# 2
# Behavioral Studies of Hearing Development

Lynne A. Werner and Lincoln Gray

## 1. Introduction

This chapter reviews progress that points to the exciting potential in studies of behavioral development. The goal is twofold: to review common trends in psychoacoustic data from different species of newborn vertebrates and to indicate the many interesting questions that remain to be answered. The purpose of the introduction is to state and to justify the assumptions that underlie that goal.[1]

## 1.1 What Does the Study of Auditory Behavioral Development Tell Us About the Development of Hearing?

### 1.1.1 Why Study Behavioral Development?

Hearing scientists generally agree on the importance of studying auditory behavior. Ultimately, hearing is only defined by the behavior of an organism. Psychoacoustics, in particular, is an important link among various aspects of hearing research, allowing comparison of humans and nonhumans and providing a link between cellular and behavioral changes (Brindley 1970; Werner 1992). From a clinical standpoint, behaviors define deafness and communicative disorders because behavioral problems are what lead people to seek professional assistance. And, of course, both psychoacoustic and clinical results are usually stable, showing little variability within and among individuals and across decades of investigation

[1] As used here, the terms "infant" and "child" refer only to humans. "Neonate," "newborns," and "birth" refer to all vertebrates. The terms "neonate" and "new-born" are intended to indicate that it has not been long since the subject was born. This could mean within the first postnatal year for humans but within a few days of hatching for a chick.

(Stevens and Newman 1936; Green 1976; Moore 1989). Such reliability is sometimes seen as the hallmark of "real science."

Hearing scientists have much greater difficulty in accepting the study of behavior as an approach to the study of development. There are at least two reasons for this difficulty. First, it is clear to all that differences between neonatal and mature responses to sound can stem from many sources. These include both sensory factors, representing primary sensory processes, and nonsensory factors such as attention or memory. In the view of many, nonsensory factors thus interfere with the isolation of the primary sensory-processing immaturities that limit true sensitivity during development. Because nonsensory factors can often not be controlled in immature organisms in this view, auditory behavior cannot provide much information about the development of hearing. Second, variability rather than stability seems to be the hallmark of developmental behavioral data. To some, this variability makes the techniques for studying the development of auditory behavior suspect. In any case, variability increases the difficulty of identifying developmental trends, leading to the conclusion that some other approach to the study of hearing development would be more useful. In the course of reviewing the literature on the development of auditory behavior, we hope to convince the reader that the contributions of nonsensory factors to age differences in auditory behavior and the variability associated with developmental behavioral data reflect important developmental processes that cannot be studied with nonbehavioral approaches.

All behavioral responses are the result of an interaction between sensory and nonsensory factors (Gray 1992b), even if it is difficult to determine their independent effects. Moreover, nonsensory factors limit sensitivity as much as sensory factors do under nearly all circumstances, even among mature listeners. In the unusual case of simple detections or discriminations by mature listeners, the effects of nonsensory factors may be minimized given the appropriate psychophysical technique and sufficient practice. Nonsensory factors become very important, however, under the complex and uncertain conditions in which organisms ordinarily listen (Green 1983; Hall, Haggard, and Fernandes 1984; Yost and Watson 1987; Neff and Callaghan 1988; Yost 1991). Sensitivity in such cases is limited not by primary sensory processing but by the attentional and memory processes that allow listeners to construct an auditory representation of the world. If age-related change in the behavioral response to all kinds of sounds reflects measurable effects of both sensory and nonsensory processes, the study of behavioral development provides a unique opportunity to understand hearing and its development.

An influential idea in the study of development has been that variability in developmental data reflects real variability in the developmental process rather than the effects of uncontrolled nuisance variables (Lerner, Perkins, and Jacobson 1993). For many characteristics, the end point of develop-ment for all individuals is the same: an efficient kidney or a finely tuned

basilar membrane. Variability in these characteristics is small when they are measured in mature individuals. If a characteristic is examined in a cross section taken at a given age during a period of development, however, variability will inevitably be high because individuals develop at somewhat different times and different rates. Such observations point to the importance of longitudinal studies but also suggest that variability is an important aspect of development. Several recent studies have shown that variability during development can actually be informative with respect to the mechanisms underlying sensory maturation (Werner, Folsom, and Mancl 1994; Peterzell, Werner, and Kaplan 1995). It is also important to note that variability is characteristic of complex and uncertain perception, even when listeners are highly trained with the most rigorous psychophysical techniques (e.g., Green 1983; Neff and Callaghan 1988). To the extent that immature nonsensory processes are important factors in neonatal audition, variability is to be expected. In sum, the variability that characterizes developmental behavioral data, although not always helpful, does not necessarily indicate a flaw in the behavioral approach.

Finally, it is important to recognize that perception of even simple sounds cannot be completely described in terms of detections and discriminations. Sounds also have attributes, perceived patterns or properties revealed by judgments (Stevens 1975). Pitch and loudness are examples of attributes. There is renewed interest in the dichotomy between attributes and detection or discrimination in mature hearing (Stebbins 1993). This is an interesting coincidence because the pattern of development of perceptual attributes is evidently different from that of detections and discriminations (e.g., Gray 1987a). In both mature and immature individuals, auditory behavior remains the most straightforward way to study perceptual attributes.

1.1.2 Comment on the Methods Used to Assess Auditory Behavior

Notwithstanding the convincing arguments for the theoretical importance of variability during development, the methods used to assess neonates' behavioral response to sound may still be insensitive or unreliable. Substantial progress has been made, however, on sensitive and unbiased methods for evaluating the hearing of neonates.

Infants make a variety of responses to sound (e.g., Watrous et al. 1975). These responses represent a general orientation to stimulation rather than a unique response to sound. Perhaps as a consequence, the responses tend to habituate rather quickly (e.g., Bridger 1961). To encourage infants to continue responding long enough to estimate a threshold, a conditioning paradigm is frequently used. The first successful technique of this type was visual reinforcement audiometry (Moore, Thompson, and Thompson 1975), so-called because a turn of the infant's head toward a sound source is reinforced by the presentation of an interesting visual display. This technique works well for infants between ~6 and 24 months of age. The observer-based psychoacoustic procedure (OPP; Olsho et al. 1987; Werner 1995) was developed to test infants younger than 6 months of age. In OPP, an observer judges on each trial whether or not a signal occurred on the basis of the infant's response. Both signal and no-signal trials are randomly presented, and the observer has no prior knowledge of trial type. If the observer is able to correctly identify a signal trial, the infant is visually reinforced for responding. Any of the many responses that an infant might make, changes in motor activity, eye movements, or head turns, can be conditioned and provide the basis of the observer's decision. Thus, even though young infants do not make directed, short-latency head turns to sound sources, they can be successfully tested with OPP. For the most part, OPP gives equivalent results to VRA among older infants (Olsho et al. 1987) and thus has the advantage that it can be applied to infants throughout the first postnatal year. Starting around 3 years of age, children are able to perform more or less standard psychophysical procedures, which are now usually disguised as video games (e.g., Wightman et al. 1989; Hall and Grose 1991).

An unbiased procedure for testing the hearing of newborn chicks has also been developed. Isolated chicks normally peep incessantly but momentarily delay their ongoing vocalizations when they hear a novel sound. Kerr, Ostapoff, and Rubel (1979) originally used this pause in peeping to study frequency generalization gradients in chicks. Gray (1987b) subsequently showed that the duration of silence during stimulus and control trials can be taken as a measure of confidence that a stimulus occurred. These "confidence ratings" can then be used to generate receiver operating characteristics (ROC), or isosensitivity, curves. Analysis of the properties of ROC derived from peep-suppression data show them to be a sensitive measure of auditory responsiveness. Classic psychophysical measures, such as thresholds and difference limens, can be rapidly and reliably measured in subjects between a few hours and 1 week of age (Gray and Rubel 1985a; Gray 1992b).

There is no way to know that a future methodological improvement will not yield lower thresholds. For that matter, we will never know the "left-hand limit" of adults' (let alone neonates') psychometric function. In the age ranges in which the development of auditory behavior has been studied most extensively, however, the consistency of recent records, obtained with somewhat different techniques, encourages the belief that the records reflect a stable process (Werner 1992). Moreover, the reasonable and consistent dependence of behavioral measures on the intensity, frequency, or azimuth of the stimulus suggests that it is hearing that is being measured (Gray 1992b; Werner 1992). In the final analysis, age-related change in the relationship between stimulus and response may well be more important to understanding auditory development than is the precise value of the threshold (Banks and Dannemiller 1987; Werner and Bargones 1992).

Currently available measurement techniques are clearly sensitive and reliable enough to describe such relationships.

## 1.2 What Do Comparisons Between Species Tell Us About the Development of Hearing?

There are clear pragmatic reasons for studying behavioral development in nonhuman species. Human infants are not ideal subjects for many studies. It is difficult and time consuming to attract large numbers of infants for extended psychoacoustic testing. In contrast, large numbers of, say, newly hatched chickens can easily be recruited to this task. Behavioral trends can be related more easily to physiological, anatomic, and biochemical data in nonhumans. The apparent effects of enriched, deprived, or traumatic early acoustic environments on human perceptual development (Besing, Koehnke, and Goulet 1993; Philbin, Balweg, and Gray 1994; Wilmington, Gray, and Jahrsdorfer 1994) can also be studied experimentally in nonhumans.

The theoretical justification for using comparisons between humans and nonhumans to understand auditory development is less apparent but still compelling. Virtually all land-dwelling vertebrates share the same fundamental problems in generating an auditory representation of the world. Parallel developmental trends in different species suggest general principles. These conservative trends likely reflect the most important determinants of perceptual development. Conversely, if differences between species can be related to the unique specializations of each species, then we glean important insight into how structural and functional characteristics are related.

Because the authors happen to study auditory behavior in humans and chickens, the review is biased toward these species. Several casual observations led to the expectation that comparisons between these species may be particularly interesting. The auditory system of chicks and humans is at a comparable stage, partially but not fully developed, at birth (Rubel 1978). Both species start hearing about two-thirds of the way through gestation (Jackson and Rubel 1978; Birnholz and Benaceraf 1983). Both species are highly responsive to naturalistic stimuli (DeCasper and Fifer 1980; Gottlieb 1985). Both chicks and infants fail to respond perfectly even to apparently audible sounds (Werner and Gillenwater 1990; Gray 1992a), and stimuli must be presented at appropriate times relative to the neonates' changing behavioral states to elicit a response (Wilson and Thompson 1984; Gray 1990a).

More important, the available data indicate that the normal development of human and nonhuman hearing is parallel in many ways. Furthermore, similar effects of abnormal experience have been identified in many species. These similarities, reviewed in Section 2, provide the strongest justification for pursuing comparisons between species as a means to understanding auditory development.

TABLE 2.1. Summary of studies of the development of auditory behavior.

| Behavior | Humans | Other mammals | Birds | Results |
|---|---|---|---|---|
| Intensity processing | | | | |
| Absolute sensitivity | 1–16 | 17–21 | 22–25 | * humans |
| Intensity discrimination | 5, 26–33 | | | ? nonhumans |
| Frequency Processing | | | | |
| Loudness and dynamic range | 34–40 | | 41 | ? |
| Frequency resolution | | | | |
| Critical ratio | 6, 42–44 | 45 | 46 | * humans |
| Critical band | 47 | | | ? nonhumans |
| Auditory filter width | 48–52 | 53 | | * |
| Frequency discrimination | 5, 27, 32, 54–59 | 60, 61 | | * |
| Frequency representation | | 62 | 63 | ? |
| Temporal Processing | | | | |
| Gap detection | 64–67 | | | ? |
| Amplitude modulation | 68, 69 | | | * humans ? nonhumans |
| Duration discrimination | 27, 70, 71 | | | ? |
| Temporal integration | 5, 72–75 | | | ? |
| Frequency modulation | 77, 78 | | 76 | * |
| Complex Sound Processing | | | | |
| Pitch | 79–82 | | | ? |
| Spectral shape discrimination, timbre | 83, 84 | | | ? |
| Comodulation masking release | 67, 85 | | | ? |
| Music | 86–110 | | | ? |
| Discrimination of species-typical vocal productions (e.g., speech) | See Table 2.2 | | 111–113 | * humans ? nonhumans |
| Cross-language perception | 114–123 | | | * |
| Localization and Binaural Processing | | | | |
| Masking level difference | 124–132 | | | ? humans |
| Location identification | 133–145 | 146–150 | 151, 152 | * humans * |
| Minimum audible angle | 137, 141, 153–158 | | | ? nonhumans * |
| Interaural time discrimination | 159–161 | | | * humans ? nonhumans ? |
| Interaural intensity discrimination | 159, 160 | | | ? |

(Continued)

TABLE 2.1. (Continued)

| Behavior | Humans | Other mammals | Birds | Results |
|---|---|---|---|---|
| Attention | | | | |
| Responsiveness and preference | 162–187 | 112, 113, | | * |
| Habituation | 207–220 | 188–206 | 221 | * |
| Distraction and selective attention | 222–232 | | 233, 234 | * |
| Representation | | | | |
| Categories | 235–249 | | | ? |
| Scales and perceptual maps | 250–252 | | 253–255 | * |

*Developmental trend is evident; ?, developmental trend is not clear. 1, Berg and Smith 1983; 2, Eisele, Berry, and Shriner 1975; 3, Elliott and Katz 1980; 4, Hoversten and Moncur 1969; 5, Maxon and Hochberg 1982; 6, Nozza and Wilson 1984; 7, Olsho et al. 1988; 8, Schneider, Trehub, and Bull, 1980; 9, Schneider et al. 1986; 10, Sinnott, Pisoni, and Aslin 1983; 11, Trehub, Schneider, and Endman 1980; 12, Trehub et al. 1988; 13, Weir 1976; 14, Weir 1979; 15, Werner and Gillenwater 1990; 16, Werner and Mancl 1993; 17, Ehret 1976; 18, Ehret and Romand 1981; 19, Pilz, Schnitzler, and Menne 1987; 20, Sheets, Dean, and Reiter 1988; 21, Zimmermann 1993; 22, Gray 1987b; 23, Gray 1992a; 24, Gray and Rubel 1985a; 25, Gray and Rubel 1985b; 26, Bull, Eilers, and Oller 1984; 27, Jensen and Neff 1993; 28, Moffitt 1973; 29, Schneider, Bull, and Trehub 1988; 30, Sinnott and Aslin 1985; 31, Steinschneider, Lipton, and Richmond 1966; 32, Stratton and Connolly 1973; 33, Tarquinio, Zelazo, and Weiss 1990; 34, Bartushuk 1964; 35, Bond and Stevens 1969; 36, Collins and Gescheider 1989; 37, Dorfman and Megling 1966; 38, Kawell, Kopun, and Stelmachowicz 1988; 39, MacPherson et al. 1991; 40, Stuart, Durieux-Smith, and Stenstrom 1991; 41, Gray and Rubel 1981; 42, Allen and Wightman 1994; 43, Schneider, Bull, and Trehub 1988; 44, Schneider, et al. 1989; 45, Ehret 1977; 46, Gray 1993a; 47, Schneider, Morrongiello, and Trehub 1990; 48, Allen et al. 1989; 49, Hall and Grose 1991; 50, Irwin, Stillman, and Schade 1986; 51, Olsho 1985; 52, Spetner and Olsho 1990; 53, Gray 1993b; 54, Leavitt et al. 1976; 55, Olsho et al. 1982a; 56, Olsho et al. 1982b; 57, Olsho 1984; 58, Olsho et al. 1987; 59, Olsho et al. 1982b; 60, Gray and Rubel 1985a; 61, Kerr, Ostapoff, and Rubel 1979; 62, Hyson and Rudy 1987; 63, Gray, unpublished data; 64, Irwin et al. 1985; 65, Werner et al. 1992; 66, Wightman et al. 1989; 67, Trehub, Schneider, and Henderson 1995; 68, Grose, Hall, and Gibbs 1993; 69, Hall and Grose 1994; 70, Elfenbein, Small, and Davis 1993; 71, Morrongiello and Trehub 1987; 72, Berg 1991; 73, Berg 1993; 74, Blumenthal, Avenando, and Berg 1987; 75, Thorpe and Schneider 1987; 76, Gray 1990b; 77, Aslin 1989; 78, Colombo and Horowitz 1986; 79, Bundy, Colombo, and Singer 1982; 80, Clarkson and Clifton 1985; 81, Clarkson and Clifton 1995; 82, Clarkson and Rogers 1995; 83, Trehub, Endman, and Thorpe 1990; 84, Clarkson, Clifton, and Perris 1988; 85, Veloso, Hall, and Grose 1990; 86, Drake and Gerard 1989; 87, Cohen, Thorpe, and Trehub 1987; 88, Krumhansl and Keil 1982; 89, Thorpe et al. 1988; 90, Trainor and Trehub 1992; 91, Trehub and Unyk 1992; 92, Trehub, Thorpe, and Trainor 1990; 93, Bartlett and Dowling 1980; 94, Chang and Trehub 1977; 95, Demany 1977; 96, Demany 1982; 97, Demany and Armand 1984; 98, Drake 1993; 99, Ferland and Mendelson 1989; 100, Juszczyk and Krumhansl 1993; 101, Lynch et al. 1990; 102, Morrongiello 1984; 103, Morrongiello, Endman, and Mendelson 1989; 104, Trainor and Trehub 1993; 105, Trehub 1989; 106, Trehub 1990; 107, Trehub, Bull, and Thorpe 1984; 108, Trehub, Thorpe, and Morrongiello 1987; 109, Trehub et al. 1986; 110, Trehub, Thorpe, and Morrongiello 1987; 111, Gray and Jahrsdoerfer 1986; 112, Pick et al. 1993; 113, Gottlieb 1974; 114, Dooling and Searcy 1980; 115, Best, McRoberts, and Sithole 1988; Eilers, Gavin, and Wilson 1979; Critique, Juszczyk, Shea, and Aslin 1984; Reply, Eilers, Gavin,

TABLE 2.1. (Continued)

and Wilson 1980; 116, Werker and Polka 1993; 117, Aslin et al. 1981; 118, Eilers, Gavin, and Oller 1982; Critique, Aslin and Pisoni 1980; Reply, Eilers et al. 1984b; 119, Lasky, Syrdal-Lasky, and Klein 1975; 120, Oller and Eilers 1983; 121, Streeter 1976; 122, Werker and Tees 1983; 123, Werker et al. 1981; 124, Werker and Tees 1984; 125, Hall and Derlacki 1988; 126, Hall, Grose, and Pillsbury 1990; 127, Hall and Grose 1990; 128, Moore, Hutchings, and Meyer 1991; 129, Nozza 1987; 130, Nozza, Wagner, and Crandell 1988; 131, Pillsbury, Grose, and Hall 1991; 132, Roush and Tait 1984; 133, Schneider, Bull, and Trehub 1988; 134, Clarkson, Clifton, and Morrongiello 1985; 135, Clifton, Morrongiello, and Dowd 1984; 136, Clifton et al. 1981; 137, Hillier, Hewitt, and Morrongiello 1992; 138, Litovsky and Macmillan 1994; 139, Litovsky and Clifton 1992; 140, Morrongiello and Clifton 1984; 141, Morrongiello, Hewitt, and Gotowiec 1991; 142, Morrongiello, Fenwick, and Chance 1990; 143, Morrongiello and Rocca 1987a; 144, Muir, Clifton, and Clarkson 1989; 145, Perris and Clifton 1988; 146, Wilmington, Gray, and Jahrsdoerfer, 1994; 147, Clements and Kelly 1978a; 148, Clements and Kelly 1978b; 149, Kelly and Potash 1986; 150, Kelly, Judge, and Fraser 1987; 151, Kelly 1986; 152, Knudsen, Knudsen, and Esterly 1982; 153, Knudsen, Esterly, and Knudsen 1984; 154, Ashmead, Clifton, and Perris 1987; 155, Ashmead et al. 1991; 156, Morrongiello 1988; 157, Morrongiello and Rocca 1987b; 158, Morrongiello and Rocca 1987c; 159, Morrongiello and Rocca 1990; 160, Ashmead et al. 1991; 161, Bundy 1980; 162, Kaga 1992; 163, Berg, Berg, and Graham 1971; 164, Clifton and Meyers 1969; 165, Ewing and Ewing 1944; 166, Heron and Jacobs 1969; 167, Leavitt et al. 1976; 168, Orchik and Rintelman 1978; 169, Rewey 1973; 170, Bohlin, Lindhagen, and Nagekull 1981; 171, Brown 1979; 172, Clarkson and Berg 1983; 173, Colombo 1985; 174, Colombo and Bundy 1981; 175, DeCasper and Fifer 1980; 176, DeCasper and Prescott 1984; 177, DeCasper and Spence 1986; 178, Fernald 1985; 179, Fernald and Kuhl 1987; 180, Flexer and Gans 1985; 181, Hutt et al. 1968; Critique, Bench 1973; Reply, Hutt 1973; 182, Johansson and Salmivalli 1983; 183, Mehler et al. 1978; 184, Mendel 1968; 185, Cooper and Aslin 1990; 186, Panneton and DeCasper 1984; 187, Segall 1972; 188, Standley and Madsen 1990; 189, Gottlieb 1971; 190, Gottlieb 1975a; 191, Gottlieb 1975b; 192, Gottlieb 1975c; 193, Gottlieb 1978; 194, Gottlieb 1979; 195, Gottlieb 1980a; 196, Gottlieb 1980b; 197, Gottlieb 1981; 198, Gottlieb 1982; 199, Gottlieb 1983; 200, Gottlieb 1984; 201, Gottlieb 1985; 202, Gottlieb 1987; 203, Gottlieb 1988; 204, Gottlieb 1991a; 205, Gray and Jahrsdoerfer 1986; 206, Miller and Gottlieb 1981; 207, Miller 1980; 208, Bartushuk 1962; 209, Berg 1972; 210, Brody, Zelazo, and Chaika 1984; 211, Clifton, Graham, and Hatton 1968; 212, Field et al. 1979; 213, Graham, Clifton, and Hatton 1968; 214, Hepper and Shahidullah 1992; 215, Kinney and Kagan 1976; 216, O'Connor 1980; 217, O'Connor, Cohen, and Parmalee 1984; 218, Segall 1972; 219, Tarquinio et al. 1991; 220, Zelazo, Brody, and Chaika 1984; 221, Zelazo et al. 1989; 222, Philbin, Balweg, and Gray 1994; 223, Bargones and Werner 1994; 224, Greenberg, Bray, and Beasley 1970; 225, Olsho 1985; 226, Pearson and Lane 1991; 227, Werner and Bargones 1991; 228, Doyle 1973; 229, Geffen and Sexton 1978; 230, Hagen 1967; 231, Maccoby and Konrad 1966; 232, Pearson and Lane 1991; 233, Hallahan, Kauffman, and Ball 1974; 234, Gray 1993b; 235, Gray 1993a; 236, Juszczyk and Thompson 1978; 237, Juszczyk, Copan, and Thompson 1978; 238, Ferland and Mendelson 1989; 239, Fodor, Garret, and Brill 1975; 240, Bertoncini et al. 1988; 241, Grieser and Kuhl 1989; 242, Hillenbrand 1983; 243, Hillenbrand 1984; Critique, Moroff 1985; Reply, Hillenbrand 1985; 244, Kuhl 1979; 245, Kuhl 1983; 246, Marean, Werner, and Kuhl 1992; 247, Miller et al. 1983; 248, Miller, Younger, and Morse 1982; 249, Morrongiello 1986; 250, Trehub and Thorpe 1989; 251, Demany and Armand 1984; 252, Gray 1991; 253, Kuhl et al. 1992; 254, Gray 1987a; 255, Gray 1991; 256, Schneider and Gray 1991.

## 2. Trends in Behavioral Development

The discussion that follows is organized around Table 2.1. This is our attempt to summarize the literature on the development of auditory behavior, a cross between Rubel (1978) and Fay (1988). Table 2.1 lists the major aspects of audition and the behavioral studies that have examined their development. Studies of humans, other mammals, and birds are listed separately. Table 1 also indicates, by empty cells, some potentially important abilities that have been measured in adults but not yet in neonates. At least two properties of this literature should be readily apparent. First, many more studies of behavioral development have been completed with humans than with any other species. This is a major limitation in our understanding of the general mechanisms underlying early development: there is basically no species for which detailed studies of behavior, physiology, and structure have been completed over the entire period of development. Second, many more developmental studies have been done in birds than in nonhuman mammals. As discussed in Section 1.2, there are several common characteristics of auditory development in humans and birds that suggest it is meaningful to compare these species. On the other hand, it would also be helpful to compare humans with other mammals, and additional work on behavioral development in nonhuman mammals is certainly needed.

In the Results column of Table 2.1, we have indicated whether the literature in this area presents to us a consistent picture of the course of development. In this context, we suggest that "a consistent picture" means that some similar developmental changes seem to have been observed. That a result is consistent does not mean that we know why or how the developmental trend occurs, only that an age-related change occurs or does not occur. A question mark is used to indicate that we do not believe that there are sufficient data at this time to make a statement about development or its course.

In the Sections 2.1–2.7, the trends (or lack of trends) summarized in Table 1 will be discussed. The intent is to describe the trends that have been demonstrated, to suggest mechanisms that could be responsible for these trends, and to point out issues that have yet to be resolved.

### 2.1 Intensity Processing

Four measures of intensity processing are included in Table 2.1: absolute sensitivity, intensity discrimination, loudness, and dynamic range. Of the four, absolute sensitivity is the only one that has been examined extensively and the only one that has been examined to any extent in nonhumans. Although absolute sensitivity is an important parameter describing any

sensory system, it is unfortunate that so little is known about the supra-threshold processing of intensity during development.

### 2.1.1 Absolute Sensitivity

Absolute thresholds are available for humans from the neonatal period through childhood and adolescence and into adulthood. A schematic illustrating the progression of absolute thresholds is shown in Figure 2.1. A few days after birth, humans tend to have thresholds that are 30–70 dB higher than those of adults (Weir 1976, 1979). The audibility curve is more or less flat at this age (Eisele, Berry, and Shriner 1975; Weir 1979). Adults' thresholds tend to get lower with increasing frequency, at least up to ~4 kHz, and as a result, neonates' thresholds are more mature at low than at high frequencies. Thresholds improve progressively during infancy. During the first 6 postnatal months, the improvement is greater at high than at low frequencies. Both 1 and 3 month olds still have more adultlike thresholds at lower frequencies (Olsho et al. 1988; Werner and Gillenwater 1990; Werner and Mancl 1993). By 6 months, thresholds above ~4 kHz are actually
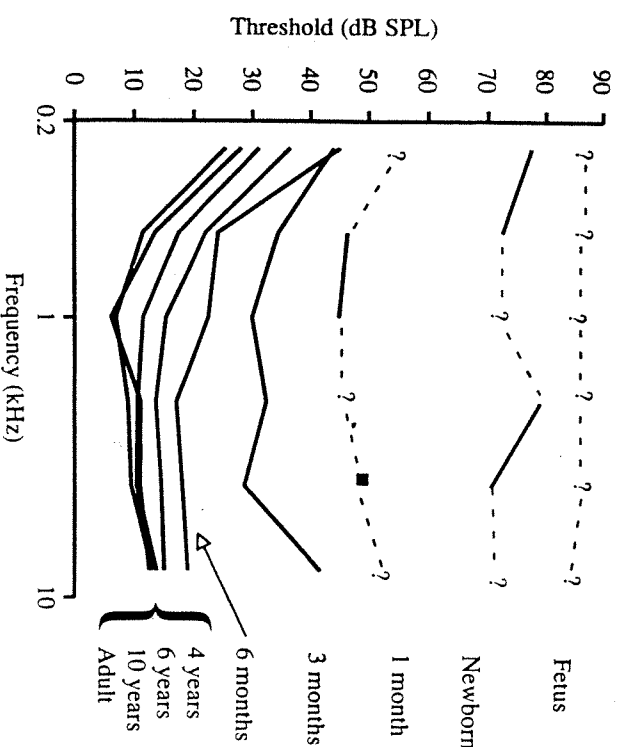


FIGURE 2.1. Hypothetical audibility curves during human auditory development (based on the results of several studies). Frequency regions where data are not available are plotted as *question marks and dashed lines; filled symbol and solid lines* are based on a summary of available data. SPL, sound pressure level. Adult data are taken from Olsho et al. (1988) with permission. From Werner and Marean 1996. Reprinted by permission of Westview Press.

Threshold (dB SPL)

Frequency (kHz)

Fetus
Newborn
1 month
3 months
6 months
4 years
6 years
10 years
Adult

closer to those of adults than are thresholds at lower frequencies (Trehub, Schneider, and Endman 1980; Nozza and Wilson 1984; Olsho et al. 1988). Schneider, Trehub, and Bull (1980), in fact, have shown that very high frequency thresholds (i.e., 10 and 19 kHz) approach adult values by 24 months of age. The "high-frequency-first" pattern of development continues through the remainder of childhood: mature thresholds are observed at progressively lower frequencies as a child grows, until ~10 years of age when thresholds are mature across the frequency range (Elliott and Katz 1980; Schneider et al. 1986; Trehub et al. 1988).

The data from nonhuman mammals are limited to a rather short period after the onset of hearing. Of course, the developmental period of other mammals is generally shorter than that of humans, but the fact remains that nonhuman threshold development has yet to be followed into adulthood by any investigator. Moreover, thresholds reported for young animals never reach the values reported in standard comparative psychophysical experiments with adults. Ehret (1976), for example, followed threshold development for mice between 11 and 19 days (summarized in Figure 2.2). Initially, thresholds are quite high and the audibility curve is relatively flat. With age, sensitivity progressively improves, with greater improvement occurring in the frequencies above 10 kHz. Around 18 postnatal days, the rate of improvement slows; however, at the oldest age tested by Ehret (1976), thresholds are still some 10 dB higher than those reported by Ehret (1974) for young adult mice.

A similar pattern of threshold development is reported for cats (Ehret and Romand 1981) and for chickens (Saunders and Salvi 1993; see Figure
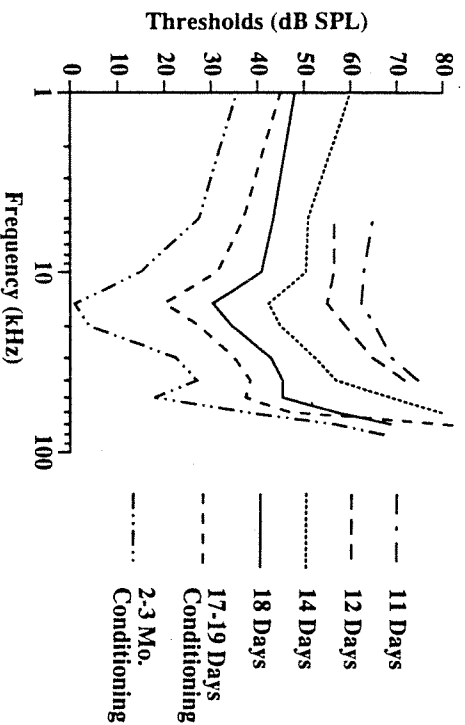


FIGURE 2.2. Audibility curves of mouse pups in days after the onset of response to sound. Thresholds for 11–18 days were based on an unconditioned response; thresholds for 17–19 days and 2–3 months were obtained in a conditioning procedure. From Ehret (1976) with permission.

2.3). The pattern reported for tree shrews (Zimmermann 1993) is slightly different in that the first change is increasing sensitivity to relatively low frequencies. But soon improvement at high frequencies accelerates, surpassing the initial gains at low frequencies to reach adult level first, leaving the final improvement at low frequencies. The progression reported for nonhumans is, thus, similar to that observed before 6 months postnatal age in humans.

One aspect of early development in nonhuman species that has not been observed in humans is the expansion of the frequency range over which a response can be observed. As Rubel (1978) noted, there is a general tendency for vertebrates to respond initially only to frequencies in the low or middle frequencies of the adult range of hearing. There is no reason to believe that this tendency is not present in humans, but, by most accounts, one would expect to see the clearest evidence for its existence during what is normally the human prenatal period. There are obvious difficulties in stimulus calibration and response recording in utero and other problems in the testing of prematurely born humans that have prevented determining whether humans also show an early frequency-range expansion.

There are basically two common accounts of the pattern of threshold development just described. The first and most prevalent is that improvement in behavioral thresholds is a direct reflection of cochlear development, which is said to be complete in mice, for example, at ~18 days postnatal age (see discussion by Walsh and McGee 1986). Any remaining difference between neonates and adults beyond the period of cochlear maturation is accounted for by unspecified nonsensory factors (Ehret 1976; Gray 1992b).
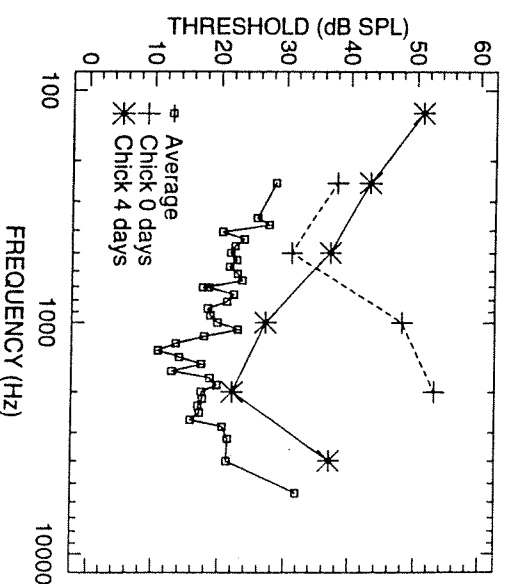


FIGURE 2.3. Audibility curves from 0-day-old, 4-day-old, and adult ("average") chickens. Chick data from Gray and Rubel (1985a); adult data from Saunders and Salvi (1993). Reprinted with permission.

his account is supported by observations that thresholds of single units from the cochlear nucleus to the auditory cortex follow the same course of development as those in the auditory nerve (Brugge, Reale, and Wilson 1988).

The second account of absolute threshold development holds that there are several functional improvements within the primary auditory system that are responsible for the age-related change in sensitivity. One of these accounts is the conductive apparatus of the ear. The resonant frequency of the external ear, for example, changes as the pinna and ear canal grow (Carlile 1991; Keefe et al. 1994). The acoustic power transmitted by the middle ear of chicks (Saunders et al. 1986), small mammals (e.g., Cohen et al. 1993), and humans (Keefe et al. 1993) continues to increase with age well beyond the time that the cochlea is considered mature. In humans, middle ear development could account for threshold development after ~6 years of age (Okabe et al. 1988). Other factors are less well established. Schneider et al. (1989), for example, have proposed that the auditory neural response grows at a slower rate with increasing intensity in infants and children and that the difference in response growth is responsible for immature thresholds. Shallow rate-intensity functions have been reported for nonhumans in the auditory nerve and brain stem just after the onset of cochlear response (Kanes and Walsh, Chapter 6). In support of this neural contribution to human threshold development, Schneider et al. (1989) cite the general correspondence between the developmental time courses of thresholds and of some evoked potential measurements (e.g., Eggermont 1985). In fact, Werner, Folsom, and Mancl (1993, 1994) recently demonstrated correlations between ABR (auditory brain stem response) threshold or interpeak latency and behavioral threshold in 3-month-old infants, but these correlations are no longer significant by 6 months of age. This pattern of results suggests that brain stem immaturity may contribute to immature thresholds early in infancy but that other factors must be responsible for immature thresholds after 6 months of age. At this point, there are no data that directly relate the immaturity of structures central to the auditory brain stem to threshold development.

Most investigators seem to agree that nonsensory processes such as attention or motivation make a contribution to early threshold development. Several attempts have been made to model the effects of a simple sort of inattentiveness (e.g., Green 1990; Viemeister and Schlauch 1992; Werner 1992; Wightman and Allen 1992). These models assume that neonates are inattentive on a certain proportion of trials and that they effectively guess whether or not a sound occurred on those trials. Although such models are consistent with the slope and upper asymptote of the psychometric function of young organisms (Gray 1992a; Allen and Wightman 1994; Bargones, Werner, and Marean 1995), among 6-month-old humans, for example, they can only account for ~3 dB of a 15-dB threshold immaturity. Other, more specific models of auditory attention, however, may be able to do a better job of explaining immature detection performance (see Section 2.2.1).

In summary, external and middle ear, cochlear, neural, and probably attentional development all contribute to absolute threshold development. In the period immediately after the onset of hearing, cochlear maturation may dominate the process, although middle ear development is probably also reflected in threshold development during this period (at least in animals that begin to hear in air). But thresholds continue to develop beyond the time when people consider the cochlea mature. The middle ear is not mature until almost adolescence in humans. Middle ear immaturity accounts for as much as 10 dB of the difference between young human infants and adults and ~3 dB to the threshold difference between 10 year olds and adults. Data from hamsters suggest that middle ear maturation contributes 10-15 dB to threshold development below 5,000 Hz (Relkin and Saunders 1980). Before 6 months of age in humans, it is clear that neural maturation plays a role in threshold development. We currently do not know what the neural structural and physiological correlates of threshold development are, whether neural development at more central parts of the auditory nervous system continues to contribute to threshold maturation in later development, or the extent to which neural contributions to threshold development will be demonstrable in nonhumans. Finally, the development of auditory attention may play a major role in threshold development. However, simple models of inattention have not succeeded in accounting for neonates' insensitivity to sound.

2.1.2 Intensity Discrimination

Although several studies have addressed the development of intensity discrimination in humans, nothing is known about its development in nonhumans. Human adults can discriminate about a 1-dB change in the intensity of a pure tone whether the tone is barely audible or at a high intensity (e.g., Viemeister 1988). Nonhuman adults generally discriminate changes on the order of a few decibels, with the best species and individuals approaching the performance of well-trained human listeners (summarized by Fay 1988).

The results of several studies of pure-tone intensity discrimination in developing humans are summarized in Figure 2.4. They suggest a definite improvement in intensity discrimination between infancy and middle childhood, but the amount of improvement and its timing are less certain. There is but one pure-tone data point for infants, that for 6 month olds tested by Sinnott and Aslin (1985). The infants are definitely and significantly poorer in intensity discrimination than adults tested in the same study. The data of Maxon and Hochberg (1982) from 4 year olds show the intensity DL (difference limen) improving from ~6 dB to ~3 dB between 6 months and 4 years of age. Thus there appears to be agreement that the intensity DL
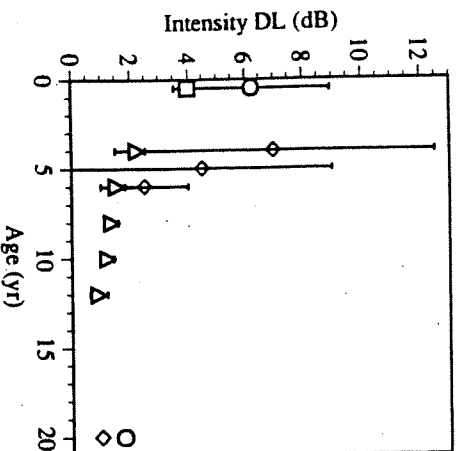
FIGURE 2.4. Intensity difference limens (DL; 10 log $[I + \Delta I]/I$) as a function of age from four studies. Error bars represent ±SE; in some cases the error bars are smaller than the plot symbols. *Squares:* Bull, Eilers, and Oller (1984); *circles:* Sinnott and Aslin (1985); *triangles:* Maxon and Hochberg (1982); *diamonds:* Jensen and Neff (1993). Data replotted with permission.

## 2.1.3 Loudness and Dynamic Range

The least studied aspects of the development of intensity coding are loudness and dynamic range. By loudness, we mean the perceived magnitude of sound; by dynamic range, we mean the range of intensities over which the perceived magnitude changes.

approaches adult values around 6 years of age in humans. What is in question is the amount and rate of improvement during infancy and early childhood, and, of course, given that this topic has not been explored in nonhumans, it is too early to conclude that the postnatal maturation of intensity discrimination constitutes a developmental trend.

A few studies have examined infants' ability to discriminate intensity changes in nonsense syllables or words and report lower intensity DLs for these stimuli than have been reported for pure tones (Bull, Eilers, and Oller 1984; Tarquinio, Zelazo, and Weiss 1990; see Figure 2.4). The difference is greater than would be expected to result from increasing the bandwidth of the stimulus (Raab and Goldberg 1975). The suggestion is that one might demonstrate better intensity discrimination, at least among infants, if one were to choose a more "attractive" stimulus (see Section 2.4.5). This would be another example of how nonsensory or attentional factors interact with sensory changes to determine the behavior of neonates.

Despite the fact that intensity discrimination seems to undergo maturation during infancy and early childhood and that intensity discrimination is related to the growth of loudness in some fashion (e.g., Schlauch and Wier 1987), what little evidence there is fails to show postnatal change in the perception of loudness. First, an early and unreplicated report by Bartushuk (1964) claimed that the degree to which a newborn infant's heart rate accelerated in response to a tone was a power function of the intensity of the tone with the same exponent as that seen for adults' numerical magnitude estimates (Stevens 1956). Second, Bond and Stevens (1969) reported that the growth of loudness was adultlike in 5-year-old children when it was measured by cross-modality matching of light brightness to tone loudness. More recently, Collins and Gescheider (1989) found that the growth of loudness in a group of children ranging from 4 to 7 years of age did not differ from that in adults. A notable feature of the Collins and Gescheider study is that they used different methods of scaling loudness, finding similar results in all cases.

The results of Gray and Rubel (1981) however, hint at early changes in the growth of loudness in chicks. Changing the intensity of a tone from 70 to 90 dB produced about the same increase in the duration of peep suppression to tones at three frequencies in 4-day-old chicks. In 1-day-old chicks, the same intensity change produced twice as great a response when the frequency was 900 Hz as when the frequency was higher or lower. The rapid rate of loudness growth for the 900-Hz tone is interesting for two reasons. First, it was not the case that 1-day-old infants' absolute thresholds were better at 900 Hz. Second, of the three frequencies tested, only 900 Hz is within the frequency range of the species' maternal assembly call. The implication is that attention and other nonsensory factors play a role in the development of loudness. We remind the reader who feels that such an effect does not truly reflect a change in *loudness* that attention does appear to influence loudness, measured in traditional psychophysical paradigms, among adult listeners (Schlauch 1992).

Dynamic range has not been assessed in neonates, so it is not clear whether it undergoes early development. A few studies have attempted to measure the upper limit of the dynamic range in children by estimating the intensity at which children report discomfort (Kawell, Kopun, and Stelmachowicz 1988; MacPherson et al. 1991). No differences between children and adults have been reported.

It should be evident that no clear developmental trend in loudness or dynamic range can be identified on the basis of the currently available information. All of the published human data are from listeners > 4 years of age. Thus recent methodological advances in the measurement of loudness in nonverbal organisms may have great impact when applied to this area.

## 2.2 Frequency Processing

Frequency processing holds a pivotal position in auditory theory and research, so it is not surprising that its development has been well studied. The major subdivisions of this topic are frequency resolution (the ability to selectively process a single component of a complex sound), frequency discrimination (the ability to distinguish between sounds of different frequency), and frequency representation (the stability of a given frequency's perceptual identity). These three processes are related through a common dependence on the width of the so-called auditory filter, the psychophysical reflection of the frequency analysis accomplished at the cochlea and maintained in some pathways throughout the auditory nervous system. However, each also depends on other mechanisms. For example, measures of frequency resolution are also influenced by intensity coding (e.g., Patterson 1974), and frequency discrimination also depends on the temporal frequency code (e.g., Moore 1974).

### 2.2.1 Frequency Resolution

Table 1 lists three general classes of psychophysical paradigms that are used to assess frequency resolution. The critical ratio is the signal-to-noise ratio at threshold for a narrow-band signal in a broadband background noise. By making some assumptions about the listener's detection criterion, or efficiency, it is possible to estimate the bandwidth of the auditory filter (Fletcher 1940). The accuracy of the estimate one obtains, of course, depends on the validity of the original assumptions. Estimates of the critical band are a more direct measure of the auditory filter width in that they estimate a bandwidth at which a change in perception (e.g., an increase in masked threshold) occurs. Finally, the family of paradigms that we have labeled "auditory filter width" includes techniques that are able to provide some information with respect to the shape of the auditory filter as well as to separate the effects of detection efficiency from those of filter width. These are the currently preferred techniques. A comparison among the results obtained with these three types of procedure provides an important lesson for those interested in the roles of sensory and nonsensory maturation in auditory development. Because nonsensory factors have different effects in different procedures, mistakes in interpretation are possible when a single method is considered. Furthermore, this is a case in which there are some clear trends across species.

Critical ratios have been estimated for infants and children, mouse pups, and chicks. For example, Schneider et al. (1989) followed the development of thresholds for octave-band noises masked by broad-band noise in infants, children, and young adults. At each of five octave-band center frequencies, masked thresholds improved by ~15 dB between 6 months and

adulthood, only approaching adult values at around 10 years of age. Ehret (1977) measured mouse pups' thresholds for tones masked by broad-band noise. Masked thresholds declined by ~20 dB across the frequency range of 2–80 kHz between 10 and 18 days of age. Gray (1993b) estimated chicks' thresholds for tones in broad-band noise; 1-day-old chicks had thresholds that were ~5 dB higher than those of 4-day-old chicks. Thus there is a consistent trend for masked thresholds, and thus critical ratios, to decline with age.

An important observation in these studies is that in many respects, neonates' masked thresholds are qualitatively adultlike. The shape of neonates' masked audibility curve is not dramatically different from that of adults, and increasing the masker level has the same effect on neonates' masked thresholds as it does on adults' (Ehret 1977; Schneider et al. 1989; Gray 1993b).

One interpretation of these findings is that the auditory filter is maturing, becoming increasingly narrow with age. There are good reasons, however, to question this interpretation. As Nozza and Wilson (1984) and Gray (1993b) noted, estimates of the bandwidth of the auditory filter based on critical ratios obtained from neonates are unreasonable. In chicks, for example, the estimated critical bandwidth is greater than the chicken's range of hearing! Furthermore, it is hard to reconcile neonates' abilities to discriminate among species-specific vocalizations, with a deficit in frequency resolution of the magnitude that their critical ratios suggest.

In fact, critical band and auditory filter width studies of neonates uniformly indicate that the width of the auditory filter is mature quite early in postnatal life. Olsho (1985) was the first to report that psychophysical tuning curves, the behavioral analog to single-unit rate-tuning curves, were adultlike in width by 6 months of age. Schneider, Morrongiello, and Trehub (1990) found that critical bandwidths were adultlike among 6-month-old infants. Although Spetner and Olsho (1990) found some immaturity of high-frequency filter widths among 3 month olds, that immaturity had disappeared by 6 months. Gray (1993a) reported that simultaneous masking patterns were adultlike in shape among 0-day-old chicks.

Although Irwin, Stillman, and Schade (1986) and Allen et al. (1989) found that filter widths estimated with notched noise maskers were broader among 4 to 6-year-old children, Hall and Grose (1991) showed that in a slightly different procedure, 4 year olds had mature auditory filter widths. Their data suggest that young children's decision strategies were responsible for the immature filter widths in previous studies. Specifically, it appears that 4 year olds only attempt to detect relatively loud tones.

The most parsimonious explanation of this body of results, then, is that auditory filter widths mature early in postnatal life. It is worth noting that the physiological measures of frequency resolution that have been examined to date (otoacoustic emissions, Bargones and Burns 1988; ABR, Folsom and Wynne 1987; Abdala and Folsom 1995) also appear to mature by 6

months of age. Single-unit recordings (Manley et al. 1991) and compound action potentials in chicks (e.g., Rebillard and Rubel 1981) also indicate early maturation of frequency resolution. Under current models of frequency resolution (e.g., Patterson et al. 1982), if the filter width remains constant, then elevated masked thresholds are accounted for by the efficiency of the filter or the signal-to-noise ratio required for detection.

There are several possible explanations for neonates' inefficiency. First, the neural response to the signal may be highly variable during development, making it more difficult for young listeners to distinguish signal from noise (Schneider et al. 1989). Higher neonatal intensity DLs (Maxon and Hochberg 1982; Sinnott and Aslin 1985; Jensen and Neff 1993) and higher variability in neonatal psychoacoustic data (Werner and Bargones 1991; Gray 1993b) are consistent with this hypothesis. Second, the neural response to the signal may grow at a slower rate during development so that a higher intensity is required to achieve a given response magnitude. That infants and young children have higher intensity DLs than adults is also consistent with this alternative, but observations that the growth in loudness is adultlike in young children are inconsistent with it (e.g., Collins and Gescheider 1989; see Section 2.1.3). Physiological data from nonhumans indicate that both response variability and shallow response growth characterize the immature auditory nervous system (Sanes and Walsh, Chapter 6).

It is also possible that the immaturity is the way that infants and children use the information provided by the sensory system. As is the case for absolute sensitivity, however, only a small part of the age difference in masked threshold can be accounted for by assuming that the neonate simply tunes out and guesses on some trials (see Section 2.1.1). Another notion about early auditory attention begins with the observation that adults selectively monitor the auditory filter centered on the signal frequency when they are detecting a tone in noise (e.g., Greenberg and Larkin 1968). If listeners monitor the wrong filter or multiple filters, masked threshold will increase by as much as 7 or 8 dB depending on the assumptions (e.g., Dai, Scharf and Buus 1991). This effect is not hard to understand: monitoring filters beside the one with the signal in it adds noise to the observation. At least one study suggests that 6-year-old children can selectively monitor the filter centered on the signal frequency (Greenberg, Bray and Beasley 1970). Six-month-old infants do not appear to be selective in the filter that they monitor (Bargones and Werner 1994), and they can readily be distracted from the signal by energy in remote spectral regions (Werner and Bargones 1991). These results suggest that the development of listening strategies contributes to the development of masked thresholds after ~6 months of age in humans. To the extent that similar patterns of development are observed in other species (as in Gray 1993a), the same mechanism may be involved.

2.2.2 Frequency Discrimination

Frequency discrimination is believed to depend on auditory filter width at high frequencies but on a temporal frequency code, or phase locking, at low frequencies (e.g., Moore 1974; Freyman and Nelson 1986). Nonuniformity in the development of frequency discrimination across frequencies could mean that frequency resolution and temporal frequency coding develop along different courses.

There appear to be two phases in the development of frequency discrimination (Figure 2.5). Early in the postnatal period, neonates are rather poor at frequency discrimination, but they are particularly poor at high frequencies. For example, Olsho, Koch, & Halpin (1987) found that 3-month-old
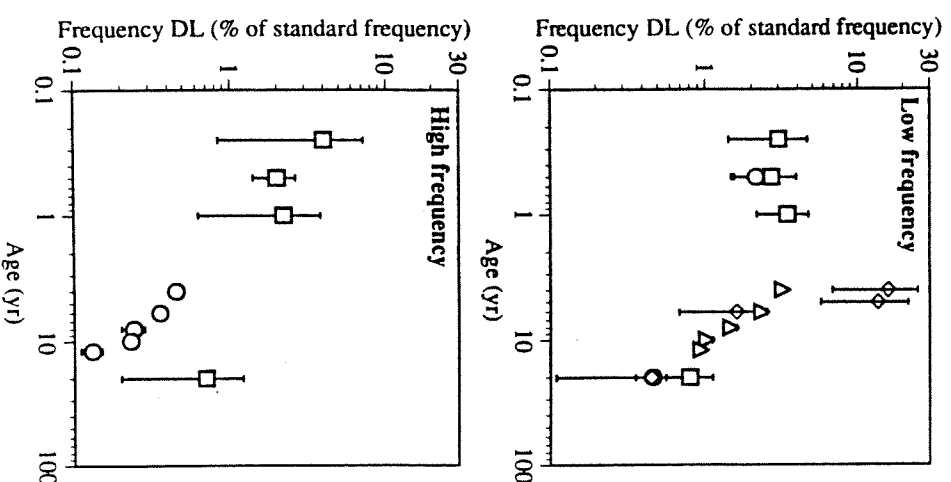


FIGURE 2.5. Frequency DL as a function of age from four studies. Error bars represent ±SE; in some cases, the error bars are smaller than the plot symbols. Top panel shows results for standard frequencies of 440 Hz (Jensen and Neff 1993; *diamonds*), 500 Hz (Olsho et al. 1987; *squares*; Maxon and Hochberg 1982; *triangles*), and 1,000 Hz (Sinnott and Aslin 1985; *circles*). Bottom panel shows results at a standard frequency of 4,000 Hz (Olsho et al. 1987; *squares*; Maxon and Hochberg 1982; *circles*). Data used with permission.

infants could discriminate a 3% change in frequency at 500 Hz but that they needed more than a 4% change to discriminate between tones around 4,000 Hz. By 6 months of age, frequency DLs at 500 Hz had decreased very little, but those at 4,000 Hz had decreased to ~2%. In fact, high-frequency DLs have been reported to be adultlike by 6 months (Olsho 1984; Olsho, Koch, & Halpin 1987). Maxon and Hochberg (1982) also found that 4 year olds could discriminate changes well under 1% at 4,000 Hz, comparable to adult performance. Similarly, Gray and Rubel (1985b) reported a greater improvement in frequency discrimination at 2,800 Hz than at either 400 or 800 Hz between 1 and 4 days of age in chicks. Thus this initial phase is characterized by immature frequency DLs, but rapid improvement in high-frequency discrimination.

The second phase of development may continue until 8 or 10 years of age in humans, but it is not clear whether or when it occurs in nonhumans. During this period, the low-frequency DL progressively improves to adult values. Several studies have reported that the frequency DL at 500 or 1,000 Hz, for example, is ~2-3% among 6-month-old infants but <1% among adults tested in a similar procedure (Olsho 1984; Sinnott and Aslin 1985; Olsho, Koch & Halpin 1987). Maxon and Hochberg (1982) reported that between 4 and 10 years of age, frequency DLs decrease from 3 to 1% at 500 Hz and from 1 to 0.4% at 1,000 Hz. Jensen and Neff (1993) found that frequency DLs at 440 Hz declined from an average of 70 Hz, or ~16%, at 4 years to an average of ~5 Hz, or just over 1% and still not quite adultlike, at 6 years. Although there is, again, some inconsistency in the precise value of the frequency DL, and when it improves, the pattern in humans is nonetheless consistent with the notion that high-frequency discrimination approaches maturity early but that low-frequency discrimination continues to develop well into childhood. This pattern is evident even when the tones are presented at equal sensation level (SL) for each subject and over a range of intensities (Maxon and Hochberg 1982; Olsho et al. 1987).

Again, there are several explanations for this pattern of development, although as yet none is widely accepted. The nonsensory hypotheses have focused on the changes in low-frequency DLs after 6 months of age. They are based on the idea that if low-frequency discrimination makes greater cognitive demands on a listener than does high-frequency discrimination, then infants and children may be especially handicapped at these frequencies because of cognitive immaturities. Olsho, Koch, & Carter (1988) explored the possibility that poor low-frequency discrimination resulted from a differential requirement for training at low frequencies, as suggested by a comparison between little-trained (Harris 1952) and well-trained listeners (Wier, Jesteadt and Green 1977). For some adults, Olsho et al. (1988) found that training effects were more pronounced at low frequencies, but a reanalysis of Olsho's (1984) infant frequency DLs suggested that training effects could not entirely account for the age differences observed in the latter study.

Sensory explanations have also been advanced. Werner (1992) suggested that the development of frequency discrimination reflected differential rates of development in frequency resolution and in temporal frequency coding, consistent with models of mature frequency discrimination. Werner noted that the improvement observed in high-frequency discrimination in the early postnatal months coincides with the final phase of maturation in frequency resolution at high frequencies (Spetner and Olsho 1990). There is evidence that phase locking is a rather late developing capacity in other mammals (Kettner, Feng and Brugge 1985), and there is one electrophysiological study suggesting that phase locking is immature in 1-month-old infants (Levi, Folsom, and Dobie 1993). These studies are consistent with the hypothesis that the maturation of phase locking is responsible for the late development of low-frequency discrimination, but further study of the development of temporal frequency coding is clearly needed.

2.2.3 Frequency Representation

One of the most interesting discoveries about audition in recent years was that the cochlear tonotopic map changes during development (Lippe and Rübsamen, Chapter 5). Ryals and Rubel (1985) and Lippe and Rubel (1985) presented data from chickens consistent with the hypothesis that a given cochlear position codes progressively higher frequencies with increasing age. Subsequently, this basic result has been confirmed and refined by observations in a variety of mammals (e.g., Arjmand, Harris, and Dallos 1988; Robertson and Irvine 1989; Rübsamen, Neuweiler, and Marimuthu 1989; Sanes, Merickel, and Rubel 1989).

It would be logical to ask how this change in tonotopy might be reflected in behavior during development. There is no direct evidence that the processes underlying the shift are also responsible for improved high-frequency sensitivity and frequency resolution in the early postnatal period. Hyson and Rudy (1987), however, demonstrated that the so-called place-code shift could have a direct impact on perception. They conditioned 15-day-old rat pups to suppress activity in response to an 8-kHz pure tone. Immediately after this training, the rat pups suppressed activity when they heard the 8-kHz tone but not when they heard tones of other frequencies. Three days later, Hyson and Rudy reexamined the pups' responses to tones of various frequencies. This time the pups suppressed activity when they heard a 12-kHz tone but not when they heard the 8-kHz tone on which they had originally been trained. This suggests not only that the tonotopic map had changed but also that, at these frequencies, the code for frequency among rat pups is based on the place in the nervous system that responds to the stimulus.

Other implications of the place-code shift have yet to be explored. For example, how is early experience with sound translated into later behavior, given this change in the organization of the auditory nervous system? This area is one of the potentially fascinating areas of behavioral development.

## 2.3 Temporal Processing

Many auditory capacities depend on accurate temporal coding, including localization, pitch perception, and sound-source segregation. Two different categories of neural information fall under the rubric of "temporal processing," and the distinction will become important to the discussion of the mechanisms underlying its development. First, for low frequencies, the input to the auditory nervous system is phase locked, and the timing of action potentials provides information about the frequency of the stimulus. Second, at all frequencies, auditory nerve responses are also phase locked to any amplitude modulation of the stimulus (e.g., Wang and Sachs 1992). In jargon, we would say that the phase-locked response to the carrier frequency encodes the fine structure of the stimulus, whereas the phase-locked response to the modulation frequency encodes the amplitude envelope.

All of the behavioral studies of auditory temporal development have examined the development of envelope coding. The data are few but are in agreement that substantial improvement occurs in envelope coding with age, at least in humans. The question of underlying mechanisms has not been answered satisfactorily, and the answer may prove to be complicated.

### 2.3.1 Envelope Processing: Gap Detection, Amplitude Modulation, and Duration Discrimination

Measures of temporal resolution are intended to determine the smallest change in the amplitude envelope that a listener can detect. In the case of gap detection, the task is to identify a brief interruption in the stimulus; the shortest detectable gap is called the gap threshold. The studies that have examined gap thresholds in infants and children have all reported age differences. Werner et al. (1992) found that 3-, 6-, and 12-month-old infants' gap thresholds were ~60 ms, in contrast to adults' gap thresholds of ~5 ms. There was little difference among infants at different ages, although variability was high among 12 month olds and some of these infants had gap thresholds that were close to adult values. Gray (unpublished observations) found only marginal responsiveness to gaps in white noise as long as 40 ms in chicks, suggesting that poor temporal resolution will be found in neonates of other species.

The results of Irwin et al. (1985) and Wightman et al. (1989) are in agreement insofar as they found that children also had immature gap thresholds. They disagree on the age at which gap thresholds mature: Irwin et al. (1985) found that gap threshold was not mature until 10–12 years, whereas Wightman et al. (1989) obtained adultlike gap thresholds among 5–7 year olds. Both Werner et al. (1992) and Wightman et al. (1989) found that the effect of stimulus frequency on gap detection was qualitatively similar at all ages; Irwin et al. (1985) found that there were greater gap detection immaturities among 6 year olds for a low frequency.

The convergence of results from different paradigms is an important tool in understanding auditory development, particularly when different paradigms may involve differential contributions of sensory and nonsensory mechanisms (see Section 2.2.1; Hall and Grose 1991). Because gap detection is a special case of amplitude modulation detection, one would predict from the gap detection results that infants and children would have difficulty processing amplitude modulation. Grose, Hall, and Gibbs (1993) have examined sensitivity to amplitude modulation in 4- to 10-year-old children using a masking-period pattern paradigm. Listeners detected a 500- or a 2,000-Hz tone when it was masked by a band-pass noise that was either modulated by a 10-Hz square wave or unmodulated. The difference between the detection thresholds for the tone in the modulated and unmodulated masking conditions is the measure of temporal resolution. All of the children had poorer temporal resolution than the adults at 500 Hz; at 2,000 Hz, the 4–5 year olds were poorer than adults. Hall and Grose (1994) subsequently examined the detection of amplitude modulation in a broadband noise. They found that 4–5 year olds required a greater modulation depth to detect modulation than adults did but that the effects of modulation rate were similar for children and adults. The latter result indicates that it is not temporal resolution per se but the representation of the intensity change that makes it difficult for infants and young children to detect changes in the amplitude envelope.

Duration discrimination has also been reported to undergo considerable development in the human postnatal period. Morrongiello and Trehub (1987) reported that 6 month olds responded to a change in the duration of a repeated 200-ms noise burst only when the duration changed by ~20 ms; 5 year olds responded when the duration changed by ~15 ms; adults responded to changes as small as 10 ms. Two other studies of duration discrimination among children agree that 4 year olds are immature on this measure, whereas by 6 years many children perform in an adultlike manner (Elfenbein, Small, and Davis 1993; Jensen and Neff 1993). Whether there are frequency gradients in the development of duration discrimination has not been explored.

It is difficult to speculate about the mechanisms that are responsible for age-related change in amplitude-envelope processing. First, all we know about this aspect of development is that infants are worse than adults. Second, there is no corresponding information on other species. Third, the processes underlying amplitude-envelope coding have not been well studied developmentally in any species.

At least at the levels of the auditory nerve and cochlear nucleus, phase locking to frequencies as low as those present in amplitude envelopes appears to be developed rather early (Kettner, Feng, and Brugge 1985). One electrophysiological study of 1-month-old humans indicates immaturity in the processing of amplitude modulation (Levi, Folsom, and Dobie 1993). A recent study by Trehub, Schneider, and Henderson (1995) reports that gap detection immaturities among 6 year olds for a low frequency.

detection performance is better, if not adultlike, when infants detect gaps between two tone pips than has been reported for continuous noise. Trehub et al. suggest that the difference results from a greater susceptibility to adaptation in younger listeners. This suggestion is consistent with the results of some evoked-potential studies (e.g., Lasky 1984; Donaldson and Rubel 1990) and with the results of one behavioral study of forward masking in infants (Werner 1996).

Whenever the data indicate a simple effect of age on performance, it is difficult to separate the development of sensory processes from that of nonsensory processes. In the case of temporal resolution, the issue has yet to be addressed directly. However, there are models of mature temporal processing that posit an explicit role for higher order mechanisms (e.g., Jones and Boltz 1989; Viemeister and Wakefield 1991; see Section 2.3.2), and these could provide a starting point.

### 2.3.2 Temporal Integration

Traditionally, measures such as gap detection have been described as measures of the minimum integration time of the auditory system, whereas temporal-integration measures address the maximum integration time of the system (Green 1985). The typical temporal-integration experiment estimates detection threshold as a function of stimulus duration; the typical result for mature listeners is that threshold improves with duration at a rate of nearly 10 dB per decade up to ~200–300 ms (e.g., Watson and Gengel 1969). The exact value of the time constant of integration depends on several factors (reviewed by Gelfand 1990).

There is a clear trend in the development of temporal integration: compared with adults, neonates' integration improves at a faster rate with increasing duration and continues to improve to longer durations. Thorpe and Schneider (1987) first reported this tendency for 6 month olds detecting a 4-kHz octave-band noise, and Gray (1990b) made the same observation for 1-day-old chicks. Blumenthal, Avenando, and Berg (1987), studying newborn infants, Berg (1991), studying 6 month olds, and Werner and Marean (1991), studying 3 and 6 month olds, concur. Maxon and Hochberg (1982) are the only investigators to have examined temporal integration in older children; they observed little change between 4 and 12 years, consistent with the idea that temporal integration is mature by this time.[2] Some recent findings by Berg (1991, 1993) indicate that the slope of infants' temporal-integration function also depends on frequency, bandwidth, and background noise in a complex way. These results will have to be taken into account by any model that accounts for the development of temporal integration.

[2]Maxon and Hochberg (1982) did not test adult listeners and their results are a little different from what one might expect of a mature well-trained listener. However, these minor differences between studies and laboratories are difficult to interpret.

Some models of mature temporal integration hold that there are auditory channels with different time constants and that a listener selects a channel depending on the requirements of the task at hand (e.g., Penner 1978; Green 1985). This idea, along with limited physiological observations of mature auditory systems (Gersuni, Baru, and Hutchinson-Clutter 1971), have led some to suggest that channels that process long-duration stimuli mature before those that process transient stimuli (e.g., Berg 1991), resulting in the steeper temporal-integration function in neonates. This is consistent with data from chicks (Gray 1990b).

A sensory explanation of the age-related change in the slope of the temporal integration function that has not been considered in the behavioral-development literature is based on age differences in the growth of neural excitation with increases in intensity. As Fay and Coombs (1983) point out, if excitation grows at a slower rate with increases in intensity, then the temporal-integration function will be steeper. It has been suggested that such a reduced rate of excitation growth is responsible for age-related improvements in absolute thresholds, masked thresholds, and intensity discrimination (e.g., Schneider et al. 1989). There are data suggesting that auditory nerve and brain stem rate-intensity functions steepen just after the onset of cochlear response for nonhumans (Sanes and Walsh, Chapter 6) and during early human infancy (Cornacchia, Martini, and Morra 1983; Durieux-Smith et al. 1985).

Another possibility is suggested by the "multiple-looks" model of temporal processing of Viemeister and Wakefield (1991), which posits two stages of temporal processing. The first stage is an integrator with a time constant similar to that estimated as the minimum time constant in gap detection or amplitude modulation detection experiments. This is followed by a memory-like stage in which the short "looks" provided by the integrator can be accumulated and combined in an intelligent fashion to form the basis of a detection decision. In this model, threshold would improve for longer duration stimuli because the larger the number of "looks," the greater the probability that the detection criterion will be exceeded. One hypothesis with respect to the development of temporal processing is that the short time-constant integrator matures early, how early is not clear, but that neonates do not combine information over time as adults do. This model could also account for the fact that measures like gap detection seem to take longer to mature than measures of temporal integration: even if the integrator provides the same input to the decision process, some decision strategies may be easier than others.

### 2.3.3 Frequency Modulation

Frequency modulation is the oddball in this section because it refers to changes in a sound's frequency, rather than intensity, with time. The perception of frequency modulation has also not been widely studied in

mature listeners (see recent review by Moore and Sek 1992) despite the fact that aspects of frequency modulation appear to be important cues to the discrimination and identification of many species-specific vocalizations (e.g., Gottlieb 1985). Because of neonates' apparently precocious ability to perceive species-specific vocalizations and because in at least one species determining neonates' preference for the vocalizations of their own species, we include two studies that have systematically studied it during development in Table 2.1. Colombo and Horowitz (1986) showed that 4-month-old infants could discriminate between two tones that were frequency modulated to different extents. The infants did not show more of a response to one sweep than the other, a fact that has some significance for understanding an infant's preference for certain types of speech (e.g., Fernald and Kuhl 1987; see Section 2.6.1). Aslin (1989) conducted several experiments addressing 6 month olds' processing of frequency modulation of a 1-kHz tone, with a view toward understanding how infants of this age may process the frequency transitions characteristic of speech sounds. The major findings of this investigation were that (1) 6 month olds do process the spectral change occurring during the frequency transition; (2) 6 month olds require larger transitions to detect a frequency change than adults do; and (3) changes in the transition, such as changing its duration or appending it to a steady-state tone affect 6-month-olds' and adults' detection of transitions in much the same way. Thus the current data suggest that infants are able to process frequency modulation in some respects as adults do.

## 2.4 Complex Sound Processing

There are many reasons why the development of complex sound processing is of interest. All other motivations aside, it is of interest to understand complex perception because that is the perceptual activity in which we are most frequently engaged. There is also the matter of concatenated complexities: if neonates have immature frequency or intensity or temporal resolution, then their perception of complex sounds may be affected by unpredictable combinations and interactions of these processes. Complex sound processing is usually held to involve more than the initial sensory processing. For example, after a complex is analyzed and temporally coded, some additional processing is deemed necessary to actually extract a pitch (e.g., Moore 1989). The maturation of these later processing stages may be an important aspect of auditory development.

There are also those who strongly believe that the psychophysical approach of using simple stimuli to probe the workings of the auditory system is an inappropriate way to study developing organisms (e.g., Turkewitz, Birch, and Cooper 1972; Gottlieb 1985). In this view, pure tones and noises are unlikely to elicit responses from neonates because organisms tend to be born selectively responsive to stimuli that are of the greatest

significance for survival: avian maternal assembly calls or human speech, for example. To the extent that any complex stimulus is more "naturalistic" than a pure tone, one might predict a greater degree of responsiveness and perhaps more mature processing in neonates' processing of complexes. There is some evidence, in fact, that newborn birds achieve lower detection thresholds when they are tested with species-appropriate stimuli (Gray and Jahrsdoerfer 1986). Developmental psychophysical data would require reinterpretation if studies using complex stimuli indicated a much greater state of auditory maturity. One of the major issues addressed in Sections 2.4.1–2.4.5, consequently, will be the extent to which the complex-processing data are consistent with results from studies of simple sounds during development.

### 2.4.1 Pitch Discrimination

The perception of pitch, the psychological correlate of acoustic frequency, is an important component of complex perception. Contemporary models of pitch perception (e.g., Srulovicz and Goldstein 1983; Rosen and Fourcin 1986; Moore 1989) recognize the influence of two peripheral processes, frequency analysis and temporal coding. A central processor must also use the information provided by peripheral processing to assign a pitch to the stimulus. Based on this very general model, one might predict that pitch perception would be immature if either frequency resolution, temporal coding, or the central pitch processor was immature.

Those immaturities of frequency resolution that have been described in 3-month-old infants (Spetner and Olsho 1990), for example, are probably not sufficient to have a major impact on pitch perception, particularly because they occur only at high frequencies. Should larger, low-frequency immaturities be found at younger ages, some impact might be expected. By 6 months, frequency resolution appears to be mature (see Section 2.2.1). Physiological data from neonates (e.g., Kettner, Feng, and Brugge 1985) indicate that phase locking to low-frequency tones continues to develop for some time during the postnatal period, and there is some indication that envelope coding may be immature among 1-month-old infants (Levi, Folsom, and Dobie 1993). Such immaturities would be expected to limit the precision with which pitch could be assigned (also see Section 2.2.2). It is difficult to make predictions about the development of the central processor without being more specific about what it does, but, of course, any model that posits a role of experience with sound (e.g., Terhardt 1974) would predict that developmental effects would be observed.

The data on the development of pitch perception are sparse. When adults are presented with a harmonic complex with the fundamental component missing, they still match the pitch of the complex to the fundamental frequency. This phenomenon is referred to as perceiving the missing fundamental or as "low pitch." Bundy, Colombo, and Singer (1982) asked

whether 4-month-old infants discriminated a change in the order of the notes in a repeated three-note sequence. Whether the fundamental was present and whether the harmonics in the complex changed from trial to trial were varied among subjects. Only infants who heard the fundamental and the same three harmonics on each presentation showed evidence of discrimination. This result provides no evidence that 4 month olds perceive complex pitch.

Studies of older infants suggest that pitch perception is at least qualitatively adultlike by 7 months. Clarkson and her colleagues have been responsible for all of this interesting work. Clarkson and Clifton (1985) first demonstrated that infants hear the missing fundamental: once infants had learned to respond to a change in pitch in complexes with the fundamental, they generalized the response to complexes without it. Clarkson and Clifton (1995) showed that infants' pitch discrimination performance was poorer for inharmonic than for harmonic complexes, as is the case for adults (e.g., Schouten, Ritsma, and Cardozo 1962). Finally, Clarkson and Rogers (1995) showed that infants perform better when a complex contains only low-frequency harmonics than they do when the complex contains only high-frequency harmonics, suggesting that the "existence region" of low pitch is similar to that of adults (Ritsma 1967).

There are clearly some questions remaining in this area. When does low pitch develop in nonhumans, where physiological data may help inform theories of mature pitch processing? Can infants younger than 7 months of age synthesize low pitch? Finally, what are the limits of pitch processing among 7 month olds? Do their complex-frequency DLs develop in parallel with their pure-tone frequency DLs?

2.4.2 Spectral Shape Discrimination, Timbre

The term timbre is generally defined, rather vaguely, as sound quality, but, in essence, it refers to whatever is left after pitch and loudness are accounted for. Spectral shape, or the relative amplitudes of different components of a complex, is an important determinant of timbre, but other parameters such as onset characteristics are also involved (e.g., see discussion by Bregman 1990). Data on the development of spectral shape discrimination have implications for our understanding of the other aspects of auditory development such as intensity discrimination and the identification of many naturally occurring sounds such as vowels. In addition, spectral shape discrimination has some implications for the development of pitch perception: infants' ability to extract pitch from spectrally varying complexes would certainly be less impressive if they were unable to discriminate the spectral changes.

Two studies have examined timbre perception in 7-month-old infants. Clarkson, Clifton, and Perris (1988) used stimuli very similar to the complexes used in their pitch discrimination experiment except that the

pitch of the stimuli was constant and the infants were conditioned to respond when they heard a change in the spectral shape (harmonic content). Infants quickly learned the task whether or not the fundamental component of the complex was present. Trehub, Endman, and Thorpe (1990) extended this result by showing that 7-8 month olds could distinguish between two spectral shapes even when the frequency, duration, and intensity of the complex were varied.

It seems clear that by 7 months human infants are capable of processing spectral shape. As was the case for pitch perception, however, it is not known whether younger infants possess the same capabilities or whether other species are as sensitive to spectral shape changes early in development. Furthermore, although we know that infants can discriminate rather gross changes in spectral shape, the limits of that ability have yet to be established.

2.4.3 Comodulation Masking Release

Pitch perception and spectral shape discrimination both indicate that mature listeners make comparisons across frequency regions in processing complex sounds. Comodulation masking release (CMR) and related phenomena (McFadden 1978; Yost and Sheft 1989) are other examples of how comparisons across frequency may be important. In the CMR paradigm, listeners are able to use the similarity in the amplitude envelope of a masking noise to the amplitude envelope of noise in other spectral regions ("flanking noise") to perceptually separate a tone from the noise (Hall et al. 1984). The improvement in threshold that results from this process is CMR. This is an interesting task developmentally because it depends on at least three developing capacities: temporal resolution, combining information across frequency regions, and selective attention to sound at a certain point in time (see Sections 2.3.1, 2.3.2, and 2.6)

CMR has not been studied in infants, nor has it been examined in nonhuman neonates. Veloso, Hall, and Grose (1990) showed that 6-year-old children had adultlike CMR in at least some conditions. Grose, Hall, and Gibbs (1993) examined thresholds for 500-Hz tones masked by modulated noise bands in 4- to 10-year-old children and in adults. Children of all ages obtained as much CMR as adults when the modulated noise extended into frequency regions away from the signal. Thus, even though children's internal representation of modulation is immature (see Section 2.3.1), they are able to improve their detection by combining information across frequency. The superiority of broadband over narrow-band sound processing in neonates may constitute an important developmental trend (see Section 2.2.1).

2.4.4 Music

The perception of music certainly involves the processes of frequency discrimination and temporal resolution. On first blush one might be

tempted to hypothesize that infants' and children's music perception would be limited by any immaturity of these processes, but the changes in frequency and timing that occur in music are well above threshold even for the immature auditory system (e.g., Trehub et al. 1986; Olsho et al. 1987). What is interesting about music perception is that it involves the perception of auditory patterns, and it is reasonable to ask how the ability to perceive such patterns develops.

In fact, infants as young as 5 months of age appear to perceive the pattern of frequency changes in a melody (i.e., the melodic contour), recognize the same contour when it is transposed to a different key (e.g., Chang and Trehub 1977; Ferland and Mendelson 1989), and detect transpositions (Trehub, Bull, and Thorpe 1984). Infants are sensitive to the temporal properties, or rhythm, of music (Trehub and Thorpe 1989), although young children may not be as accurate as adults at reproducing any but simple rhythms (Drake 1993). Juscyzk and Krumhansl (1993) showed that 4.5-month-old infants were sensitive to the cues (e.g., note duration and pitch contour) that signal the end of a musical phrase in much the same way that slightly older infants have been shown to be sensitive to the phrase structure of speech (e.g., Juscyzk et al. 1992). Thus, in many respects, it appears that the basics of this type of auditory pattern perception are in place within a few months of birth, although the performance of infants in experiments involving music discrimination tends to be mediocre. The age at which these capacities are first demonstrated is not clear.

Adult listeners consistently judge certain musical patterns as sounding better than others, and they may be more accurate in detecting changes to the better sounding patterns (e.g., Cuddy, Cohen, and Miller 1979). Because many aspects of what is considered a good musical pattern vary from culture to culture, it is held that music perception is largely determined by experience with the music of a specific culture (e.g., Krumhansl 1990). In fact, North American infants and adults appear to be affected differently by manipulations of culture-specific musical relations. For example, a change in musical scale that makes melody discriminations more difficult for adults or older children appear to make little difference to the discrimination performance of 6- to 11-month-old infants (Cuddy, Cohen, and Mewhort 1981; Trehub et al. 1986; Lynch et al. 1990). In at least one case, however, an effect in adults attributed to acculturation (Bartlett and Dowling 1980) has also been demonstrated in infants of this age (Trainor and Trehub 1993).

Findings that infants demonstrate certain effects in music perception that were believed to result from musical acculturation has been taken to mean that these effects may actually represent "natural proclivities" in auditory perception (e.g., Trainor and Trehub 1993). The infants tested in these studies, however, are at least 5 months old and usually 8 or more months old. Kuhl et al. (1992) have shown that 6-month-old infants discriminate between vowels in a way that reflects their experience with their native

language, and in the case of visual patterns, young infants may recognize the prototypical aspects of a pattern after a very limited exposure (Walton and Bower 1993). Thus it is not out of the question that infants' superior performance on some musical patterns reflects their postnatal experience with Western music.

As a final note, research into the development of music perception frequently parallels studies of the development of speech perception. For example, just as infants are initially capable of discriminating speech sounds from nonnative languages, they are capable of discriminating changes in melodies based on nonnative musical scales. In both cases, older children and adults are incapable or less capable of making the discrimination. Such findings would suggest that general perceptual processes, rather than specific speech or music perceptual processes, are developing. Unfortunately, there are instances in which such parallels break down. For example, although variation around a prototypical vowel is less discriminable than variation around a bad example of a vowel (Kuhl 1991), discrimination is better when prototypical musical patterns are involved. Furthermore, the perceptual correlates of a space formed by the formant frequencies of vowels are generally accepted as the space within which vowel prototypes exist. The dimensions of the "culture-specific schemata" (Trainor and Trehub 1993) for music have not been specified. Thus whether similar organizational processes are operating in music and speech perception is uncertain.

## 2.4.5 Discrimination of Species-Typical Vocal Productions

Developing organisms show strong tendencies to attend to or to approach the sources of species-typical vocalizations (e.g., Hutt et al. 1968; Gottlieb 1985). An interesting question is how these tendencies in developing animals are related to, or interact with, the developing auditory system.

In the case of humans, the most important species-typical vocalization is speech. The development of speech perception has been so widely studied that a summary of that research requires a table of its own (Table 2.2). A variety of issues peculiar to the study of speech and language have been addressed. These issues are yet to be settled, and a full treatment of them would require more space than available here. The studies in Table 2.2 are also categorized according to whether their results showed infants or children to be mature ("Positive or Adultlike") or immature ("Negative or Not Adultlike"). For many of the speech perception topics that have been examined developmentally, there are many more entries under "Positive or Adultlike" than there are under "Negative or Not Adultlike." Moreover, many of these positive reports involve very young infants. Many speech sounds, for example, can be discriminated by infants within a few days of birth, and both native language and mother's voice are apparently recognized as well. Such observations have led some to refer to the "surprising"

TABLE 2.2. Summary of speech discrimination developmental studies.

| Topic | Positive or Adultlike | Negative or Not Adultlike | Results |
|---|---|---|---|
| Phonetic Discrimination | | | |
|   Yes/no | 1–35 | 22, 22, 24, 36 | * |
|   Accuracy | 37–46 | 37–39, 41–43, 46–48 | ? |
|   Cues for discrimination | 4, 7, 22, 36, 49–53 | 50, 54–57 | ? |
| Identification | | | |
|   Boundaries | 37, 45, 50, 58–60 | 37, 60, 61 | ? |
|   Function slope | 44, 45, 60, 61 | 50, 58–61 | ? |
| Isolated Features or Nonspeech Analogues | 2, 26, 28, 32, 62 | 63, 64 | ? |
| Stress and Prosody | 11, 27, 32, 65–71 | | * |
| Voice discrimination | 66, 72–75 | 72 | * |

Positive, study shows that neonates can discriminate along the given dimension; negative, It does not; adultlike, study shows that neonates can discriminate along the given dimension as adults can; not adultlike, it does not; *, developmental trend in this type of discrimination is evident; ?, there is no clear trend. 1, Eilers et al. 1989; 2, Eimas 1974; 3, Eimas 1975; 4, Eimas and Miller 1980a; 5, Eimas and Miller 1992; 6, Eimas et al. 1971; 7, Fowler, Best and McRoberts 1990; 8, Karzon 1985; 9, Kuhl 1979; 10, Kuhl 1983; 11, Kuhl and Miller 1982; 12, Marean, Werner, and Kuhl 1992; 13, Moon and Fifer 1990; 14, Murphy, Shea, and Aslin 1989; 15, Swoboda, Morse, and Leavitt 1976; 16, Trehub 1973; 17, Walley, Pisoni, and Aslin 1984; 18, Abbs and Minifie 1969; 19, Bertoncini and Mehler 1981; 20, Bertoncini et al. 1987; 21, Eilers and Minifie 1975; 22, Eilers, Wilson, and Moore 1977; 23, Eimas and Miller 1980b; 24, Hillenbrand, Minifie, and Edwards 1979; 25, Holmberg, Morgan, and Kuhl 1977; 26, Jusczyk et al. 1977; 27, Jusczyk and Thompson 1978; 28, Jusczyk et al. 1989; 29, Leavitt et al. 1976; 30, Moffitt 1971; 31, Moon, Bever, and Fifer 1992; 32, Morse 1972; 33, Swoboda, Morse, and Leavitt 1976; 34, Swoboda et al. 1978; 35, Trehub and Rabinovitch 1972; 36, Eilers 1977; 37, Elliott et al. 1986; 38, Menary, Trehub, and McNutt 1982; 39, Abbs and Minifie 1969; 40, Barton 1980; 41, Eilers and Oller 1976; 42, Graham and House 1970; 43, Shvachkin 1973; 44, Strange and Broen 1980; 45, Wolf 1973; 46, Elliott 1986; 47, Velleman 1988; 48, Aslin et al. 1981; 49, Greenlee 1980; 50, Nittrouer and Studdert-Kennedy 1987; 51, Levitt et al. 1988; 52, Miller et al. 1983; 53, De Weirdt 1987; 54, Allen and Norwood 1988; 55, Morrongiello and Robson 1984; 56, Eilers et al. 1984a; 57, Walley and Carrell 1983; 58, Burnham, Earnshaw, and Clark 1991; 59, Elliott et al. 1981b; 60, Zlatin and Koenigsnecht 1975; 61, Simon and Fourcin 1978; 62, Jusczyk et al. 1983; 63, Elliott et al. 1989; 64, Jusczyk et al. 1980; 65, Bull, Eilers, and Oller 1984; 66, Jusczyk et al. 1992; 67, Karzon and Nicholas 1989; 68, Culp and Boyd 1974; 69, Hirsh-Pasek et al. 1987; 70, Kemler Nelson et al. 1989; 71, Spring and Dale 1977; 72, Mehler et al. 1978; 73, Miller et al. 1982; 74, Miller 1983; 75, Mills and Melhuish, 1974.

or "highly developed" speech-processing capacities of infants (Eimas, Miller, and Jusczyk 1987; Kuhl 1990). If, as described in Sections 2.1–2.3, newborns have elevated detection thresholds, poor temporal resolution, and perhaps immature frequency resolution, how can they be so good at discriminating speech sounds?

There are two common answers to this question. The first is based on the idea that infants attend more to speech than they do to boring tones and noises. By this account, infants will appear to be more sensitive when tested with speech than with nonspeech. Thus the immaturity in detection threshold or in temporal resolution results from a failure of attention rather than immature sensory processing. Enhanced sensitivity to species-typical stimuli has been demonstrated in neonatal birds (Gray and Jahrsdoerfer 1986). Several studies of infants and children, however, find that detection thresholds are no lower for speech sounds than for tones (Elliott et al. 1981a; Nozza, Wagner, and Crandell 1988). Moreover, Nozza et al. (1991) and Elliott et al. (1981a) reported that infants and children only achieved adultlike speech discrimination performance when the level of the speech sounds was adjusted to compensate for age differences in absolute sensitivity.

The second answer to the question is that psychoacoustic measures reflect immaturities of sensory processing but that speech perception measures used with young infants are not sensitive to these immaturities. When testing speech discrimination in infant subjects, the issue is whether or not a discrimination can be made with a relatively large difference between stimuli ("Phonetic discrimination, Yes/no" in Table 2.2). These studies do not ask how well infants can make the discrimination. One exception is the study by Aslin et al. (1981), which showed that infants' threshold for discriminating a change in voice onset time was poorer than that of adults. Once children reach the age when methods are available for establishing threshold or another measure of sensitivity, it is common to find reports of immature speech discrimination, as indicated in Table 2.2 ("Phonetic discrimination, Accuracy"). Thus an argument can be made for the position that processing of sound, including speech, improves with age. At the same time, young infants' fuzzy representations of speech sounds are clearly sufficient to allow them to discriminate among many speech sounds.

There are at least three hypothetical ways in which auditory constraints on speech perception could be exhibited. First, the timing of age-related changes in speech perception could depend on the maturation of basic capacities such as frequency and temporal resolution. Changes in the perception of native and nonnative speech sounds occur at apparently regular ages during infancy (Best 1993; Kuhl 1993; Werker and Polka 1993), and there are interesting parallels in the timing of maturation of basic auditory capacities. Second, infants or young children could use different acoustic cues than adults to identify speech sounds and thus compensate for immaturities in auditory processing. Although there are indications that even young infants can use some of the same acoustic cues that adults use to discriminate speech sounds, there is evidence that the relative importance of various cues is different for older children than it is for adults ("Phonetic discrimination, Cues for discrimination" in Table 2.2). Third, the exaggerated prosodic features typical of speech directed toward infants (e.g., Fernald 1985) may compensate for auditory limitations. In fact, there is some indication that infants' very early sensitivity to changes in stress within

words, prosodic features such as intonation contour, and differences among voices depends on the prosodic exaggerations that occur in infant-directed speech (e.g., Mehler et al. 1978).

There is a troubling paucity of rigorous psychoacoustic data quantifying developmental changes in the perception of naturalistic stimuli in nonhumans. Gray and Jahrsdoerfer (1986) used trial-by-trial data from an adaptive procedure to show that newborn ducks had a steeper psychometric function than newborn chicks for detecting a ducklike sound, but the stimulus was a pulsed filtered noise, not truly natural. The probability of a correct head turn toward a naturalistic stimulus presented from speakers separated by 180° has been quantified (e.g., Kelly, Judge, and Fraser 1987). Such data would allow the calculation of traditional psychoacoustic measures such as percent correct, false alarms, and fits to a psychometric function. To date, however, we know of no studies that have used this approach to quantify the limits of neonatal responsiveness to naturalistic stimuli. A complexity of social communication comparable to that in mammals is evident in song birds, and the acquisition of bird song is similar in many ways to the acquisition of human speech. Many investigators (reviewed in Fay 1988) have applied traditional psychoacoustic techniques to song birds, but the perceptual studies have only been done on mature birds (but see Dooling and Searcy 1980). Clearly, this area makes fertile territory for important future research.

## 2.5 Localization and Binaural Processing

The development of localization and binaural hearing have received attention for many reasons. Probably the major reason is that these are basic auditory processes in which the brain plays an obvious role. It is natural that researchers would be interested in studying a process that is likely to show age-related change, and the brain appears to undergo more extensive postnatal development than the ear. In addition, binaural hearing represents the auditory parallel to binocular vision, which develops substantially in the postnatal period and depends on normal input to develop normally (see Shimojo 1993 for a review).

### 2.5.1 Binaural Masking Level Difference

The masking-level difference (MLD) refers to the improvement in the detection of a signal under dichotic listening conditions. Its development has been examined in humans but not in nonhumans. Nozza and his colleagues (Nozza 1987; Nozza, Wagner, and Crandell 1988) demonstrated that 6-month-old infants derive less benefit than adults from interaural phase differences in the signal. Schneider et al. (1988), using a somewhat different paradigm, found that 12 month olds similarly derived less benefit from interaural differences. By about 5 years of age, the MLD appears to be mature (Nozza, Wagner, and Crandell 1988; Hall and Grose 1990). Abnormal experience with sound, caused by otitis media or another conductive disorder, appears to affect the size of the MLD (Hall and Derlacki 1988; Hall, Grose and Pillsbury 1990; Moore, Hutchings, and Meyer 1991; Pillsbury, Grose and Hall 1991; Wilmington, Gray, and Jahrsdorfer 1994).

### 2.5.2 Localization

Even newborn humans are capable of making at least crude localizations of a sound source. Muir and Field (1979) were the first to convincingly demonstrate that, within a few days of birth, infants would make slow long-latency head turns to the left or right toward a sound source. Whether the response is present in preterm infants is not known. Subsequent investigations (summarized by Clarkson and Clifton 1991) showed that this response depends on the duration and repetition rate of the stimulus and that only certain stimuli (e.g., rattle sounds, speech) elicit the response reliably. It is interesting that the response tends to "disappear" around 2 months of age, and when it reappears, it is quicker and shorter in latency (Muir, Clifton, and Clarkson 1989). Morrongiello and Rocca (1987a) found that the accuracy with which infants turned to face a sound source when only auditory cues were available increases progressively until ~18 months of age. Even though the development of distance perception has not been widely studied, it appears that 7 month olds can use intensity cues to judge whether a sound source is within reach or out of reach (Clifton, Perris, and Bullinger 1991).

Young rats (Potash and Kelly 1980) will approach a social call but not a distress call or noise played at a moderate level. Gerbils (Kelly and Potash 1986) and guinea pigs (Clements and Kelly 1978a) show similar unconditioned approach responses. Cats can be trained to approach an attractive sound for milk (Clements and Kelly 1978b; Olmstead and Villablanca 1980). Approach responses are similar to the early head turns observed in infants in that they depend on the stimulus and they disappear as the subjects age. It is also notable that young dogs, beginning at ~16 days of age, and rat pups, beginning on day 14, show consistent head turns toward a sound opposite one ear (Ashmead, Clifton, and Reese 1986; Kelly, Judge, and Fraser 1987)[3].

Several studies of infants have examined the development of the minimum audible angle (MAA), or the threshold for detection of a change in sound source location. Morrongiello and her colleagues (e.g., Morrongiello

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[3] An important research program on sound localization in owls (Knudsen, Knudsen, and Esterly 1982; Knudsen, Esterly, and Knudsen 1984; Knudsen 1988) is not reviewed here. Although owls provide exciting details about the roles of early experience, the original emergence of the binaural behavioral responses has not been studied.

1988; Morrongiello, Fenwick, and Chance 1990; Morrongiello and Rocca 1990) have followed the development of the MAA over the longest age range, finding a progressive decrease from 2 months until sometime between 18 months and 5 years of age. The MAAs measured in other laboratories (summarized by Clifton 1992; Fig. 2.6) agree well with those estimated in these studies. Thus the development of the MAA seems to parallel that of the MLD. Although detecting changes in the elevation of a sound source does not depend on interaural differences, it should be noted that Morrongiello and Rocca (1987c) reported that the MAA for elevation also improves during infancy but appears adultlike by ~18 months.

An obvious question is whether the development of the MAA is the result of an improvement in the coding of the binaural cues for localization: interaural intensity and interaural time differences (IIDs and ITDs, respectively). Improvements in interaural cue discriminations have been reported among infants (Bundy 1980) and into childhood (Kaga 1992). Ashmead et al. (1991), however, found that ITD threshold did not change between 16 and 28 weeks of age, an age period during which the MAA improves substantially. Furthermore, infants' MAAs are far worse than their ITD discrimination performance would predict. This implies that an age-related change in the MAA cannot be accounted for by an age-related change in ITD coding. If infants are poor at discriminating IIDs and nonetheless depend on IIDs to localize sound in azimuth, their MAAs would be poor. Parallels in IID discrimination and MAAs during development have not yet been examined.
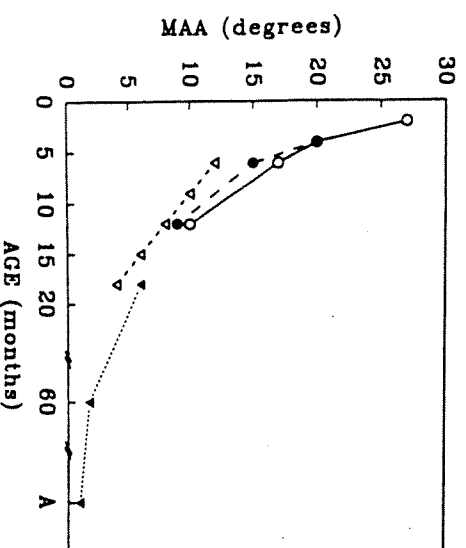


FIGURE 2.6. Minimum audible angle (MAA) as a function of age from several studies. *Filled circles:* Ashmead et al. (1991); *filled triangles:* Litovsky and MacMillan (1994); *open triangles:* Morrongiello (1988); *open circles:* Morrongiello, Fenwick, and Chance (1990). Reprinted from Clifton (1992) with permission.

Another potential contributor to immature localization is the way in which interaural differences are mapped onto positions in space. Because head size increases with age, the interaural cues that specify a particular location change with age. Thus the interaural cues might be in a state of flux during infancy and early childhood, a situation that is unlikely to promote accurate localization. Gray (unpublished observations) applied both signal-detection and multidimensional-scaling analyses to the responses of 0- and 4-day-old chicks to changes in the source of noise bursts from one speaker to another in a pentagonal array of speakers. The signal-detection analysis showed that the newborn chicks were as sensitive as the older chicks to small changes in sound source location. But although young chicks responded for the same duration to large and small location changes, the responses of older chicks were graded with the size of the location change. Multidimensional scaling of the duration of chicks' responses to different-size location changes was used to construct a perceptual "map" of the pentagonal speaker array (see Section 2.7.2). These maps are shown in Figure 2.7, where it is evident that it was not until 4 days of age that the chicks' responses reflected a realistic representation of the speaker positions. It is not the perception of the cues that is changing but rather the organization of a subjective map of auditory space. This aspect of development may reflect age-related changes in the neural map of
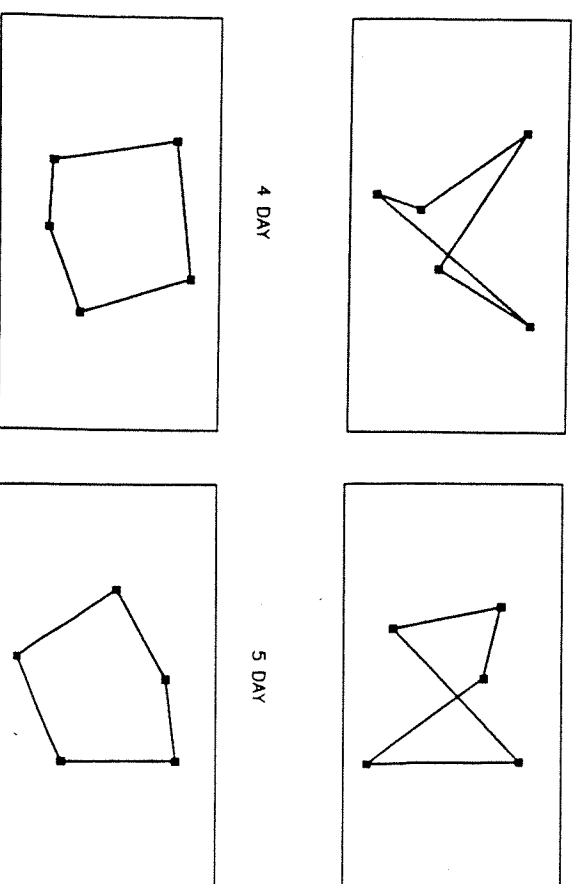


FIGURE 2.7. "Maps" of auditory space derived from chicks' response durations with multiple dimensional scaling.

auditory-visual space, as in the superior colliculus (Withington-Wray, Binns, and Keating 1990). Whether infants' MAAs are constrained by disorganized auditory spatial maps remains an interesting but unanswered question.

## 2.6 Attention

We use the term attention to mean a selective processing of a sound or a dimension of sound. Immaturity of attention has figured prominently in explanations for immature thresholds of all kinds, and the specific effects of inattention on thresholds are beginning to be described (see Sections 2.1, 2.2, 2.3, and 2.4). Studies explicitly addressing the development of auditory attention suggest that neonates show little evidence of "listening" in the sense of directing attention toward an expected frequency or spectral pattern, a skill at which adults excel (e.g., Schlauch and Hafter 1991). Although school-age children may be able to accomplish such selectivity for simple tasks, they appear to have difficulty with more complex listening situations.

There is a literature characterizing infants' and children's attention to sound in various ways that is typically not considered by those of us who use psychoacoustic methods to study development. Because studies in this category strongly influence developmental psychologists' views of neonatal attention, they are reviewed before more conventional studies of attention. These studies suggest that neonates are not entirely unselective in their listening behavior in that they prefer or show differential responsiveness to some sounds over others. Furthermore, normal newborns quickly learn to ignore repeated signals but redirect attention when the stimulus has changed.

### 2.6.1 Responsiveness and Preference

As mentioned in Section 2.4.5, infants are more likely to respond to some sounds than others, and if given a choice between sounds, they will chose to listen to some sounds over others. Responsiveness and preference are often taken as evidence that a sound has captured or kept infants' attention.

The acoustic parameters that regulate infants' responsiveness and preferences have not been extensively studied. Although bandwidth, intensity, and frequency have all been suggested as important factors (e.g., Hutt et al. 1968; Mendel 1968; Turkewitz, Birch, and Cooper 1972; Flexer and Gans 1985), in many studies supporting these suggestions, the stimuli used confounded two or more variables or the stimuli were not specified sufficiently to eliminate other possibilities (e.g., Hutt et al. 1968; Eisenberg 1976). Pulsed sounds seem to produce a greater response than continuous sounds among infants younger than 4 months but not among older infants (Mendel 1968; Bohlin, Lindhagen, and Nagekull 1981; Clarkson and Berg

1983). The one thing on which there is a consensus is that infants are more responsive to speech than to other sounds (Hutt et al. 1968; Colombo and Bundy 1981; Standley and Madsen 1990). Note that "more responsive" does not necessarily mean "more sensitive" (see Section 2.4.5).

There are numerous studies of infants' preferences for a particular type of speech, so-called "motherese" or infant-directed speech. When adults speak to infants, they tend to increase the extent of both amplitude and frequency modulation of the fundamental frequency and the duration of syllables (e.g., Fernald and Kuhl 1987). They speak more clearly, they use simple sentences, and they tend to repeat themselves (reviewed by Cooper 1993). If looking at a visual display is reinforced by the presentation of speech, even neonates will look longer at a display producing infant-directed speech than at one producing adult-directed speech (Cooper and Aslin 1990). The extent of fundamental frequency modulation appears to be an important determinant of the preference, but the aspects of infant-directed speech responsible for the preference may change during early infancy (Fernald and Kuhl 1987; Cooper 1993). Considerable attention has been given to the idea that infant-directed speech may help the infant to segment running speech into sentences, phrases, and words. Although there is some evidence for this idea (e.g., Fernald and Mazzie 1991), it remains controversial (e.g., Aslin 1993). Little attention has been given to the idea that these changes in speech may represent a parental adaptation to immature sensory processing, particularly for young infants. There is at present no empirical support for the latter idea.

A final factor that is known to influence infant preferences is familiarity. Within a few days of birth, infants show preferences for their own mother's voice over the voice of another infant's mother (DeCasper and Fifer 1980). That this preference results from prenatal experience is suggested by the finding that newborns prefer to hear a recording of one highly inflected story over another if their mothers read that story aloud during the pregnancy (DeCasper and Spence 1986). The preference for the mother's voice may depend on whether the mother uses infant-directed speech (Mehler et al. 1978). Newborn infants do not show a preference for their father's voice over that of someone else's father, although they appear to be able to discriminate the voices (DeCasper and Prescott 1984). Familiarity also affects infants' responses to nonspeech sounds (e.g., Zelazo and Komer 1971).

A similar pattern of preferences is exhibited by chicks and ducklings. Gottlieb and his colleagues have conducted an extensive series of experiments demonstrating that ducklings will approach a maternal call typical of their own species but not calls of other species (summarized by Gottlieb 1985). Mallard ducks use the repetition rate to identify the maternal call of their species (Miller 1980), and wood ducks use frequency modulation (Gottlieb 1974). Early experience is crucial in the development of appropriate preferences. Hearing the subject's own vocalization is sufficient for

mallards (Gottlieb 1980a); hearing a sibling is necessary for wood ducks (Gottlieb 1983). Ducklings exposed to the maternal call of a chicken prenatally will approach the chicken maternal call after hatching (Gottlieb 1991b). Fledgling song birds also show preferential responses to conspecific songs, even before they produce songs themselves, but the role of experience in establishing this preference is uncertain (Dooling and Searcy 1980).

In summary, it is clear that neonates of several species exhibit acoustic preferences. The nature of the factors that regulate this behavior in humans is not well understood. Are neonates born with a built-in "neonate-directed vocalization detector"? Are neonates actually more sensitive to sounds with the acoustic characteristics of neonate-directed vocalizations? What sorts of prenatal experience are necessary for the development of these preferences?

## 2.6.2 Habituation

Habituation is a ubiquitous phenomenon in behavior. Subjects normally decrease responsiveness when a moderate stimulus is repeatedly presented. Just as responsiveness is taken as a sign of a neonates' attention, habituation is taken as an indication of neonates' inattention.

Neonatal habituation is believed to reflect some internal representation of the stimulus, although there is no consensus about the mechanisms involved (e.g., Dannemiller and Banks 1983; Slater and Morison 1985; Dannemiller and Banks 1986; Malcuit, Pomerleau, and Lamarre 1988; McCall 1988; Ackles and Karrer 1991). There have been few studies directed at the nature of habituation among neonates, but many studies have used habituation to one stimulus and a recovery of responsiveness when the stimulus is changed as evidence of discrimination between the original and changed stimuli. Rovee-Collier (1987) provides a complete description of the uses of habituation in infant research. In any case, habituation is normal. Rapid habituation seems to be a "cost of doing business" in neonatal psychoacoustic studies: normal mature subjects may respond sensitively at both ends of a long testing session, but neonates typically do not.

Although the assumption is that habituation reflects the same process regardless of the modality of stimulation, studies of the process of habituation and its development have tended to use visual stimuli (discussed by Horowitz 1974). Moreover, it has been noted that patterns of habituation to auditory and visual stimuli can be quite different (McCall 1979). The available studies of auditory habituation identify a few factors that are known to affect the rate of habituation and the extent to which the response will be reinstated when the stimulus is changed. Stimulus-variable effects have been assessed in a few studies. Clifton, Graham, and Hatton (1968) showed that the rate of infant habituation is inversely related to stimulus duration. Berg (1972) similarly showed that infants habituate more rapidly to sounds with long rise times than they do to sounds with short rise times. The infant's initial familiarity with the stimulus as well as the relationship

between the stimulus and stimuli that the infant has heard previously both affect habituation and response recovery (e.g., Kinney and Kagan 1976; McCall and McGhee 1977; McCall 1988). Familiarity also affects habituation in newborn chicks (Gray 1992a).

A common question asked about habituation has been whether the rate of habituation or response recovery during infancy is predictive of later cognitive or intellectual abilities (e.g., O'Connor 1980; O'Connor, Cohen and Parmelee 1984; Bornstein 1985; see review by Rovee-Collier 1987). It has been demonstrated that high-risk and premature infants differ from normal infants in both the rate of habituation and extent of response recovery to change (Segall 1972; O'Connor 1980; Brazelton 1984; Zelazo et al. 1989), and atypical postnatal experience among high-risk infants has been suggested as a cause (e.g., Segall 1972). Atypical early experience also appears to affect the rate of habituation in nonhuman neonates: chicks that are exposed to noise[4] for 4 days just after hatching fail to habituate to repeated presentations of brief noise bursts in a quiet testing chamber (Philbin, Balweg, and Gray 1994). Whether high-risk infants and noise-exposed chicks have trouble forming an adequate representation of the sound or inhibiting their response is not clear. It has also been suggested that early visual experience affects visual attention (e.g., Movshon and Van Sluyters 1981). One wonders how many of the reported effects of early experience (e.g., otitis media) on speech and language development (e.g., Kavanagh 1986) may be mediated by deficits or delays in the development of attention.

## 2.6.3 Distraction and Selective Attention

Distraction, or attentional, masking was first described in infants by Werner and Bargones (1991). The task was to detect a pure tone in the presence of a noise so different in frequency from the signal that it could not possibly cause peripheral interference. Such noise increases thresholds in neonates but not adults. Similar processes appear to affect the responsiveness of chicks by about the same amount (Gray 1993b). The characteristics of the distractor (e.g., bandwidth) may be an important determinant for the degree of distraction in neonates (Gray 1993a,b).

Among humans, the development of resistance to distraction appears to continue well into childhood, although the paradigms used to assess children are quite different from that of Werner and Bargones (1991). Studies of children typically use a dichotic listening task in which different sounds are presented to the two ears and the subject is instructed to process the sound arriving at one (attended) ear in some way but to ignore the sound arriving at the other (unattended) ear. In general, the results of these studies

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[4]The chicks were exposed to noise recorded in a human neonatal intensive care nursery.

show that, with age, there is a progressive improvement in processing sounds from the attended ear and a progressive decrease in the number of "intrusions" from the unattended ear. The exact age at which performance becomes adultlike is not clear; estimates range from 10 to sometime after 3 years. Similar effects are observed in still other paradigms with visual stimuli (see review by Lane and Pearson 1982).

Questions about the nature of the development of resistance to distraction remain. Lane and Pearson (1982) list several processes that could be involved. Infants and children may encode sounds more holistically than adults (see Section 2.7), be less selective in choosing stimuli for processing, and/or be unable to inhibit a response to an irrelevant sound.

A few studies support the contention that selectivity in the choice of stimuli develops between infancy and childhood. Bargones and Werner (1994), for example, showed that although adults detect a tone at an expected frequency better than they detect tones at unexpected frequencies, 7- to 9-month-old infants detect equal sensation-level expected and unexpected tones equally well. Greenberg, Bray, and Beasley (1970) found that by 6 years of age children listen as selectively as adults in this paradigm. Dichotic listening studies, however, show that 7- or 8-year-old children still have difficulty "directing attention"; they are worse than older children or adults in switching attention between ears (Pearson and Lane 1991) and in dividing attention between two ears.

It is not entirely clear how we can model this lack of selective listening. One possibility has to do with the way that attention is directed. Neonates may listen in a "broadband mode"; that is, they may monitor the output of many auditory filters even when it would be beneficial to monitor only one. Alternatively, neonates may not actively listen at all but wait for a sound to capture their attention. More salient stimuli (broader bandwidths, longer durations, and species-specific vocalizations) are more effective at capturing attention and thus receive preferential processing. Both of these models are consistent with the characteristics of neonates' psychometric function in detection (e.g., Dai, Scharf, and Buus 1991; Gray 1992a; Hubner 1993; Allen and Wightman 1994; Bargones, Werner, and Marean 1995).

## 2.7 Representation

Throughout the discussion so far, we have referred to cases in which the internal representation of sound may play an important role in the development of auditory behavior. One explanation for immature localization is the detail available in an internal "map" of auditory space (see Section 2.5), and the detail in representations may be a limiting factor for selective attention in early life (see Section 2.6). This section discusses two types of studies of the development of auditory representation: categorization, because sounds cannot be categorized along a dimension that is not

represented; and perceptual maps, which involve the way that the representations of sounds are related to each other in perceptual space.

### 2.7.1 Categories

It is abundantly clear that neonates categorize sounds as well as sights (see, e.g., Quinn and Eimas 1986). Fodor, Garrett, and Brill (1975) first demonstrated that 14- to 18-week-old infants learned to respond to two syllables and not to a third more readily if the two syllables shared a common initial consonant than if they did not. In other words, infants are sensitive to the fact that the syllables with common consonants shared some feature; they place them within the same category. Subsequent to that study there have been demonstrations that infants can also categorize vowels (e.g., Kuhl 1979; Marean, Werner, and Kuhl 1992), voice gender (Miller 1983), musical contours (Ferland and Mendelson 1989), and musical rhythms (Trehub and Thorpe 1989).

Because infants are categorizing sounds that vary along some well-defined dimension, the assumption is often made that infants are using the same physical dimensions as adults to form categories and, hence, must represent sound in an adultlike way. The validity of this assumption has not been explored extensively. Hillenbrand (1983, 1984) showed that infants' categorization of speech sounds is probably not accomplished by simply "memorizing" which sounds go in which group. Infants must be recognizing some acoustic similarity between the members of a speech category. Miller, Younger, and Morse (1982) showed that even though 7 month olds correctly classified male and female voices, they did not learn to form voice categories on the basis of fundamental frequency alone. This suggests that some other dimension (e.g., spectral shape or timbre) is the basis of the categorization of voices.

There has been some debate as to whether infants represent speech as a string of phonetic segments or in a more "holistic" form such as syllables (e.g., Jusczyk and Krumhansl 1993; Kuhl 1993). Although infants must clearly represent the acoustic properties of speech that signal a change in a phonetic segment to be able to perform the many speech discriminations of which they are capable, it is quite possible that they do not represent those acoustic properties as a unit separate from the rest of a syllable or multisyllable utterance. Two varieties of evidence support the idea that neonates' speech representations are more holistic than those of adults. The results of several studies (e.g., Jusczyk and Derrah 1987; Bertoncini et al. 1988) find that infants do not respond to changes in all the phonetic segments in a syllable any differently than they do to a change in a single phonetic segment. Furthermore, preliterate children and adults tend to have difficulty in speech tasks that involve manipulations of individual phonetic segments, suggesting that the representation of words as a string of phonemes is the result of learning letter-sound correspondences in reading

change in auditory behavior are at this point larger than the gaps in the descriptions of the trends. An overriding theme in this review has been the complexity of the sensory and nonsensory maturation that gives rise to the development of auditory behavior. The cases in which we can identify specific sensory processes responsible for behavioral development are few. It is clear that the cochlea is a primary limit on early sensitivity and that the middle ear continues to limit sensitivity over a longer time period. The limits imposed on hearing by primary neural immaturity and the important implications of immature attentional and representational processes for auditory sensitivity are just beginning to be appreciated. If any conclusion is justified, it is that the sources of development in auditory behavior are neither trivial nor easily understood. The exciting aspect of the field is that powerful methods and approaches to understanding the development of auditory behavior are in hand and waiting to be applied to many interesting questions.

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