Auditory Development of the Hearing Child

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Auditory perception is defined, here, as the interpretation of sensory evidence, derived from sound, in terms of the objects and events that caused the sound. Like other kinds of perception, it involves the use, not only of sensory evidence, but also of contextual evidence, prior knowledge, memory, attention, and processing skills. Auditory speech perception is special because the events to be perceived are those of language. Similarly, the listener's knowledge base and processing skills must include those related to language in general, and spoken language in particular. The auditory system is complete and functional at birth but myelination continues for several years in the higher auditory pathways. This pattern of anatomical maturation is reflected in electrophysiological responses. Similarly, infants display sophisticated discrimination and recognition ability but psychoacoustic performance does not reach adult levels for several years. Empirical data on the development of auditory processing are sparse, but much work has been done on auditory speech perception. Infants at 6 months demonstrate the beginnings of phonemic classification, and performance improves during childhood in a variety of areas. These include: phonetic contrast perception, phoneme recognition, perception of speech in noise, selective attention, and the use of linguistic context. Experience obviously plays a key role in the development of the knowledge and skills required for auditory perception in general and auditory speech perception in particular. It is tempting to assume that the sensory evidence available to the developing child is determined only by the functional integrity of the peripheral auditory system, independent of auditory experience. There is, however, increasing evidence in animals of the influence of auditory experience on the organization of the auditory pathways. Such organization could increase the sensory evidence made available from patterns of neural excitation produced in the cochlea.

Key words: Audition, child, development, hearing.

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Introduction and Purpose

If we are to understand and manage childhood hearing impairment, it is important to have some understanding of normal hearing and its development. The purpose of this paper is to address four questions: (1) What is auditory perception? (2) What is auditory speech perception, and is it different, in some essential way, from general auditory perception? (3) How does auditory perception develop? And (4) What is the role of experience in that development?

What is auditory perception? For the purposes of this paper, I will define auditory perception as: ... the interpretation of sensory evidence, produced by the ears in response sound, in terms of the objects and events that caused the sound.

It is important to realize that auditory perception is not about the perception of sound itself but about the perception of the objects and events that produce sound. In fact it is mostly about the perception of events rather than objects. We do not hear a dog but we may hear a dog barking. We do not hear a window but we may hear a window closing. And we do not hear a person but we may hear a person talking. It is events that disturb the air and it is events that we identify from those disturbances. We only identify the objects because we know about the sound-making events in which they are likely to engage. It is true that we can, to a certain extent, perceive objects from patterns of reflected sound, just as bats and dolphins do. But, in humans, this ability is rudimentary. The definition just offered seems simple, but the process it defines is extremely complex. Bregman (1990) has written, at length, about this process. To emphasize both its nature and complexity, he refers to it as 'auditory scene analysis'. He also offers a vivid analogy. Suppose you are at the edge of a lake and you dig two channels in the sand into which some of the water can flow. You now hold two handkerchiefs in the water and watch them as they move with the ripples. From those movements you must determine how many boats are on the lake, where they are, how fast they are going and in which direction, which are rowing boats, and which are canoes, who is fishing and who is snoozing. This task would be daunting, to say the least, but it is exactly what we do when we examine the movement of our tympanic membranes in order to perceive sound-generating

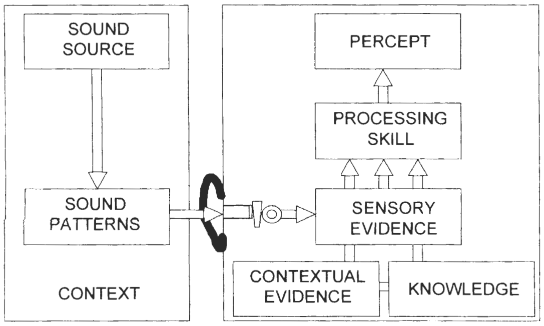


Fig. 1. Schematic illustration of the process of auditory perception. Objects and events produce sound patterns from which the peripheral auditory system generates sensory evidence. The context provides contextual evidence. These two sources of evidence, whose value depends on the perceiver's knowledge, are evaluated as the perceiver decides among possible interpretations. These interpretations—the percepts—are internal representations of the probable source of the sound patterns.

objects and events in our environment. As pointed out by Bregman in his landmark text on this topic, the amount of research effort devoted to understanding this task has been small compared with that devoted to exploring the basic relationships between the properties of simple sound patterns and the properties of the sensations they produce. This last has been the traditional interest of psychoacousticians.

Fig. 1 encapsulates some of the components of auditory perception:

1. At the core of auditory perception is the generation of sensory evidence from sound patterns arriving at the ears (without the sensory evidence there can be no auditory perception—only auditory hallucination.)

2. The outcome of auditory perception consists of percepts. These are internal representations of the objects and events that we decide most probably generated the sound patterns. Note the introduction of the idea of decision-making. When arriving at a percept we are essentially deciding among the possible interpretations of sensory evidence.

3. We cannot recognize objects and events unless we already know something about them. It is from our existing knowledge of the world that the possible percepts come.

4. The objects and events, and the sounds they produce at the ear, exist in a context. This context also contains evidence that the perceiver may use in making decisions about the source of the sounds.

5. Contextual evidence, like sensory evidence, is only useful in relation to pre-existing knowledge and must be evaluated in the light of that knowledge.

6. To arrive at percepts in a minimum of time, with a minimum of effort, with a minimum of error, and with optimal use of evidence and knowledge, requires the possession and co-ordination of numerous processing skills.

Is Auditory Speech Perception Special?

We now turn to the secondary questions, "What is auditory speech perception and is it special?" To adapt the model just presented to a description of auditory speech perception actually requires little effort, as shown in Fig. 2. The sound source becomes speech movements which have been generated by the talker in order to represent language patterns. That apparently simple change, however, carries enormous implications. For example:

1. The percepts are no longer internal representations of sound-generating objects and events but internal representations of language patterns—phonemes, syllables, words, phrases, sentences, and narratives. Moreover, the words, phrases, sentences, and narratives carry meaning in relation to the physical and social worlds shared by talker and listener.

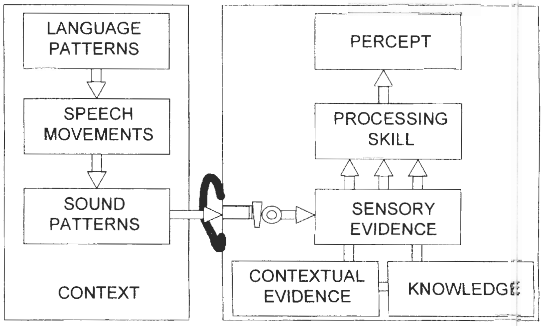


Fig. 2. The obvious difference between auditory perception and auditory speech perception is that the sound source becomes the speech movements of a talker. These movements are intended to represent language patterns. This simple change, however, has enormous implications for the nature of the context, the knowledge needed by the perceiver, and the skills that must be brought to bear on the interpretation of the evidence. Note that the percepts are no longer just of the sound source but of the underlying language patterns, the message encoded in those patterns, and the intent of the talker in expressing that message. It is the nature of the stimulus and its possible interpretations that make speech perception special.

2. The context now includes a language component. Speech sounds occur in the context of words which occur in the context of phrases, which occur in the context of sentences, which occur in the context of conversations, and so on.

3. The knowledge indicated by the box on the lower right must include the listener's linguistic knowledge. This has many components—phonetic, phonological, lexical, syntactic, semantic, socio-linguistic, and pragmatic.

4. The box labelled ''processing skill'' must now include skills related to the retrieval, management, and use of linguistic knowledge.

Thus, although auditory speech perception uses a general purpose auditory substrate, the nature of the stimulus requires special knowledge and skills. These are not specific to the auditory system. Moreover, they are presumably more extensive and more complex than those required for general auditory perception. The extent to which speech perception transcends general auditory perception becomes clear when we consider that speech perception can occur without hearing—as in speechreading.

How Does Auditory Perception Develop?

The development of auditory perception is typically studied, not via intervention, but by examining various aspects of audition as a function of age. The studies generally fall under one of four headings: (i) Anatomy and physiology, (ii) developmental studies of sensitivity to the differences among simple sound patterns; (iii) developmental studies of responses to complex non-speech sound patterns; (iv) developmental studies of responses to speech sounds.

1. *Physiology* (Salamy et al., 1994). The auditory system is complete and functional at birth. There is evidence from animal studies to suggest that neural connections may increase in density after birth but comparative data are not available for humans. There is human evidence, however, to show that the myelin sheaths that surround nerve fibres (and serve to speed the transmission of neural signals) continue to develop in humans after birth.

The available data indicate that myelination of the auditory nerve and brainstem are complete by around 6 months of age, but myelination of radiations from the brainstem to the auditory cortex continues until around 5 years of age. It is interesting to note, also, that myelination of the corpus callosum, which connects the right and left sides of the brain, continues until 15 to 20 years of age. Although the corpus callosum is not usually considered a part of the auditory system, the integration of information from the two hemispheres may well play a role in the auditory perception of spoken language. Recent research by Jerger et al. (1995), for example, has suggested that a breakdown of that integration contributes to the auditory speech perception problems of the elderly.

The data on myelination are nicely paralleled by the results of studies on electrophysiological responses to sound. Responses at the level of the auditory nerve reach adult levels of amplitude and latency by about 1 month of age. Later components of the auditory brainstem response are generally considered to be adult-like by around 1 year of age, although measurable changes occur after this. The middle latency responses which reflect activity at the level of the auditory cortex do not fully mature until 10 to 14 years of age. And P300, which is a response to overt awareness of change in the pattern of sound input, may not be fully mature until 15 to 20 years of age.

A relationship between surface recordings of electrical responses to sound and the myelination of nerve fibres is not surprising. The detection of those responses requires summation of many responses to single trials. That summation only occurs when there is synchrony between the sound stimulus and the electrical response. It is reasonable to assume that the increased transmission speed accompanying myelination will result in increased synchrony of electrical discharges.

The general conclusion to be drawn from this work is that the auditory system of the developing child is fairly complete but that its refinement continues throughout childhood and adolescence.

2. *Psychoacoustics*. Psychoacoustics is the study of the relationship between the sound stimulus and the resulting sound sensations. To study this relationship, psychoacousticians have developed a variety of tasks in which the response depends mainly on auditory evidence without confounding by auditory knowledge and processing skills, or by other factors such as memory, attention, motivation, and understanding of the task. Although the methods have been adapted for work with infants and young children, the elimination of factors other than sensory evidence is almost impossible. Nevertheless, a considerable body of useful data is being assembled, much of which is reviewed in a recent text edited by Werner & Rubel (1992).

In the intensity domain, behavioural threshold responses can be obtained within 15 dB of adult norms by 6 months of age. Threshold in noise, however, does not reach adult-like levels until 5 or 6 years of age. It is not clear how much of this delay might be caused by physiological immaturity of the cochlea, how much by physiological immaturity of the neural pathways, and how much by incomplete development of the necessary processing skills.

In the frequency domain, frequency resolution, as measured by psychoacoustic tuning curves, is adult-like in the low frequencies by 3 months of age and in the high frequencies by 6 months. Frequency discrimination, however, the demonstration of different responses to different frequencies, is about three times poorer than normal at 6 months. The discrepancy may well be caused by the more demanding nature of the discrimination task. Again, however, there is a discrepancy between results for low and high frequencies, suggesting that the use of temporal information may develop somewhat more rapidly than the use of cochlear place information.

In the time domain itself, considerable immaturity is observed in 6-month-old infants. Their responses to temporal gaps in a continuous stimulus is some 10 times poorer than that in adults. There are, as yet, insufficient data to show how much of this effect is psychoacoustic and how much the result of higher level processes.

As indicated earlier, these findings are difficult to interpret. Nevertheless, they are consistent with the physiological data in suggesting that the auditory system is well developed at birth but that refinement continues during childhood.

3. *Auditory processing*. Most of the developmental research on auditory processing has been carried out in the context of auditory speech processing and will be discussed in the next section. There has, however, been some non-speech research on pitch perception and localization (Bundy et al., 1982; Clarkson & Clifton, 1985; Muir et al., 1989). As with the psychoacoustic data, the results have indicated early appearance of sophisticated processing abilities and a considerable period of development before they reach adult-like levels.

At a theoretical level it is clear that most of the components of Fig. 1 must follow a developmental course. Much of the knowledge on which perceptual decisions are based can only be acquired through experience. Children must learn the templates, or most probable sound patterns, associated with possible events. They must also learn the range of permissible deviation from those templates and the probabilities associated with those deviations.

Similarly, auditory processing skill must contain components that depend on practice and experience. For example, selective attention, establishing appropriate decision criteria, modifying those criteria in response to contextual evidence, and maximizing processing speed while minimizing the probability of error.

Fig. 3 illustrates some of the learning that might be involved in the apparently simple task of differentiating two sound sources along a single dimension of sound sensation. The sources are labelled A and B. The curves represent the probability density distribution of each sound along a dimension of sound sensation (e.g., pitch or timbre). The peaks of these distributions may be thought of as templates for the two sources. Because their possible ranges of variation overlap, a decision criterion must be established. When the sound sensation is to the left of this criterion the percept will be of source A. When it is to the right, the percept will be of source B. The criterion can move but its optimal placement requires that the combined probability of mistaking A for B (the area labelled "misses") and B for A is as small as possible. Under the conditions assumed here, this minimum error occurs when the criterion is midway between the two templates. Note that at least five kinds of learning are implied in this simple illustration:

1. Learning the existence of the sources A and B.

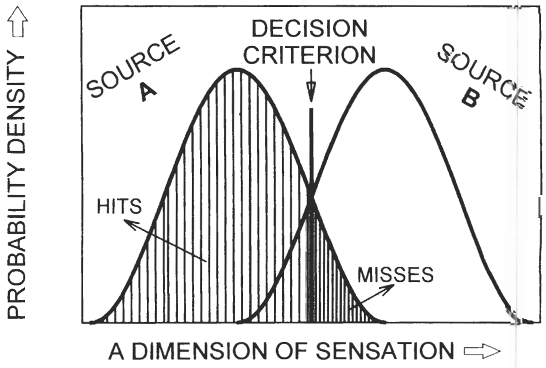


Fig. 3. This figure illustrates the complexity of a simple auditory discrimination task. Two sound sources, A and B, are to be identified from their representation along a single acoustic dimension. Although each source has a clearly defined acoustic template, there is a range of possible variation along the dimension of interest, represented here by Gaussian probability density functions. Moreover, the functions for the two sources overlap, leading to unavoidable errors. The perceiver needs to adopt a decision criterion such that the probability of mistaking A for B, and vice versa, is as small as possible. At least five factors are involved in learning this task, as outlined in the text.

2. Learning their auditory templates.

3. Learning the permissible range of deviation from those templates together with the associated probability density functions.

4. Establishing a decision criterion.

5. Adjusting that criterion for minimum error probability.

The developing child must also learn to accommodate differences in a priori probabilities between the two possible interpretations of sensory evidence, as illustrated in Fig. 4. If the a priori probability for the occurrence of source B is low, then an optimal decision strategy involves shifting the decision criterion in the direction of the template for B. This addition provides three more opportunities for learning:

6. Learning the differences in frequency of occurrence of the sources.

7. Learning how context affects probability of occurrence.

8. Learning how to adjust decision criteria accordingly.

While it is reasonable to assume that the bases of this learning are innate, it seems clear that its completion and refinement must be based on exposure to sounds and practice in their interpretation. It would be expected, therefore, to follow a developmental course.

4. *Auditory speech processing*: In contrast to the sparse data on the development of general auditory processing, there is considerable evidence about the development of auditory speech perception. Much of this evidence comes from the developmental language literature and relates to the child's knowledge. By 6 months of age, children demonstrate a beginning knowledge of the phonology of their native language. Refinement of that knowledge continues, however, possibly until puberty. Lexical knowledge is first evidenced between 1 and 1.5 years of age and grows rapidly between 2 and 4 years of age. It continues to expand, though at a lower rate, throughout life. Syntactic knowledge is first demonstrated around 1.5 to 2 years of age, develops rapidly until 4 years, and is virtually complete by 6 or 7 years. This knowledge not only provides the developing child with the possible interpretation of acoustic speech input but also renders the linguistic context increasingly useful in the decision-making process. There is also evidence of development of processing skills, selective attention, the extraction of speech information from noise, and the exploitation of linguistic context.

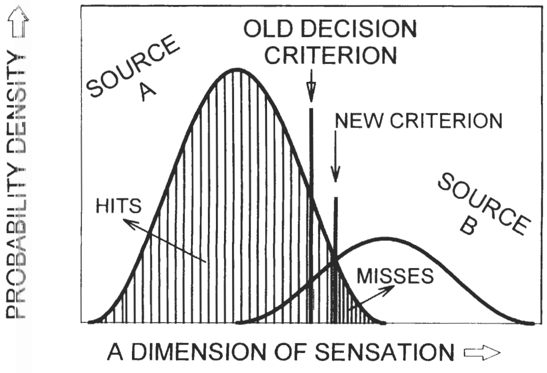


Fig. 4. The simple discrimination task of Fig. 3 becomes more complicated when the probabilities of occurrence of the two sources are unequal. Optimal performance now calls for a shift in decision criterion—analogous to the use of contextual information. The perceptual learner must now deal with three additional factors, if he or she is to take advantage of context and prior knowledge, as outlined in the text.

The work of Kuhl (1992) has provided valuable insights into the early appearance of phonological knowledge. At 3 months of age, children respond to acoustic changes in a vowel, even though these changes are not large enough to change the identity of the vowel. At 6 months they stop responding to those changes if the vowel is part of their native system. This finding indicates that by 6 months children are beginning to perceive a range of sounds as representing variations of a single language pattern. To use the language of the illustration in Fig. 3, they show that they have learned something about a source, its auditory template, and the permissible range of deviation from that template. This phenomenon has been demonstrated in children from English- and Swedish-speaking environments.

Laipply (1990) has studied phonetic contrast perception in children from age 5 through 12, by means of the THRIFT test (Boothroyd, 1995). Her results are shown in Fig. 5. The THRIFT test uses an oddity task in which the child must identify the position of the odd-man-out in a string of three syllables. The odd-man-out differs from the other two along a single phonologically significant dimension such as vowel height or initial consonant voicing. The stimuli are naturally produced and the phonetic context changes from trial to trial. The goal is to obtain a context-free estimate of the sensory evidence available to the child in a manner that is predictive of performance at the sentence level and that does not require reading skill, speech skills or advanced language knowledge (Boothroyd, 1995). The data in Fig. 5 show composite performance, averaged over several phonetic contrasts, as a function of age. Squares show results for auditory perception. Triangles show data for visual perception (i.e., speechreading). The solid lines show best fitting exponential growth functions. Several things should be noted:

1. By extrapolation, performance is at around chance levels for children in the 4 to 5 year range.

2. Performance improves rapidly between 5 and 7 years.

3. Performance continues to improve after 7 years—approaching an asymptote by around 12 years.

4. The data for auditory and visual perception parallel each other but, as expected, the visual asymptote is considerably lower.

Much of the inferior performance of the younger children in Laippley's study may be attributed to the fact that the three-interval oddity task is cognitively and attentionally demanding. Moreover, it is extremely boring and motivation is hard to sustain. Nevertheless, there was evidence from Laipply's data that the poorer performance of the younger children was specific to certain contrasts – especially consonant place. This finding strongly suggests a phonological component to the growth functions shown in Fig. 5.

This last conclusion is supported by some data from a study by Boothroyd in which phoneme and word recognition were measured in the context of CVC monosyllabic words in normally hearing children (Boothroyd, 1971). The children listened at a comfortable level, well above threshold. Fig. 6 shows means for three groups aged around 5.5 years, 7 years, and 9.5 years. Phoneme recognition rises from 93% to 98% during this period. Thus, although word repetition is a much easier task than oddity detection, the data showed improvement during the childhood years.

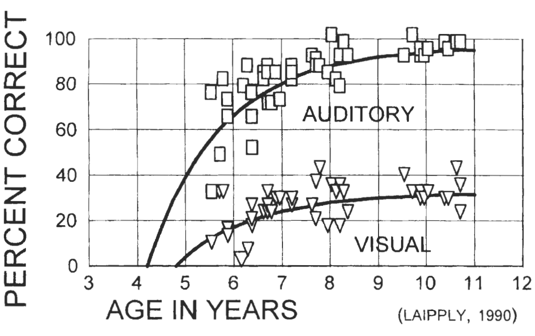


Fig. 5. Data from Laipply (1990) show age-related changes in performance on a three-interval forced-choice task of the perception of phonologically significant contrasts, presented in a varying phonetic context. Performance by hearing is much better than by speechreading, but the two show similar growth functions, approaching asymptotic performance around age 12.

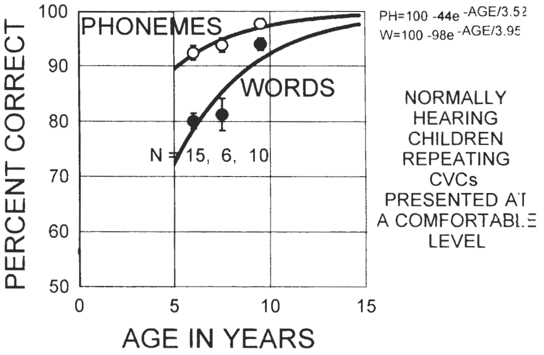


Fig. 6. Data from Boothroyd (1971) show evidence of age-related changes in performance on a task involving the repetition of consonant-vowel-consonant words in relative quiet. Data are shown in terms of percent recognition of both whole words, and their constituent phonemes. As with Laipply's data (Fig. 5), these results suggest that asymptotic performance is approached at around age 12.

Fig. 7 shows data on the same task as a function of signal-to-noise ratio in 5-year-old children and young adults. These data were collected as part of a study concerned with the use of lexical and sentential context in normally hearing pre-schoolers, young adults, and geriatrics (Nittrouer & Boothroyd, 1990). The vertical axis shows percent phonemes recognized in meaningful CVC monosyllables. The horizontal axis shows rms signal-to-noise ratio. The masking noise was pink noise. In both cases, the mean score improves with signal-to-noise ratio but it will be seen that the children perform

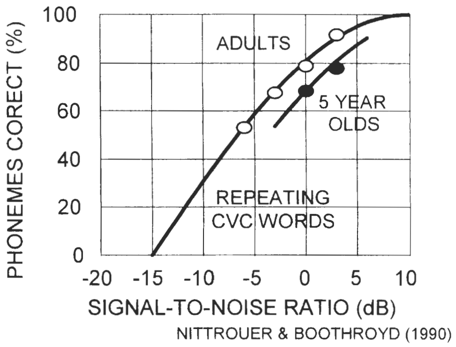
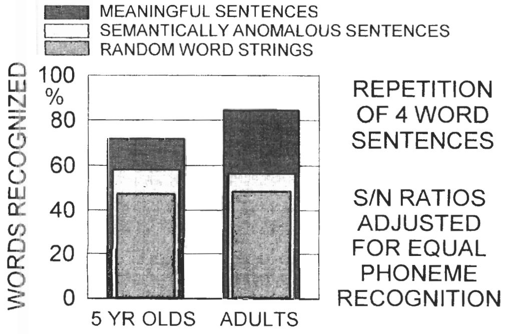


Fig. 7. Data from Nittrouer & Boothroyd (1990) show percent recognition of phonemes in consonant-vowel-consonant words as a function of signal-to-noise ratio. The results suggest that normally hearing 5-year-olds are at a 3 dB disadvantage compared with young adults.

less well than adults at each level. These data suggest a 3 dB disadvantage for the 5-year-olds. That is, they need 3 dB less noise in order to score as well as the young adults. Some of this effect may reflect the influence of lexical knowledge on performance. Other research, however, has shown that the phoneme score in this type of task is relatively insensitive to lexical knowledge. It is difficult to escape the conclusion that some of the difficulty experienced by the children is that they have not fully mastered the skills of separating the speech signal from the noise.

Fig. 8 shows sentence level data for the same group of subjects. The vertical axis shows percent words recognized in sentences. All the sentences were four words long and there were three types: Meaningful sentences such as ''most birds can fly''; semantically anomalous, but syntactically correct, sentences such as ''ducks eat old tape''; and random word strings such as ''run girls green like''. Data on the left are for 5-year-olds. Those on the right are for young adults. The signal-to-noise ratios differ by 3 dB for the two groups. This was done in order to match the mean phoneme recognition scores for the groups (see Fig. 7). It will be seen that the preschoolers and young adults do not differ in terms of recognition of random word strings or the additional benefit that comes with the introduction of the simple syntax in four-word sentences. The adults, however, show about twice as much improvement as the children when the sentences become semantically appropriate. The implication is that the children are less able to take advantage of semantic context in this task. This is not a surprising finding. It is a characteristic of young children that they don't know much. In fact they spend a lot of time listening to sentences that are syntactically appropriate but, to them, semantically anomalous.



NITTROUER & BOOTHROYD (1990)

Fig. 8. When 5-year-olds and young adults are compared in terms of the recognition of words in short sentences, they show little difference for random word strings and semantically anomalous (but syntactically appropriate) sentences. The adults, however, gain about twice as much benefit as the children when highly probable sentence meaning is added. Note that the adults and children were tested at signal-to-noise ratios differing by 3 dB in order to equate phoneme recognition (see Fig. 7).

In answer to the question about the developmental course of auditory perception it is clear that children perform less well than adults in terms of knowledge, skill, and the use of context. It is also clear that performance improves over time. The most interesting aspect of these findings, however, is that the presence of phonological knowledge and skills, though immature, can be demonstrated well within the first year of life.

What is the Role of Experience?

Returning to the models of auditory perception and auditory speech perception of Figs 1 and 2, it is clear that experience must play a key role in the development of the knowledge and skill. In the case of speech perception this experience includes all the communicative interactions that contribute to language development.

In contrast, it would seem that the amount of sensory evidence available to the listener depends only on the status of the peripheral hearing mechanism—and this is independent of experience. There are, however, data to suggest that sensory evidence depends not only on the integrity of the peripheral mechanism but also on interactions between peripheral and central mechanisms—and that experience can play a major role in the development of that interaction.

By way of illustration, consider the results of a recent experiment by Stanton & Harrison (1996). Newborn kittens were raised in the presence of a continuous 8 kHz tone until they were 3 months old. As adults, their auditory cortices were explored in terms of the spatial distribution of optimal responses to tones of various frequencies. It was found that the area devoted to the octave frequency band centred on 8 kHz was almost twice that of cats raised in a normal acoustic environment. This finding carries two important implications: (1) The spatial organization of the auditory cortex is influenced by the properties of the acoustic enviroment in which an infant is raised, and (2) it is not necessary for the sounds in that environment to have behavioural significance in order for them to influence development. (Presumably the kitten's allocation of additional cortical resources to a meaningless sound was based on the system's reasonable assumption that a sound's presence implied its potential importance.)

The finding is in keeping with the hypothesis that auditory experience plays a role in the development of an auditory system that is optimally organized for the generation of sensory evidence from acoustic inputs. It has considerable relevance to the issues of early amplification, auditory deprivation, and auditory acclimatization in hearing-impaired subjects.

In Summary

1. Auditory perception is the interpretation of sensory evidence, generated by sound; in terms of the source of that sound. It involves not just sensory evidence but also contextual evidence, knowledge, and skill.

2. Auditory speech perception is special because the source is language. Similarly, the context, knowledge, and skills involved in auditory speech perception have major linguistic components.

3. Infants demonstrate sophisticated auditory perception skills by 6 months of age, but refinement continues throughout childhood. Development is observed in such areas as contrast perception, phoneme and word recognition, perception in noise, and the use of context.

4. The role of experience in development is self-evident in terms of the knowledge and skills required for auditory perception—especially auditory speech perception.

5. There are animal data to suggest that experience may also be important in terms of organization of the auditory pathways for optimal generation of sensory evidence from sound patterns.

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References

Boothroyd A. Developmental factors in speech perception. Int Audiol 1971; 9: 30–8.

Boothroyd A. Speech perception tests and hearing-impaired children. In: Plant G, Spens KE, eds. Profound deafness and speech communication. London: Whurr Publishers, 1995; 345–71.

Bregman AS. Auditory scene analysis. Cambridge, MA: MIT Press, 1990.

Bundy RS, Colombo J, Singer J. Pitch perception in young infants. Dev Psychol 1982; 18: 10–4.

Clarkson MG, Clifton RK. Infant pitch perception: evidence for responding to pitch categories and the missing fundamental. J Acoust Soc Am 1985; 60: 863–9.

Jerger J, Alford B, Lew H, Rivera V, Chmeil R. Dichotic listening, event-related potentials, and interhemispheric transfer in the elderly. Ear Hear 1995; 16: 482–98.

Kuhl PK. Psychoacoustics and speech perception: internal standards, perceptual anchors, and prototypes. In: Werner LA, Rubel EW, eds. Developmental psychoacoustics. Washington, D.C.: APA, 1992.

Laipply EM. Chronological age effects on the audio/visual perception of phonologically significant speech feature contrasts. Unpublished Master's Thesis, University of Florida, Tampa, 1990.

McPhee JR, Van De Water T. Structural and functional development of the ear. In: Jahn AF, Santos Sacchi J, eds. Physiology of the ear. New York: Raven Press, 1988.

Muir DW, Clifton RK, Clarkson MG. The development of a human auditory localization response. Can J Psychol 1989; 43: 199–216.

Nittrouer S, Boothroyd A. Context effects in phoneme and word recognition by young children and older adults. J Acoust Soc Am 1990; 87: 2705–15.

Salamy A, Eggermont J, Eldredge L. Neuro development and applications in evoked auditory potentials. Boston, MA: Allyn & Bacon, 1994.

Stanton SG, Harrison RV. Abnormal cochleotopic organisation in the auditory cortex of cats reared in a frequency augmented environment. Auditory Neurosci 1996; 2: 97–107.

Werner LA, Rubel EW, eds. Developmental psychoacoustics. Washington, D.C.: APA, 1992.