child Psych. 44, 413-426.

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

Nakai, Y. 1970. An electron microscopic study of the human fetus cochlea. Pract. Otol. Rhinol. Laryngol. 32, 257-267.

Neff, D. L. 1995. Signal properties that reduce masking by simultaneous, random-frequency maskers. J. Acoust. Soc. Am. 98, 1909-1920.

Neff, D. L. and Callaghan, B. P. 1988. Effective properties of multicomponent simultaneous maskers under conditions of uncertainty. J. Acoust. Soc. Am. 83, 1833-1838.

Neff, D. L. and Green, D. M. 1987. Masking produced by spectral uncertainty with multicomponent maskers. Percept. Psychophys. 41, 409-415.

Newman, R. S. and Jusczyk, P. W. 1996. The cocktail party effect in infants. Percept. Psychophys. 58, 1145-1156.

Nittrouer, S. 1996. Discriminability and perceptual weighting of some acoustic cues to speech perception by 3-year-olds. J. Speech Hear. Res. 39, 278-297.

Nittrouer, S. 2005. Age-related differences in weighting and masking of two cues to word-final stop voicing in noise. J. Acoust. Soc. Am. 118, 1072-1088.

Nittrouer, S. and Boothroyd, A. 1990. Context effects in phoneme and word recognition by young children and older adults. J. Acoust. Soc. Am. 87, 2705-2715.

Nittrouer, S. and Crowther, C. S. 1998. Examining the role of auditory sensitivity in the developmental weighting shift. J. Speech Lang. Hear. Res. 41, 809-818.

Nittrouer, S. and Crowther, C. S. 2001. Coherence in children's speech perception. J. Acoust. Soc. Am. 110, 2129-40.

Nittrouer, S., Crowther, C. S. and Miller, M. E. 1998. The relative weighting of acoustic properties in the perception of s +stop clusters by children and adults. Percept. Psychophys. 60, 51-64.

Nittrouer, S. and Miller, M. E. 1997. Predicting developmental shifts in perceptual weighting schemes. J. Acoust. Soc. Am. 101, 3353-3366.

Nittrouer, S. and Studdert-Kennedy, M. 1987. The role of coarticulatory effects in the perception of fricatives by children and adults. J. Speech Hear. Res. 30, 319-329.

Nozza, R. J. 1987. The binaural masking level difference in infants and adults: Developmental change in binaural hearing. Infant Beh. Dev. 10, 105-110.

Nozza, R. J., Wagner, E. F. and Crandell, M. A. 1988. Binaural release from masking for a speech sound in infants, preschoolers, and adults. J. Speech Hear. Res. 31, 212-218.

Nozza, R. J. and Wilson, W. R. 1984. Masked and unmasked pure-tone thresholds of infants and adults: Development of auditory frequency selectivity and sensitivity. J. Speech Hear. Res. 27, 613-622.

Oh, E. L., Wightman, F. and Lutfi, R. A. 2001. Children's detection of pure-tone signals with random multitone maskers. J. Acoust. Soc. Am. 109, 2888-2895.

Okabe, K. S., Tanaka, S., Hamada, H., Miura, T. and Funai, H. 1988. Acoustic impedance measured on normal ears of children. J. Acoust. Soc. Jap. 9, 287-294.

Olsho, L. W. 1985. Infant auditory perception: Tonal masking. Infant Beh. Dev. 7, 27-35.

Olsho, L. W., Koch, E. G. and Carter, E. A. 1988a. Nonsensory factors in infant frequency discrimination. Infant Beh. Dev. 11, 205-222.

Olsho, L. W., Koch, E. G., Carter, E. A., Halpin, C. F. and Spetner, N. B. 1988b. Pure-tone sensitivity of human infants. J. Acoust. Soc. Am. 84, 1316-1324.

Olsho, L. W., Koch, E. G. and Halpin, C. F. 1987. Level and age effects in infant frequency discrimination. J. Acoust. Soc. Am. 82, 454-464.

Parrish, H. K. and Werner, L. A. 2004. Listening windows in infants and adults. Paper presented at the meeting of the American Auditory Society Meeting, Scottsdale, AZ.

Plinkert, P. K., Sesterhenn, G., Arold, R. and Zenner, H. P. 1990. Evaluation of otoacoustic emisssions in high-risk infants by using an easy and rapid objective auditory screening method. Eur. Arch. Otorhinolaryngol. 247, 356-360.

Ponton, C. W., Eggermont, J. J., Kwong, B. and Don, M. 2000. Maturation of human central auditory system activity: evidence from multi-channel evoked potentials. Clin. Neurophysiol. 111, 220-236.

Ponton, C. W., Moore, J. K. and Eggermont, J. J. 1996. Auditory brain stem response generation by parallel pathways: differential maturation of axonal conduction time and synaptic transmission. Ear Hear. 17, 402-10.

Pujol, R. and Lavigne-Rebillard, M. 1992. Development of neurosensory structures in the human cochlea. Acta Otolaryngol. (Stockh.) 112, 259-264.

Pujol, R., Lavigne-Rebillard, M. and Uziel, A. 1990. Physiological correlates of development of the human cochlea. Semin. Perinatol. 14, 275-80.

Pujol, R., Lavigne-Rebillard, M. and Uziel, A. 1991. Development of the human cochlea. Acta Otolaryngol. (Stockh.) Suppl 482, 7-12.

Querleu, D., Renard, X., Versyp, F., Paris-Delrue, L. and Crepin, G. 1988. Fetal hearing. Eur. J. Ob. Gyn. Repro. Biol. 29, 191-212.

Rickard, L. K. 1988. Auditory brainstem responses from infants and adults to extended high-frequency tone pips. Masters thesis, University of Washington, Seattle, WA.

Salamy, A., Mckean, C. M. and Buda, F. B. 1975. Maturational changes in auditory transmission as reflected in human brain stem potentials. Brain Res. 96, 361-366.

Sanes, D. H. and Walsh, E. J. 1998. The development of central auditory function. In: Development of the auditory system (eds. E. W. Rubel, R. R. Fay and A. N. Popper), p. 271-314. New York, Springer Verlag.

Schneider, B. A., Morrongiello, B. A. and Trehub, S. E. 1990. The size of the critical band in infants, children, and adults. J. Exp. Psych. [Hum. Percept. Perform.] 16, 642-652.

Schneider, B. A. and Trehub, S. E. 1992. Sources of developmental change in auditory sensitivity. In: Developmental psychoacoustics (eds. L. A. Werner and E. W. Rubel), p. 3-46. Washington, D.C., American Psychological Association.

Schneider, B. A., Trehub, S. E. and Bull, D. 1979. The development of basic auditory processes in infants. Can. J. Psychol. 33, 306-319.

Schneider, B. A., Trehub, S. E., Morrongiello, B. A. and Thorpe, L. A. 1989. Developmental changes in masked thresholds. J. Acoust. Soc. Am. 86, 1733-1742.

Sharma, A., Kraus, N., Mcgee, T. and Nicol, T. 1997. Developmental changes in P1 and N1 central auditory responses elicited by consonant-vowel syllables. Evoked Potentials Electroenceph. Clin. Neurophysiol. 104, 540-545.

Shimizu, T., Salvador, L., Allanson, J., Hughes-Benzie, R. and Nimrod, C. 1991. Ultrasonographic measurements of the fetal ear. Obstet. Gynecol. 80, 381-384.

Sininger, Y. and Abdala, C. 1996. Auditory brainstem response thresholds of newborns based on ear canal levels. Ear Hear. 17, 395-401.

Sininger, Y. S., Abdala, C. and Cone-Wesson, B. 1997. Auditory threshold sensitivity of the human neonate as measured by the auditory brainstem response. Hear. Res. 104, 1-22.

Sinnott, J. M. and Aslin, R. N. 1985. Frequency and intensity discrimination in human infants and adults. J. Acoust. Soc. Am. 78, 1986-1992.

Sinnott, J. M., Pisoni, D. B. and Aslin, R. M. 1983. A comparison of pure tone auditory thresholds in human infants and adults. Infant Beh. Dev. 6, 3-17.

Soderquist, D. R. and Moore, M. 1970. Effect of training on frequency discrimination in primary school children. J. Aud. Res. 10, 185-192.

Spetner, N. B. and Olsho, L. W. 1990. Auditory frequency resolution in human infancy. Child Dev. 61, 632-652.

Steinschneider, A., Lipton, E. L. and Richmond, J. B. 1966. Auditory sensitivity in the infant: Effect of intensity on cardiac and motor responsivity. Child Dev. 37, 233-252.

Stellmack, M. A., Willihnganz, M. S., Wightman, F. L. and Lutfi, R. A. 1997. Spectral weights in level discrimination by preschool children: analytic listening conditions. J. Acoust. Soc. Am. 101, 2811-21.

Stevens, J. C., Webb, H. D., Smith, M. F. and Buffin, J. T. 1990. The effect of stimulus level on click evoked oto-acoustic emissions and brainstem responses in neonates under intensive care. Br. J. Audiol. 24, 293-300.

Streeter, G. L. 1906. On the development of the membranous labyrinth and the acoustic and facial nerves in the human embryo. Am. J. Anat. 6, 139-165.

Streeter, G. L. 1917. The development of the scala tympani, scala vestibuli and perioticular cistern in the human embryo. Am. J. Anat. 21, 299-320.

Stuart, A., Yang, E. Y., Stenstroml, R. and Reindorp, A. G. 1993. Auditory brainstem response thresholds to air and bone conducted clicks in neonates and adults. Am. J. Otol. 14, 176-182.

Teas, D. C., Klein, A. J. and Kramer, S. J. 1982. An analysis of auditory brainstem responses in infants. Hear. Res. 7, 19-54.

Tharpe, A. M. and Ashmead, D. H. 2001. A longitudinal investigation of infant auditory sensitivity. Am. J. Audiol. 10, 104-112.

Trainor, L. J., Samuel, S. S., Desjardins, R. N. and Sonnadara, R. R. 2001. Measuring temporal resolution in infants using mismatch negativity. Neuroreport 12, 2443-8.

Trehub, S. E., Endman, M. W. and Thorpe, L. A. 1990. Infants' perception of timbre: Classification of complex tones by spectral structure. J. Exp. Child. Psychol. 49, 300-313.

Trehub, S. E., Schneider, B. A. and Endman, M. 1980. Developmental changes in infants' sensitivity to octave-band noises. J. Exp. Child Psychol. 29, 282-293.

Trehub, S. E., Schneider, B. A. and Henderson, J. 1995. Gap detection in infants, children, and adults. J. Acoust. Soc. Am. 98, 2532-2541.

Trehub, S. E., Schneider, B. A., Thorpe, L. A. and Judge, P. 1991. Observational measures of auditory sensitivity in early infancy. Dev. Psychol. 27, 40-49.

Viemeister, N. F. 1979. Temporal modulation transfer functions based upon modulation thresholds. J. Acoust. Soc. Am. 66, 1564-1380.

Viemeister, N. F. and Schlauch, R. S. 1992. Issues in infant psychoacoustics. In: Developmental psychoacoustics (eds. L. A. Werner and E. W. Rubel), p. 191-210. Washington, D.C., American Psychological Association.

Weir, C. 1976. Auditory frequency sensitivity in the neonate: A signal detection analysis. J. Exp. Child Psychol. 21, 219-225.

Weir, C. 1979. Auditory frequency sensitivity of human newborns: Some data with improved acoustic and behavioral controls. Percept. Psychophys. 26, 287-294.

Werner, L. A. 1995. Observer-based approaches to human infant psychoacoustics. In: Methods in comparative psychoacoustics (eds. G. M. Klump, R. J. Dooling, R. R. Fay and W. C. Stebbins), p. 135-146. Boston, Birkhauser Verlag.

Werner, L. A. 1996. The development of auditory behavior (or what the anatomists and physiologists have to explain). Ear Hear. 17, 438-46.

Werner, L. A. 1999. Forward masking among infant and adult listeners. J. Acoust. Soc. Am. 105, 2445-53.

Werner, L. A. 2006. Preliminary observations on the temporal modulation transfer functions of infants and adults. Paper presented at the meeting of the American Auditory Society, Scottsdale, AZ.

Werner, L. A. and Bargones, J. Y. 1991. Sources of auditory masking in infants: Distraction effects. Percept. Psychophys. 50, 405-412.

Werner, L. A. and Bargones, J. Y. 1992. Psychoacoustic development of human infants. In: Advances in infancy research (eds. C. Rovee-Collier and L. Lipsitt), p. 103-45. Norwood, NJ, Ablex.

Werner, L. A. and Boike, K. 2001. Infants' sensitivity to broadband noise. J. Acoust. Soc. Am. 109, 2101-2111.

Werner, L. A., Constantino, J. C. and Mancl, L. R. 1994a. Gap detection by human infants. J. Acoust. Soc. Am. 95, 2940.

Werner, L. A., Folsom, R. C. and Mancl, L. R. 1993. The relationship between auditory brainstem response and behavioral thresholds in normal hearing infants and adults. Hear. Res. 68, 131-141.

Werner, L. A., Folsom, R. C. and Mancl, L. R. 1994b. The relationship between auditory brainstem response latencies and behavioral thresholds in normal hearing infants and adults. Hear. Res. 77, 88-98.

Werner, L. A., Folsom, R. C., Mancl, L. R. and Syapin, C. 2001. Human auditory brainstem response to temporal gaps in noise. J. Speech Lang. Hear. Res. 44, 737-750.

Werner, L. A. and Gillenwater, J. M. 1990. Pure-tone sensitivity of 2- to 5-week-old infants. Infant Beh. Dev. 13, 355-375.

Werner, L. A. and Holmer, N. M. 2002. Infant hearing thresholds measured in the ear canal. Paper presented at the meeting of the American Auditory Society, Scottsdale, AZ.

Werner, L. A. and Mancl, L. R. 1993. Pure-tone thresholds of 1-month-old human infants. J. Acoust. Soc. Am. 93, 2367.

Werner, L. A., Marean, G. C., Halpin, C. F., Spetner, N. B. and Gillenwater, J. M. 1992. Infant auditory temporal acuity: Gap detection. Child Dev. 63, 260-272.

Werner, L. A. and Rubel, E. W. (Eds.) 1992. Developmental psychoacoustics, Washington, D.C., American Psychological Association.

Wightman, F. and Allen, P. 1992. Individual differences in auditory capability among preschool children. In: Developmental psychoacoustics (eds. L. A. Werner and E. W. Rubel), p. 113-133. Washington, D.C., American Psychological Association.

Wightman, F., Allen, P., Dolan, T., Kistler, D. and Jamieson, D. 1989. Temporal resolution in children. Child Dev. 60, 611-624.

Wightman, F., Callahan, M. R., Lutfi, R. A., Kistler, D. J. and Oh, E. 2003. Children's detection of pure-tone signals: Informational masking with contralateral maskers. J. Acoust. Soc. Am. 113, 3297-3305.

Wightman, F. L. and Kistler, D. J. 2005. Informational masking of speech in children: Effects of ipsilateral and contralateral distracters. J. Acoust. Soc. Am. 118, 3164-3176.

Willihnganz, M. S., Stellmack, M. A., Lutfi, R. A. and Wightman, F. L. 1997. Spectral weights in level discrimination by preschool children: synthetic listening conditions. J. Acoust. Soc. Am. 101, 2803-10.

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

Yost, W. A. 1991. Auditory image perception and analysis: the basis for hearing. Hear. Res. 56, 8-18.

Zeng, F., Kong, Y., Michalewski, H. and Starr, A. 2005 Perceptual consequences of disrupted auditory nerve activity J. Neurophysiol. 93, 3050-3063.

Zimmermann, E. 1993. Behavioral measures of auditory thresholds in developing tree shrews (Tupaia belageri). J. Acoust. Soc. Am. 94, 3071-3075.

FIGURE CAPTIONS

Figure 1. Thresholds for octave bands of noise masked by broadband noise, as a function of the center frequency of the noise band, for six age groups. Data replotted from Schneider et al. (1989)

Figure 2. A summary of the development of the audibility curve, abstracted from several studies (see text).

Figure 3. A summary of the development of intensity discrimination, taken from four different studies. Error bars represent ± 1 standard deviation. Stimuli varied across studies (see text).

Figure 4. Temporal modulation transfer functions fit to the modulation detection data of four age groups. The functions are superimposed at the bottom of the panel to emphasize the similarity in shape. From Hall and Grose (1994).

Figure 5. Examples of stimulus sequences used in an auditory streaming experiment with infant subjects. The vertical dimension in each panel is fundamental frequency. The circles represent synthetic vibraphone tones that were played from a speaker to one side of the infant's head. The squares represent trumpet tones that were played from a speaker on the opposite side of the infant's head. Adults listening to both sequences reported hearing two auditory streams. In the top panel, a slowly repeated trumpet tone was heard in one stream, while in the other, a descending ('initial sequence') or ascending ('retrograde sequence') series of faster vibraphone tones was heard. In the bottom panel, a series of alternating high and low vibraphone tones was heard in one stream, while in the other a slightly lower alternating high and low sequence of trumpet tones were heard. When the initial sequence in the top panel was played in

reverse, adults could discriminate the change. In the bottom panel, if adults had heard the sound as a single stream, they would be able to discriminate the initial sequence from its reverse, because the pitch would now decrease, rather than increase, across each repetition of the 4-tone sequence. However, when the adults heard the stimulus as two streams, the same alternating high-low sequence could be heard whether the sequence was played forward or backward. Infants listening to these two stimulus configurations discriminated the initial sequence in the top panel from its retrograde, but showed no evidence of discriminating the initial sequence in the bottom panel from its retrograde. The latter result suggests that infants heard the sequence in the bottom panel as two auditory streams, as adults did. From McAdams and Bertoncini (1997)

Figure 1

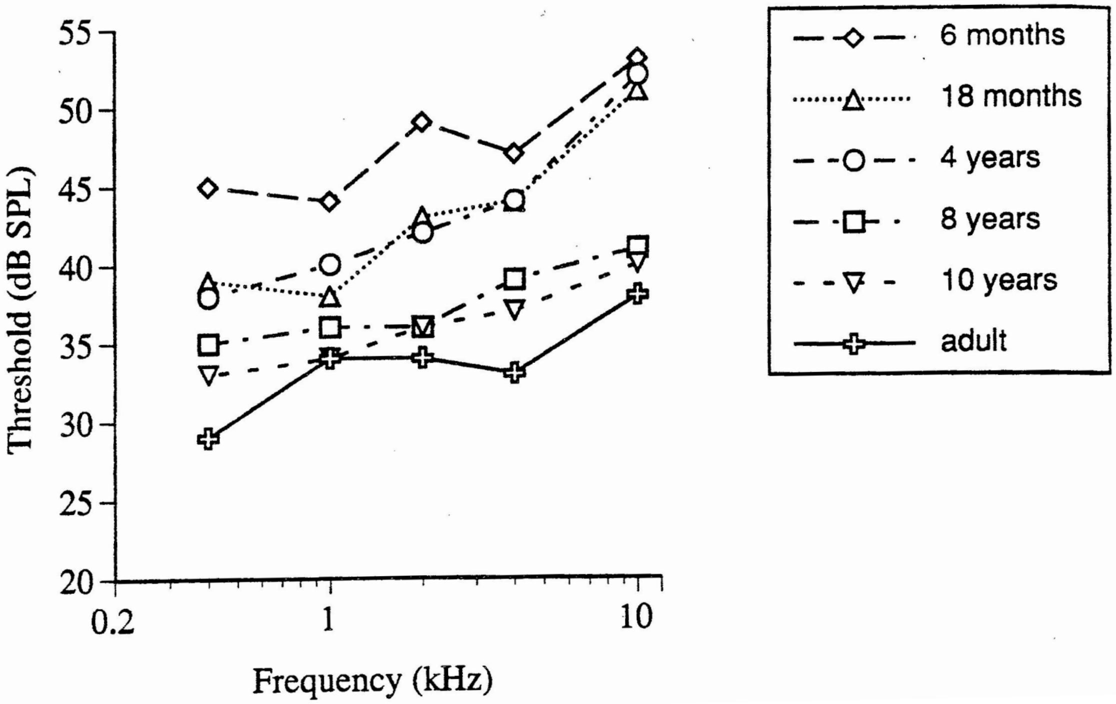

Threshold (dB SPL)
55
50
45
40
35
30
25
20
0.2
1
10
Frequency (kHz)
6 months
18 months
4 years
8 years
10 years
adult

Figure 2

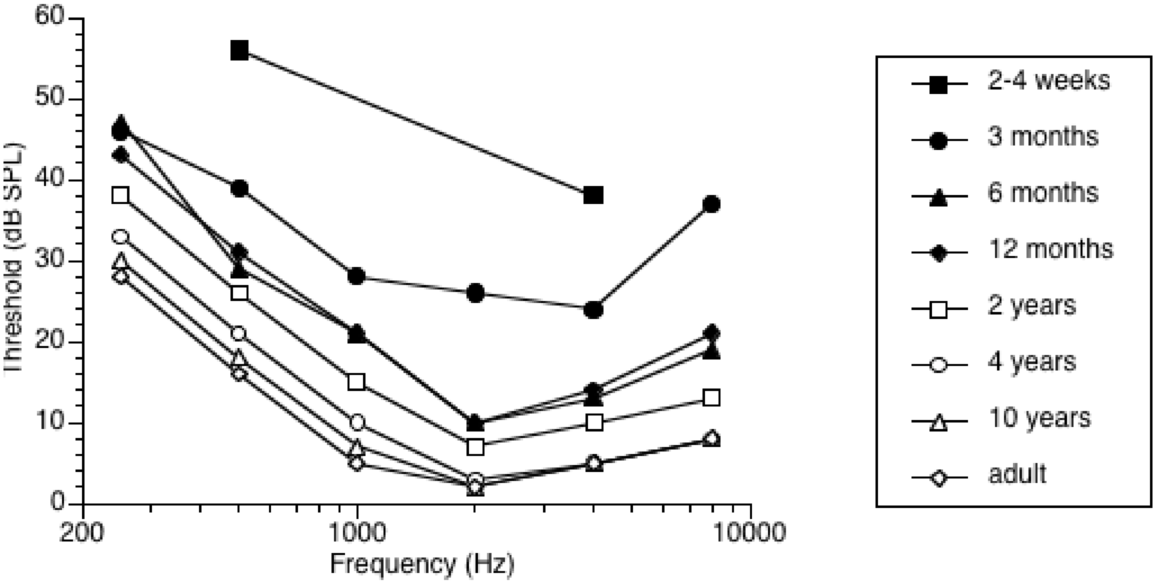

60
50
40
30
20
10
0
Threshold (dB SPL)
200
1000
10000
Frequency (Hz)
2-4 weeks
3 months
6 months
12 months
2 years
4 years
10 years
adult

Figure 3

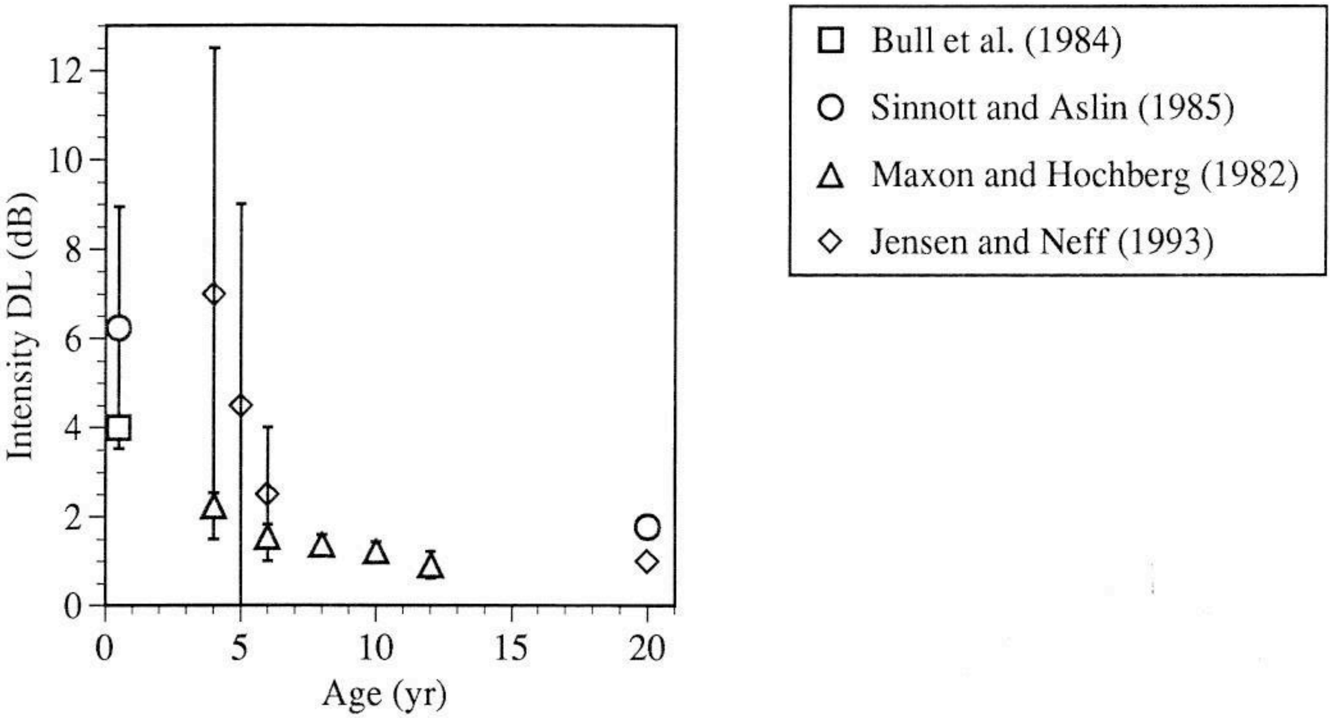

Intensity DL (dB)
0
2
4
6
8
10
12
Age (yr)
0
5
10
15
20
□ Bull et al. (1984)
○ Sinnott and Aslin (1985)
△ Maxon and Hochberg (1982)
◇ Jensen and Neff (1993)

Figure 4

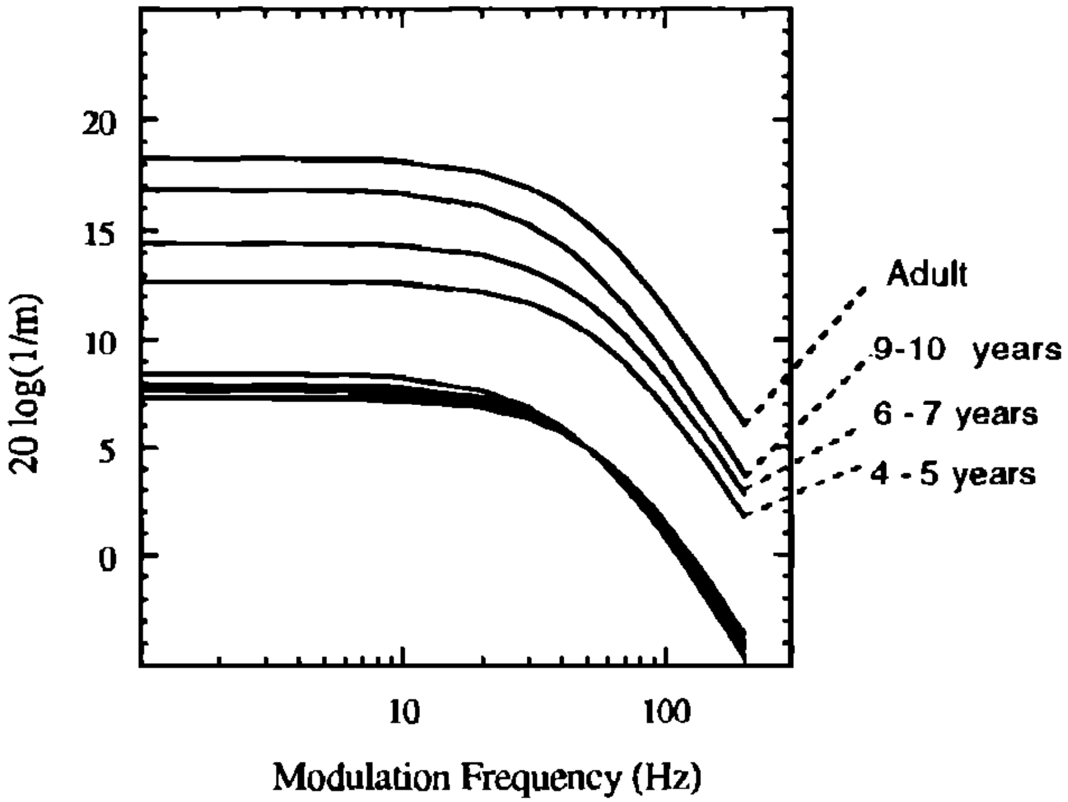
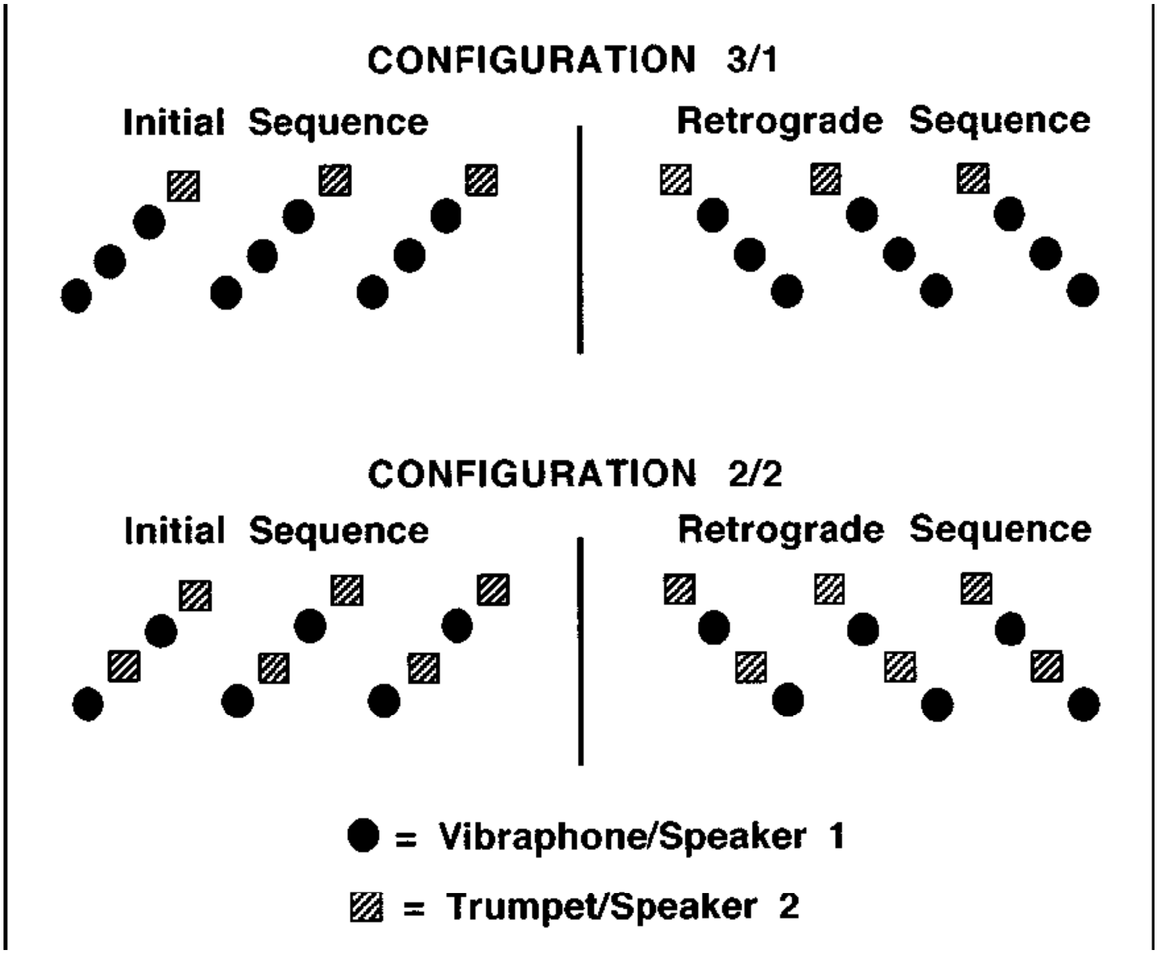

20
15
10
5
0
20 log(1/m)
10
100
Modulation Frequency (Hz)
Adult
9-10 years
6 - 7 years
4 - 5 years

Figure 5


CONFIGURATION 3/1
Initial Sequence
Retrograde Sequence
CONFIGURATION 2/2
Initial Sequence
Retrograde Sequence
● = Vibraphone/Speaker 1
▨ = Trumpet/Speaker 2