INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road. Ann Arbor. MI 48106-1346 USA
313/761-4700 800/521-0600

Intensity discrimination abilities of infants and adults: Implications for underlying processes

by

Beth Ann Kopyar

A dissertation submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

University of Washington

1997

Approved by Lynne A. Werner
Chairperson of Supervisory Committee

Program Authorized
to Offer Degree Department of Speech & Hearing Sciences

Date 9 Jun 97

UMI Number: 9736310

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

In presenting this dissertation in partial fulfillment of the requirements for the Doctoral degree at the University of Washington, I agree that the Library shall make its copies freely available for inspection. I further agree that extensive copying of this dissertation is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for copying or reproduction of this dissertation may be referred to University Microfilms, 1490 Eisenhower Place, P.O. Box 975, Ann Arbor, MI 48106, to whom the author has granted "the right to reproduce and sell (a) copies of the manuscript in microform and/or (b) printed copies of the manuscript made from microform."

Signature Beth A. Kopjar

Date June 9, 1997

University of Washington

Abstract

Intensity discrimination abilities of infants and adults: Implications for underlying processes

by Beth Ann Kopyar

Chairperson of the Supervisory Committee: Associate Professor Lynne A. Werner
Department of Speech and Hearing Sciences

It is known that infants' ability to recognize intensity variations, an important aspect of speech processing, is immature. However, processes contributing to this immaturity have not been identified. Measuring the intensity discrimination abilities of infants in two separate experiments provided an opportunity to examine these underlying mechanisms.

In Experiment 1, individual psychometric functions for intensity discrimination were obtained for broadband noise from 6- to 9-month-old infants and untrained adults. Infant functions exhibited shallower slopes and poorer thresholds than adult functions. The average infant upper asymptote did not reach adultlike performance. These results provide support for a combination of reduced growth of neural excitation and immature attention as causes for immature intensity processing.

In Experiment 2, intensity difference limens (DLs) were obtained from adults and infants in both gated- and continuous-pedestal paradigms for either pure tone or broadband stimuli. Adults showed the expected performance improvement in the continuous-pedestal paradigm compared to the gated-pedestal paradigm for both stimuli. While infants exhibited better continuous-pedestal DLs for broadband noise, there was no gated-continuous DL difference for the pure tone. The pattern of infant results is consistent with the predictions of models positing immature listening band strategies but mature across-channel mechanisms contributing to improved continuous pedestal DLs. However, this model cannot account for the overall size of the infant DLs. At this time, no model consistently accounts for all observations of infants' detection of sound.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I thank my advisor, Lynne Werner, for extensive and superb guidance in developing and completing this research. A careful and knowledgeable scientist, she has been a model of excellence. I am grateful to the members of my Reading Committee, Ed Burns and Rich Folsom, for their help and cooperation, and to the other members of my Supervisory Committee, Pat Kuhl, Ed Rubel and most recently, Ilene Bernstein.

This project could not have been completed without the assistance of members of the Infant Hearing Lab. Kelli Lehargoue, Julianne Siebens and Bonnie McTaggart spent many hours on the telephone scheduling infant and adult subjects. Roger Neate's software ran the experiments. Testing assistants Joy Barney-Tomalin, Anissa Bezanson, Mary Chollman, Janelle Constantino, Arlene Gicole, Bonnie McTaggart, Melanie Gicole Mercado, Rosemary Mitchell, Karin Perlotto, Jenna Perry, Marcos Quintana, Julianne Siebens, Sara Teller and Monica Valenzuela contributed their special skills in keeping babies cooperative and responsive during testing sessions.

I thank my colleagues Jude Steinberg, Sandra Serafini, Erika Zettner and Marilyn Dille for support at various stages of this research. I learned much from my colleagues Jill Bargones and Ellen Levi, who shared many hours in helpful and thoughtful discussions.

Finally, I am deeply grateful to the members of my family for their encouragement over the years. My parents, sister and brother-- Rose, Tom, Cynthia and Tony Kopyar-- have believed in and supported me in every phase of my doctoral program. I thank my husband, Craig Fujisaki, for his willingness to walk with me throughout my doctoral journey.

Support for this project was provided, in part, by grants from the Bailey and Babette Gatzert Foundation for Child Welfare, NIDCD (DC00396) and NICHD (HD7391).

Chapter 1.

Background

The ability to discriminate intensity variation is an important aspect of speech processing. Research indicates that infants use intensity cues in combination with frequency and duration cues to recognize stressed syllables (Spring and Dale, 1977) and that the perceptual salience of the stress patterns of native language increases during infancy (Jusczyk, Cutler and Redanz, 1993). It is also known that infant intensity discrimination thresholds are worse than those of adults (Tarquinio, Zelazo and Weiss, 1990; Bull, Eilers and Oller, 1984; Sinnott and Aslin, 1985; Schneider, Bull and Trehub, 1988). While it is known that infants' ability to recognize intensity variations is developing, the mechanisms underlying its development have not been identified. A study of intensity discrimination abilities of infants provides an opportunity to examine these underlying mechanisms.

The developmental processes contributing to auditory detection are expected to affect intensity discrimination as well. Models of infant auditory detection propose that some sensory immaturities in the primary auditory system and/or a nonsensory immaturity such as attention may contribute to immature psychometric functions for auditory detection (Schneider, Trehub, Morrongiello and Thorpe, 1989; Viemeister and Schlauch, 1992; Wightman and Allen, 1992; Hubner, 1993; Bargones and Werner, 1994; Bargones, Werner and Marean, 1995). Each model predicts certain effects on the shape of the psychometric function, so the validity of the model is judged by how well the predictions match the observed psychometric function. Such predictions would also apply to intensity discrimination.

The intensity difference limen or DL, is the smallest detectable change in intensity. Intensity DLs are worse when two discrete sounds are compared (gated-pedestal paradigm) as opposed to when a level increment in a continuous sound is detected (continuous pedestal paradigm). Several candidates have been proposed to account for this difference in adults (Campbell, 1966; Fastl and Schorn, 1981; Carlyon and Moore, 1984; Viemeister and Bacon, 1988). Interestingly, many of the same processes whose immaturity may account for immature intensity discrimination are among these candidates.

The development of intensity discrimination in infants was investigated using a "two-pronged attack." In Experiment 1, psychometric functions for intensity discrimination were obtained from 6- to 9-month-old infant and adults. In Experiment 2, the gated-continuous intensity DL difference was measured in 6- to 9-month-old infants and adults. Infant intensity discrimination results from both experiments are examined in the framework of the predictions of models of sensory and nonsensory underlying processes.

I. Intensity discrimination abilities in adult listeners

Psychoacoustic experiments have shown that humans are capable of detecting small changes in intensity across a wide range of standard intensities and frequencies (*e.g.*, Green and Sewall, 1962; Jesteadt, Wier and Green, 1977; Viemeister and Bacon, 1988; Florentine, Buus and Mason, 1987). Viemeister and Bacon (1988) reported that fine discrimination of intensity changes in 1-kHz tone bursts is maintained across nearly the entire dynamic range of hearing which spans approximately 120 dB. This fine intensity discrimination holds for pure tones from .25 to 16 kHz (*e.g.* Penner, Leshowitz, Cudahy and Ricard, 1974; Rabinowitz, Lim, Braida and Durlach, 1976; Jesteadt et al., 1977; Viemeister and Bacon, 1988; Carlyon and Moore, 1984; Florentine et al., 1987), and for broadband noise (Green and Sewall, 1962; Houtsma, Durlach and Braida, 1980). In the following sections, the reader will be introduced to techniques used to measure intensity discrimination in adults, effects of experimental parameters on discrimination and the currently accepted theory of the neural code for intensity in the auditory system.

A. Terminology

The reader should be aware that several measures of the size of intensity change appear in the literature. In an attempt to facilitate better understanding, a description of common physical measures of the stimulus in intensity discrimination experiments follows.

Figure 1 shows two common paradigms used in intensity discrimination experiments. The top diagram shows a gated-pedestal paradigm, where the pedestal, or comparison intensity, is gated on in the first interval and the pedestal and the intensity increment together are gated on in the second interval. The bottom diagram shows a continuous-pedestal paradigm, where the pedestal is continuously present in both intervals and the intensity increment is added to the pedestal in the second interval.

The auditory stimulus can be measured either in terms of acoustic intensity (power) or acoustic pressure (amplitude). Assuming a constant impedance, acoustic intensity is proportional to acoustic pressure squared. Metrics based on intensity will be described first. If the pedestal intensity, the increment intensity, and the pedestal-plus-increment intensity are known, several different magnitude measures can be calculated. Increment intensity, ΔI, is the difference in intensity between the pedestal-plus-increment and the pedestal. The relative increment intensity is expressed as a ratio, $\Delta I/I$, and is the increment intensity divided by the pedestal intensity. This ratio is often referred to as the Weber fraction. The Weber fraction is converted to decibels by taking $10 \log (\Delta I/I)$.

Metrics based on acoustic pressure are similar to the intensity terms just described. The relative change in pressure is $\Delta p/p$, the pressure of the increment divided by the pressure of the pedestal. The relative increment pressure is converted to decibels with the formula: $20 \log (\Delta p/p)$. ΔL, sometimes called ΔI in dB, is the level difference between the pedestal-plus-increment expressed in decibels and the pedestal expressed in decibels. It can be calculated with either of the following formulae:

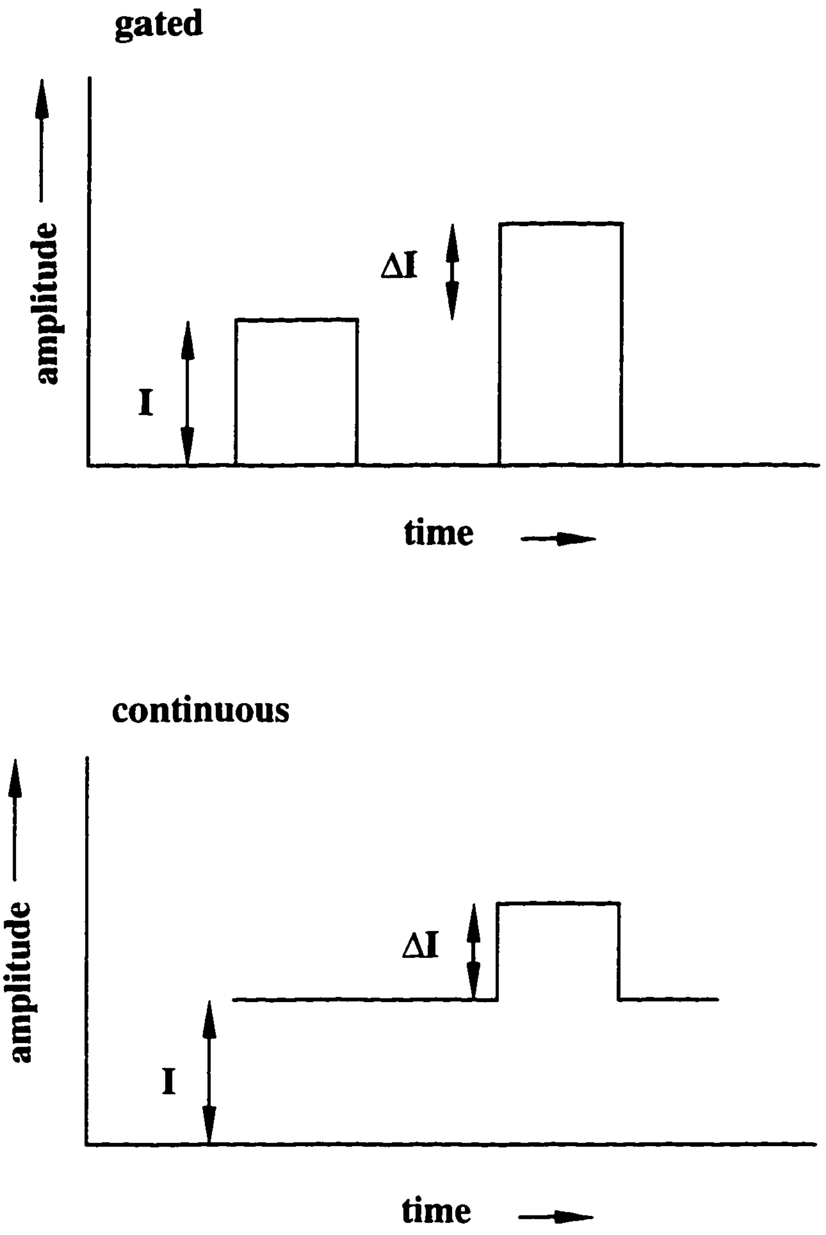

Figure 1. Two paradigms used in intensity discrimination experiments.

$$\Delta L = 10 \log [(\Delta I + I)/I] = 10 \log [(\Delta I/I) + 1] \text{ or}$$

$$\Delta L = 20 \log [(\Delta A + A)/A] = 20 \log [\Delta A/A + 1]$$

Grantham and Yost (1982) provide an extensive discussion of the multiple measures of intensity discrimination.

Does one "proper" measure of intensity discrimination exist? Buus and Florentine (1991) make a convincing case for the use of ΔL. Using a wide range of intensity increment sizes, they measured adult intensity discrimination for both long-duration, pure tones and short-duration, pure tones. Psychometric functions for intensity discrimination were plotted as d'[1] as a function of either ΔL, $\Delta p/p$ or $\Delta I/I$ on log-log coordinates. If d' is a power function of the independent variable then the plot will be a straight line in these coordinates. If d' is directly proportional to the intensity measure, the slope of the line (the exponent), should be 1. The slope varied across the range of intensity increments when measured in $\Delta p/p$ and $\Delta I/I$ but remained approximately unity for all increment sizes when ΔL was the metric. Thus, Buus and Florentine (1991) argue that because d' is approximately proportional to ΔL across a wide range of intensity increments, ΔL provides the most reasonable representation of intensity discrimination performance. In addition, many auditory scientists are accustomed to working in units of dB SPL and find ΔL to be the most intuitive metric. One disadvantage of ΔL as an intensity discrimination metric is that it is a compressive measure. The range of $10 \log \Delta I/I$, for example, is much greater than the range of ΔL over which changes in intensity discrimination occur. Thus, it may be difficult to identify differences between infants and adults in ΔL that would be evident in $10 \log \Delta I/I$.

---

[1] d' is a bias-free, parametric measure of sensitivity. It is based on the assumption that the distributions of sensory evidence used to make discrimination decisions are normal and equivariate.

Intensity discrimination will be described in ΔL throughout the text for ease of exposition. Analyses will be done in 10 log ΔI/I, and equivalent ΔL values given.

B. Parametric effects

In some cases, intensity discrimination varies with the level of the pedestal. The DL in a typical intensity discrimination experiment is defined as the intensity change required to achieve some fixed level of performance. This is usually 70.7% correct performance in a 2IFC adaptive procedure. Depending on the experiment, the DL has been variously reported using one of the metrics described in section I.A.2.

Weber's law states that the smallest detectable change in a stimulus is proportional to the magnitude of that stimulus; that is, that the Weber fraction is a constant for a given discrimination. Weber's law for intensity, then, predicts that the DL remains constant regardless of the pedestal intensity.

While Weber's law holds for broadband clicks (Penner and Viemeister, 1973) and reproducible broadband noise bursts (Raab and Goldberg, 1975), it does not hold for pure-tone stimuli. Instead of remaining constant, the Weber fraction generally becomes smaller as the pedestal intensity increases (*e.g.*, Schacknow and Raab, 1973; Penner et al., 1974; Jesteadt et al., 1977; Viemeister and Bacon, 1988; Long and Cullen, 1985). In other words, intensity discrimination gets better as the pedestal level increases. This is termed the "near miss" to Weber's law, and is reported for most low-and mid-frequency stimuli.

The near miss to Weber's law has been reported for stimulus frequencies from .15 to 12 kHz (Schacknow and Raab, 1973; Penner et al., 1974; Jesteadt et al., 1977; Viemeister and Bacon, 1988; Long and Cullen, 1985). At 14 kHz, however, intensity DLs are consistent with Weber's law (Florentine et al., 1987). While Florentine et al. (1987) reported intensity DLs exhibiting the near miss at stimulus frequencies from .25 to 4 kHz, at frequencies from 8 to 12 kHz, they reported a deviation from the consistent decrease in

DLs as the pedestal level increases. This deviation was termed a "midlevel bump" because the intensity DLs were larger at mid-intensity pedestal levels (typically 40 to 60 dB SPL) than at low or high pedestal levels. Carlyon and Moore (1984) reported a similar pattern of results: intensity DLs exhibited the near miss at stimulus frequencies of .5 and 4 kHz, while showing the midlevel bump at 6.5 kHz. In summary, intensity DLs exhibit the near miss to Weber's law for stimulus frequencies up to 4 kHz. The results of some studies show the near miss pattern for stimulus frequencies from 4 to 12 kHz, while other results show a midlevel bump for frequencies from 6.5 to 12 kHz. At 14 kHz, intensity DLs obey Weber's law.

Generally, the intensity DL for pure tones shows no effect of stimulus frequency for frequencies up to about 9 kHz (Penner et al., 1974; Jesteadt et al., 1977). In an extensive study, Florentine et al. (1987) show that the intensity DL increases (i.e., performance gets worse) as the stimulus frequency increases, up to 16 kHz. At low to middle frequencies, this frequency effect is very slight; it is most evident at the highest stimulus frequencies (8 - 16 kHz) and at high pedestal levels (>60 dB SPL).

Intensity discrimination performance, like detection performance, improves with increasing signal duration. Auditory integration time, the maximum duration at which performance continues to improve with the length of the signal, has been reported as approximately 200 ms for detection of pure tones (Watson and Gengel, 1969) and for intensity discrimination of white noise (Viemeister, 1974). For pure-tone stimuli, two studies of integration time for intensity discrimination report values that differ by an order of magnitude or more. Henning (1970) reported integration times of 100 ms for a .25 kHz stimulus, 25 ms for a 1 kHz stimulus and 10 ms for a 4 kHz stimulus, all with a pedestal level of 85 dB SPL. A more recent and extensive study by Florentine (1986) reported integration times for intensity discrimination of approximately 500 ms for a .25 kHz stimulus, 1000 ms for a 1 kHz stimulus and 2000 ms for an 8 kHz stimulus. (These values are an approximate summary across pedestal levels of 40, 65 and 85 dB SPL; see Table I in Florentine, 1986 for more detail.) In conclusion, intensity discrimination performance improves with signal duration up to 200 ms for white noise and up to at least 500 ms for pure tones, depending on the stimulus frequency.

Adult intensity discrimination performance is better when the task is detection of an increment in a continuous stimulus (continuous-pedestal paradigm) rather than when the task is discrimination between discrete stimuli (gated-pedestal paradigm). As described in section I.A., the difference in performance seen when comparing the results from the gated-pedestal paradigm to the results from the continuous-pedestal paradigm is called the gated-continuous difference. It is seen for pure-tone and noise stimuli over a range of stimulus frequencies, durations, and pedestal intensities with the exception of low pedestal intensities (Green and Sewall, 1962; Campbell, 1966; Campbell and Lasky, 1967; Green, Nachmias, Kearney and Jeffress, 1979; Carlyon and Moore, 1986; Viemeister and Bacon, 1988; Turner, Zwislocki and Filion, 1989; Bacon and Viemeister, 1994; Schlauch, 1994). Possible mechanisms underlying the gated-continuous difference will be examined in later sections.

C. Physiology: Models of intensity coding

The combined psychophysical results of intensity discrimination experiments provided the initial framework for examining the auditory system's intensity code. In experiments where the results were consistent with Weber's law--meaning that the intensity DL was constant across the range of pedestal levels--the stimuli had a commonality. They all prevented the use of intensity information provided by the spread of excitation along the cochlea. Such stimuli are broadband clicks (Penner and Viemeister, 1973) and reproducible broadband noise (Raab and Goldberg, 1975) which stimulate a large portion of the cochlea at even low pedestal levels by virtue of their broad frequency spectra. Pure tones (Moore and Raab, 1974) and noise bands (Viemeister, 1983) presented in a notched noise effectively eliminate the intensity information from areas of the cochlea stimulated by the notched noise, restricting the area of excitation to the characteristic frequency place of the stimulus. Other experiments have shown that intensity discrimination gets better with increasing pedestal level--the near miss to Weber's law. The stimuli in these experiments were all pure tones in quiet (McGill and Goldberg, 1968; Penner et al., 1974; Rabinowitz et al., 1976; Jesteadt et al., 1977). It was assumed that as the pedestal intensity increased, excitation spread across a greater length of the cochlea, thereby enhancing performance. Thus, the emerging picture of intensity coding was that information from a frequency-limited area of the cochlea led to Weber's law performance, while additional information from areas beyond the characteristic frequency of the stimulus, added by the spread of excitation, led to the near miss to Weber's law. Models of intensity coding first sought to explain how the auditory system used information provided by the spread of excitation (Bos and de Boer, 1966; Moore and Raab, 1974; Florentine and Buus, 1981). The most recent of this group of models, Florentine and Buus's model, will be described below.

1. Multiband excitation pattern model. Florentine and Buus (1981) described a multiband excitation pattern model of intensity coding. Their model is based on an earlier, single-band excitation pattern model (Zwicker, 1970). The multiband excitation pattern model is based on Zwicker's psychophysical masking patterns, which define the excitation level in each frequency-localized population of neurons (Florentine and Buus, 1981). Put simply, a change in intensity produces a change in excitation level in one or more frequency-localized neural populations or "channels". Combined information across channels is proposed as the code for intensity. As intensity increases, the excitation pattern becomes broader and the number of channels contributing information about excitation level differences increases. The multiband excitation pattern model provides a reasonable explanation for the near miss to Weber's Law. The model assumes that within one channel, the change in excitation level provides enough information to produce adherence to Weber's law. However, the model does not explain how this would be possible, since data from the cat indicate that most auditory neurons at any characteristic frequency saturate within 30-60 dB of their thresholds (*e.g.*, Sachs and Abbas, 1974; Evans and Palmer, 1980).

2. *Rate-based models.* Viemeister (1988) and Delgutte (1987) have proposed models of auditory intensity coding that address the ability to maintain Weber's law performance when it is presumed that the intensity information is available in a single, frequency-localized population of neurons. Both Viemeister's and Delgutte's models are based on discharge-rate information from a frequency-localized population of low-, medium- and high-spontaneous-rate, auditory-nerve fibers with a continuum of thresholds. Viemeister's model is based on physiological data from cat auditory nerve fibers: single-unit threshold, spontaneous rate and dynamic range values (Liberman, 1978; Schalk and Sachs, 1980; Evans and Palmer, 1980) and measures of the variance-to-mean ratio of individual fiber firing rate (Teich and Khanna, 1985). In simple form, the model proposes that at low intensities, spike-count information is provided by high-spontaneous-rate, low-threshold fibers. At higher intensities, these fibers reach saturation and spike count information is then provided by the low-spontaneous-rate, high-threshold fibers. Viemeister's analysis shows that optimally-combined information from a limited number of frequency-localized fibers can account for the results of human psychophysical intensity discrimination experiments in which Weber's law holds. Although it is not known how information is pooled across fibers in the auditory system, current physiological data suggests that a rate-based general code for intensity is possible and the model is widely accepted.

Delgutte's model draws upon the same body of single-unit cat data as Viemeister's model does, while featuring two stages. The first stage attempts to account for human psychophysical results that conform to Weber's law, while the second stage attempts to explain psychophysical results that exhibit the near miss to Weber's law. The first stage is not much different from Viemeister's model: it describes intensity coding by spike rate information from a frequency-localized group of auditory nerve fibers with a continuum of thresholds and spontaneous rates. The second stage of Delgutte's model is very similar to the Florentine and Buus multiband excitation pattern model (Florentine and Buus, 1981). Delgutte's model describes the combination of intensity information across populations of frequency-localized auditory nerve fibers. Delgutte postulates that as intensity increases, unsaturated auditory nerve fibers with characteristic frequencies away from the signal frequency provide additional discharge rate information. This additional information accounts for the near miss to Weber's law. The strength of Delgutte's model is that it provides an explanation for both the psychophysical intensity discrimination results that exhibit the near miss and those that follow Weber's law.

In summary, Delgutte's and Viemeister's models, along with the model of Florentine and Buus, are all consistent with the idea that the basic code for intensity is auditory-nerve fiber spike rate. Spike rate information from just one frequency-localized population of auditory nerve fibers seems to be sufficient for fine intensity discrimination performance (Weber's law holds). If additional spike rate information from other frequency-localized populations of auditory-nerve fibers becomes available by the spread of excitation, intensity discrimination performance becomes even better (thus the near miss to Weber's law). Delgutte's and Viemeister's models, based on physiological data, predict better performance than is seen in human psychophysical results. Thus, it would appear that more than enough information is sent up the auditory pathway by the periphery, and that central processing may be limiting psychophysical performance. The possibility of central contributions to the peripheral intensity code are discussed below.

3. Evidence for central contributions to intensity coding: Explanations for the midlevel bump. Models of intensity coding based on peripheral mechanisms were detailed in the previous section. Because the models suggest that more than enough peripheral information is available to account for human psychophysical performance, one conclusion is that central mechanisms limit intensity discrimination performance. A series of forward- and backward-masked intensity discrimination experiments has examined the issue of peripheral versus central intensity-coding mechanisms. In this section, results of these experiments and their implications for peripheral and central contributions to intensity coding will be discussed.

The midlevel bump in the function describing intensity discrimination DLs as a function of pedestal level has been shown for high-frequency signals (as detailed in section I.B.) and when the signal is preceded by a masker. Several authors have proposed a peripherally-based explanation that is consistent with Viemeister's and Delgutte's spike rate models of intensity coding. Low-spontaneous-rate, high-threshold, auditory-nerve fibers take longer to recover from forward masking than high-spontaneous-rate, low-threshold, auditory-nerve fibers do (Relkin and Doucet, 1991). In a pair of human psychophysical experiments, the pure-tone pedestal and increment were forward-masked by either the same-frequency pure tone or a narrowband noise centered on the signal frequency (Zeng, Turner and Relkin, 1991; Zeng and Turner, 1992). Thus the masker is assumed to stimulate the same channel as the pedestal and increment. The intensity discrimination functions obtained in these forward masking psychophysical experiments exhibited the midlevel bump. Zeng and colleagues (Zeng et al., 1991; Zeng and Turner, 1992) proposed that at moderate signal levels, high-spontaneous-rate fibers are saturated and the low-spontaneous-rate fibers have not yet recovered from the forward masking and therefore have elevated thresholds. Thus, the pedestal and increment intensities fall between the saturation level of the high-spontaneous-rate fibers and the elevated threshold of the low-spontaneous-rate fibers. This causes reduced intensity information at moderate pedestal levels, manifested as the midlevel bump.

A subsequent psychophysical study calls into question an exclusive peripheral mechanism underlying the mid-intensity elevation in psychophysical intensity discrimination. Plack and Viemeister (1992b) examined intensity discrimination under backward masking and found the mid-intensity bump. Backward masking is not evident at the periphery except at much shorter probe-masker intervals than those used by Plack and Viemeister (eg., Kiang, Watanabe, Thomas and Clark, 1965). Thus, it is difficult to explain Plack and Viemeister's results on the basis of a peripheral mechanism.

In summary, combined data from the studies cited above indicate that the major intensity-coding mechanism is at the periphery. However, recent results of intensity discrimination experiments using backward masking (Plack and Viemeister, 1992b) argue against an exclusively peripheral intensity code. Additional central mechanisms are involved.

II. Psychometric functions for intensity discrimination

Psychometric functions show how performance on a task changes as the magnitude of the stimulus increases. In intensity discrimination experiments the stimulus is either an increment or a decrement in intensity. A psychometric function for intensity discrimination shows the relationship between auditory performance and the size of the intensity change. The DL (*i.e.*, threshold) for intensity discrimination is defined as the size of intensity change corresponding to a chosen level of performance. As explained in section I.B., the DL obtained in a 2IFC adaptive procedure usually corresponds to the 70.7% correct performance, roughly halfway between chance (50%) and upper asymptote (assumed to be nearly 100% for adults). The intensity DL is but one point on the psychometric function. The shape of a complete psychometric function can provide additional information about possible processes underlying the ability being measured.

A. Adult performance

Adult psychometric functions for intensity discrimination of pure-tone stimuli have shown that d′ is proportional to relative increment amplitude, $\Delta p/p$ (Hanna, von Gierke and Green, 1986; Laming, 1986) when the intensity increments are small ($\Delta p/p \ll 1$). Since $\Delta p/p$ is proportional to $\Delta I/I$, a linear relationship between d′ and $\Delta I/I$ or between log d′ and ΔL would also be expected for small increments (ΔL approximately ≤ 1). However, for large intensity increments ($\Delta L \gg 1$) the plot describing d′ as a function of the intensity increment changes depending upon the metric used. A typical psychometric function for intensity discrimination measured from a trained adult listener has a DL (ΔL) of about .5 dB (Buus and Florentine, 1991). The slope, which is the exponent of the power function for d′ as a function of ΔL plotted in log-log coordinates, is around 1.0, indicating direct proportionality of log d′ and log ΔL (Buus and Florentine, 1991). For example, a psychometric function obtained from one listener showed a d′ of 1 corresponding to a ΔL of .4, a d′ of 2 corresponding to a ΔL of .8 and a d′ of 3 corresponding to a ΔL of 1.2 (Figure 1 from Buus and Florentine, 1991).

B. Infant performance

Psychoacoustic studies of suprathreshold intensity coding in infants and children typically report the DL for intensity discrimination. As in other auditory tasks, infants' and children's intensity DLs are different from those of adults. A brief description of these studies will be presented followed by models of mechanisms underlying the infant-adult difference.

Tarquinio et al. (1990) measured recovery from habituation in response to intensity decrements from 96 full-term neonates. The neonates initially exhibited head-turn responses to speech stimuli, "nana" or "titi", in the sound field at intensities of 72 or 78 dB SPL. After the neonates habituated to the stimulus, they recovered from habituation when the stimuli decreased in intensity by either 6 or 12 dB. In another study of discrimination of changes in the intensity of speech stimuli, Bull, Eilers and Oller (1984) measured head-turn responses from 5- to 11-month-olds to increments in synthesized multisyllabic speech stimuli at a pedestal level of 60 dB SPL. The DLs were 4 dB for bisyllabic stimuli and > 6 dB for trisyllabic stimuli.

Sinnott and Aslin (1985) measured intensity DLs for tones for 7- to 9-month-old infants and adults using a yes-no, head-turn procedure in the sound field. Increments and decrements were added to a 60 dB SPL, constantly repeating, 1-kHz tone burst. A one-up, one-down adaptive procedure was used to estimate the DL and converged on the intensity change value corresponding to a 50% hit rate. Infant DLs ranged from 2 to 12.5 dB, with an average of 6.24 dB and a standard deviation of 2.71 dB. Adult DLs were between 1.5 and 2 dB, with an average of 1.78 dB and a standard deviation of .25 dB. Interestingly, decrements in intensity could not be consistently detected by the infants, even for intensity changes of -20 and -25 dB. The authors propose that more central processes are involved in the encoding of intensity decrements and that these processes mature later than the more peripheral coding of excitatory events (i.e., increases in intensity). These results are surprising considering that Tarquinio et al. (1990) reported that neonates can consistently detect 6 or 12 dB decrements in the intensity of speech stimuli. Perhaps the discrimination task is more difficult when a tonal stimulus is employed, although Sinnott and Aslin (1983) reported intensity DLs obtained with a single vowel /a/ that were similar to those obtained with tones.

Schneider et al. (1988), in a study with 12-month-olds and adults, reported the percentage of correct localization responses to a broadband noise increment added to the output of one of two loudspeakers producing a continuous broadband noise pedestal. The infant group DL, estimated from the 70% correct point on the group psychometric function, was 2.2 dB while the adult group DL was .55 dB.

Intensity discrimination has been examined in preschool and school-age children. Jensen and Neff (1993) measured intensity DLs from 4-, 5-, and 6-year-olds and adults using a three-interval, forced-choice procedure in which the subject chose the interval that was "not the same." The pedestal was a 440-Hz, 400-ms tone burst at an intensity of 70 dB SPL. The mean adult DL for intensity discrimination was 1 dB, with a range of 1 - 2.5 dB. Surprisingly, the 4-to 6-year-olds' performance was worse than the infant performance reported by Sinnott and Aslin (1985). The average DL for the 4-year-old group was 7 dB, with a range of 1 - 20 dB. The 5-year-old group had an average DL of 4 dB, with a range of 1 - 16 dB. The 6-year-old group average, at 2.5 dB, was almost adultlike; however the range of 1 - 20 dB was still huge. Jensen and Neff (1993) report that no data collection sessions were excluded from their study. In other studies, sessions were excluded for what might be termed "suboptimum listening behavior": where the subject could not be trained to participate in play audiometry (Maxon and Hochberg, 1982) or the subject missed two consecutive "easy" intensity changes (Sinnott and Aslin, 1985). Thus the high variability and especially the large DLs from the children in Jensen and Neff's study may result from lapses of attention or decreased motivation.

Maxon and Hochberg (1982) conducted a systematic study of the effects of level and frequency on intensity discrimination in children. Intensity DLs were obtained from 4- to 12-year-old children using .5-, 1-, 2- and 4-kHz tone bursts at pedestal intensities of 10, 20, 40 and 60 dB SL. Tone bursts were presented in two intervals and the listener decided whether the presentations were "the same" or "different." At the high standard level, 60 dB SL (about 78 dB SPL), intensity DLs, expressed as ΔL, were 2.25 dB for the 4-year-olds and 1.55 dB for the 6-year-olds at 500 Hz. These results are not consistent with the Jensen and Neff (1993) data, which indicated far worse performance from children at the same ages with a pedestal of similar frequency and intensity. Childrens' intensity discrimination performance was independent of frequency, consistent with adult intensity discrimination performance (Jesteadt et al., 1977). Sensation level effects of the standard were seen in the 4- to 12-year-olds, in the same direction seen in adults: the DL decreased monotonically with an increase in pedestal intensity. Unfortunately, no adult data are reported in this paper. Consequently, it is impossible to compare the children's data in this study with data from adults run in the same experimental paradigm or to assess the validity of results obtained in this paradigm by comparison with published adult data.

In summary, intensity discrimination performance in infants and children is worse than adult performance. Intensity DLs obtained from infants are larger and more variable than those obtained from adults. One study indicates that intensity DLs decrease during the preschool years to approach adult values by 6 years of age, while another study reports that 4-year-olds' intensity DLs are worse than those of infants and performance is still not adultlike at 6 years of age. While the results of these studies characterize developing intensity DLs, the mechanisms underlying this development are unknown. The next section explores some possible mechanisms underlying immature intensity discrimination.

C. Models for developing intensity discrimination: Effects on the psychometric function

Models suggesting either sensory or nonsensory immaturities have been proposed to explain the infant-adult difference in psychometric functions for detection of narrowband signals, either pure tones or octave-band noises in broadband noise. In essence, these are intensity discrimination experiments: the noise is the pedestal and the narrowband signal is the increment. Each model makes specific predictions about the effect of the proposed immaturity on the shape of the psychometric function. The following section will describe each model, present evidence relevant to the validity of the models and detail predictions for the shape of the psychometric function.

1. Neural variability. Schneider et al. (1989) propose that increased variability in the neural representation of intensity may be the underlying mechanism for immature intensity discrimination. These authors hypothesize that variability in the neural encoding of intensity in an immature auditory pathway might cause the auditory system's response to a sound of a given intensity to vary from presentation to presentation. Thus, the immature listener would require larger changes in the stimulus intensity before she recognizes it as a true intensity change rather than a random neural variation. In the gerbil lateral superior olive, evidence of neural variability is manifested in the unreliability of action potential occurrence to the same stimulus (Sanes, 1993). This variability is seen only shortly after the onset of hearing. Neural variability could also be manifested as immature adaptation (discussed in Trehub, Schneider and Henderson, 1995).

Schneider et al. (1989) predict that increased neural variability will result in a psychometric function with a decreased slope and an increased threshold compared to an adult function, but with an adultlike upper asymptote. Sinnott and Aslin's (1985) group infant psychometric function (i.e., averaged across individual infants) for intensity discrimination exhibits this shape. However, it is impossible to know if the group function is a fair representation of individual performance. Bargones et al. (1995) obtained individual psychometric functions from 6- to 9-month-old infants and from adults for detection of a tone in noise. In general, the individual infant psychometric functions had decreased slopes, increased thresholds and decreased upper asymptotes compared to those of adults. Recall that the theory of neural variability in intensity coding predicts a psychometric function with a shallower slope and higher threshold than adults but with an adultlike upper asymptote. While results from the Bargones et al. (1995) experiment show the slope and threshold changes predicted by the neural variability model, the measured upper asymptote differs from the model's prediction. Although these results do not completely support neural variability as the sole mechanism underlying immature intensity discrimination, they do indicate that neural variability in combination with other mechanisms could contribute to the immaturity.

To extend the predictions of the neural variability model to broadband stimuli (*i.e.*, broadband pedestal and increment) the amplitude fluctuations inherent in the noise must be considered. If the combination of the "external" variability of the stimulus and "internal" variability of the neural representation is multiplicative, the effect of neural variability on decreasing the psychometric function slope could be greater for broadband stimuli than for pure tones.

2. *General inattention.* Adult listeners, when observed in an intensity discrimination task, appear to concentrate and listen carefully. Evidence of their attentiveness can be found in adult psychometric functions for intensity discrimination: the function rises steeply and reaches an upper asymptotic performance with a proportion correct near 1.0, indicating that the listener achieved perfect or near-perfect performance (McGill and Goldberg, 1968; Kopyar and Werner, pilot data). Do infants listen attentively in an auditory task? During any given intensity discrimination experimental session, infants do not sit quietly for all trials in the same way that adults do. Indeed, the infant may sit quietly for a short time and then begin moving on the parent's lap, vocalizing, sucking on a finger, etc. Any or all of these behaviors may prevent the infant from being an attentive listener. Even if the infant is sitting quietly, occasionally she appears to stare at a boring toy rather than attend to the auditory stimuli. An infant's auditory performance may be affected by "general inattention"-- that is, ignoring the stimulus and simply guessing on some trials during an experimental session.

In addressing immature performance on auditory detection tasks, several investigators have proposed a simple model to show how inattention might influence the psychometric function for detection (*e.g.* Viemeister and Schlauch, 1992; Wightman and Allen, 1992; Bargones, 1992; Allen and Wightman, 1994). This model assumes that the underlying psychometric function is the same for infants and children as it is for adults, but that the infants and children are inattentive on a certain number of trials. On these trials, the infant or child would be correct half of the time, just by chance or guessing. On the trials in which the infant or child is paying attention, performance should be related to the signal intensity. The general inattention model hypothesizes that the upper asymptote of the infant or child's psychometric function is 1 - (.5 x the inattention rate). For example, if the infant or child were inattentive on 34% of the trials, the upper asymptote of the psychometric function would be .83. The "general inattention" model predicts a psychometric function with a reduced upper asymptote, reduced slope and increased threshold, relative to an adult function.

Psychometric function measures of auditory detection in noise (a form of intensity discrimination) from infants provide partial support for a general inattention model of immature auditory performance. Recall that the model predicts a reduced upper asymptote. Psychometric functions from 6- to 11-month-old infants generally display a reduced upper asymptote, ranging from 73% to 95% correct (Schneider et al., 1988; Schneider et al., 1989; Nozza, Rossman, Bond and Miller, 1990; Bargones et al., 1995). Bargones et al. (1995) report average infant psychometric functions for detection in noise that have reduced upper asymptotes, shallower slopes and increased thresholds when compared to adult functions. Although the magnitude of the upper asymptote and slope reduction can be explained by the general inattention model, the threshold change is much greater than that predicted by the model. The authors suggest that primary neural immaturity together with general inattentiveness could explain immature auditory detection. Schneider et al. (1989) reported group psychometric functions for detection of octave-band noise signals in broadband noise background. Subjects were 6.5-month-olds, 13-month-olds, 18-month-olds, 4-year-olds, 10-year-olds and adults. Group functions obtained from the 6.5-month-old infants for octave-band noises with center frequencies ranging from .4 kHz to 10 kHz display the reduced upper asymptotes and shallower slopes consistent with predictions of a general inattention model. However, the threshold increase reported for the 6.5-month-olds is greater than that predicted by the model.

Broadband noise may have a stimulus-specific effect on a psychometric function shaped by inattention. It is interesting to note that across studies of infant detection in noise, the upper asymptote of the psychometric function becomes more adultlike as the spectral composition of the signal widens (Bargones et al., 1995; Schneider et al., 1989; Nozza et al., 1990; Schneider et al., 1988). As the frequency width of the signal increases, a steady increase in asymptotic percent correct performance is seen, from .83 for detection of pure tones in noise (Bargones et al., 1995) to .95 for detection of broadband noise in noise (Schneider et al., 1988). In so far as the upper asymptote is a direct measure of the rate of inattention, it can be predicted that inattention will have a minimal effect on intensity discrimination for a broadband stimulus.

3. Reduced growth of excitation. Schneider et al. (1989) proposed that a nonlinear change in the growth of excitation with intensity may be responsible for immature intensity discrimination. One interpretation of this idea is that less information would be available at any signal intensity for infants and children. Assuming that the auditory system uses absolute spike rate to code intensity, a reduced maximum spike rate would translate into a reduction in the amount of information available. Single-unit data from developing nonhumans show a reduced maximum spike rate and reduced resolution or slope change in spike rate/change in dB intensity during the period following the onset of hearing at the level of the cochlear nucleus (Brugge, Javel and Kitzes, 1978; Brugge, Kitzes and Javel, 1981; Woolf and Ryan, 1985) and the superior olive (Sanes and Rubel, 1988).

Studies in human infants suggest that the intensity-coding properties of the auditory system continue to mature through infancy. Cornacchia, Martini and Morra (1983) measured wave V auditory brainstem response (ABR) amplitude-intensity functions from 6- to 10-month-old infants and adults. Wave V responses were evoked by click stimuli from 20 dB nHL to 60 dB nHL. The shape of the infant functions paralleled the adult functions, indicating that wave V amplitude growth with increasing intensity was adultlike. These results suggest that a suprathreshold response of a large population of auditory nerve fibers through the level of the brainstem may be mature by six months of age in humans. Middle latency response measures suggest that intensity coding central to the brainstem may continue to develop into childhood (Kraus, Smith, Reed, Stein and Cartee, 1985).

Synaptic efficiency could be the mechanism underlying the maturation of the growth of excitation with increasing intensity. In the developing auditory system, inefficient synapses may cause a loss of spike rate information. Werner, Folsom and Mancl (1994) reported a significant correlation between ABR response latency measures and behavioral threshold in 3-month-old infants. They suggest that synaptic immaturity in the brainstem could account for both the increased ABR latencies and the immature behavioral threshold. However, no correlation was seen between latency measures and behavioral thresholds from 6-month-olds and adults. These results indicate that, after 6 months of age, a mechanism other than brainstem transmission must be responsible for immature behavioral thresholds. Synaptic inefficiency in the auditory system central to the brainstem is a possible contributor to immature behavioral thresholds and would be expected to affect suprathreshold intensity coding as well.

The psychometric function predicted by a reduced growth of excitation is similar to that of an adult, but less sensitive. In other words, predicted threshold would be significantly worse than adults, while the predicted slope decrease would be so small that it may be hard to demonstrate with limited infant data. The predicted upper asymptote is adultlike. However, as described in section II.C.2., adultlike upper asymptotes are not consistent with published infant data.

Schneider et al. (1989) attribute their infant-adult masked threshold differences to a reduced growth of excitation in infants, with similar effects seen across increasingly-wide octave band signals. Thus, reduced growth of excitation is expected to have a similar effect for broadband stimuli as for pure tone or narrowband stimuli.

4. Stimulus uncertainty. The intensity discrimination results of Green and Sewall (1962) suggest that listener uncertainty about the exact time the stimulus occurs, the exact duration, intensity or frequency of the stimulus steepens the psychometric functions for intensity discrimination of broadband noise in adults[2]. Uncertainty effects have been shown to steepen the slope and increase the threshold of the psychometric function for detection (Green and Swets, 1966). Stimulus frequency uncertainty develops when the listener has a less-than-accurate expectation of the signal frequency. This type of uncertainty is expected to have a greater effect for pure tone stimuli than broadband stimuli. Temporal uncertainty concerning the stimulus would be expected in a typical infant psychophysical experiment where the listener is not notified of the beginning or end of a trial. After listening to a few training trials, the adult and infant listener will have some expectation of when a trial will start. If the infant develops less accurate expectations of signal frequency representation, of trial onset times, or does not use temporal cues, greater stimulus uncertainty is predicted for infant listeners as compared to adults. The predicted infant psychometric function has a steeper slope and an increased threshold relative to adult functions. While an increased threshold is consistent with published infant psychometric functions for auditory tasks, a steeper slope is not.

5. Listening strategies. Immature listening strategies have also been proposed to account for immature psychometric functions for detection of tones in noise (Bargones et

---

[2] Green and Sewall (1962) predicted greater temporal stimulus uncertainty for intensity discrimination in the continuous-pedestal paradigm than in the gated-pedestal paradigm. Therefore, they expected steeper psychometric functions and increased thresholds for the continuous-pedestal paradigm. Their results do show steeper slopes for psychometric functions obtained in the continuous-pedestal paradigm. However, the thresholds are *better* for the continuous-pedestal paradigm, a result which is not consistent with the model of stimulus uncertainty.

al., 1995). The auditory system has been modeled as an overlapping bank of narrow filters, each centered at a different portion of the range of audible frequencies. The filter or group of filters to which a listener attends can be called a listening band. For known signal frequencies, adult listeners direct their attention to, or listen at, a single listening band that is centered on the signal frequency (Dai, Scharf and Buus,1991; Schlauch and Hafter, 1991). A single, wandering listening band is expected to produce a psychometric function with a shallower slope, increased threshold and an upper asymptote that may be reduced compared with an adult function. These characteristics are qualitatively consistent with the results of Bargones et al., (1995). For broadband stimuli, a single, wandering listening band is expected to have little effect on the slope of the psychometric function. Thus, if a single, wandering listening band does contribute to the immature detection of tones in noise, it is expected that infant psychometric functions for intensity discrimination obtained with broadband noise will exhibit steeper slopes than those obtained with pure-tone stimuli.

D. Summary

Infant psychometric functions for auditory detection in noise are characterized by shallower slopes and reduced upper asymptotes as compared to adult functions. In addition, infant thresholds are much worse than adults'. Reduced upper asymptotes and slopes are consistent with a model of inattention, although observed infant thresholds are much worse than can be explained by inattention alone. Sensory immaturity (*e.g.*, neural variability, reduced growth of excitation), which is expected to produce increased thresholds, combined with the effects of inattention, may contribute to immature detection in noise and immature intensity discrimination.

III. Gated- versus continuous-pedestal DL difference

A. Adult performance

In general, intensity discrimination performance in a continuous-pedestal paradigm is better than performance in a gated-pedestal paradigm. This positive difference between gated-pedestal and continuous-pedestal DLs has been measured in many different stimulus conditions. Intensity DLs are better in the continuous-pedestal paradigm compared to the gated-pedestal paradigm for noise increment/noise pedestal experiments (Green and Sewall, 1962) as well as in pure-tone increment/pure-tone pedestal experiments (Campbell, 1966; Campbell and Lasky, 1967; Green et al., 1979; Viemeister and Bacon, 1988; Turner et al., 1989; Schlauch, 1994). Worse performance in the continuous-pedestal condition than in the gated-pedestal condition has been reported only at low pedestal levels (Viemeister and Bacon, 1988).

The magnitude of the gated-continuous DL difference does seem to vary with the type of stimulus. At medium-to-high pedestal intensities, the difference between DLs, converted to ΔL, in the gated-pedestal paradigm versus the continuous-pedestal paradigm is only .05 - .61 dB for a broadband noise stimulus (Green and Sewall, 1962). Similarly, for a .5 kHz stimulus, the gated-continuous DL difference is .16 - .41 dB across a wide range of pedestal levels. For stimulus frequencies of .25, 1 and 4 kHz, the gated-continuous DL difference averages approximately 1 dB. For all stimuli, the gated-continuous DL difference varies with the level of the pedestal, but does not seem to vary in a systematic way.

B. Proposed mechanisms underlying the gated-continuous DL difference

1. Adaptation. Adaptation has been proposed as the mechanism underlying the gated-continuous pedestal performance difference (Viemeister and Bacon, 1988; Turner et al., 1989). In a typical auditory intensity discrimination task, the intensity of the increment is compared with the intensity of the pedestal. If the intensity code is spike rate, then the auditory system compares the spike rate produced by the increment intensity with the spike rate produced by the pedestal intensity. When a difference between the two spike rates being compared is recognized, the increment is detected. Adaptation reduces the firing rate response to a continuous stimulus over time. The firing rate levels off after a stimulus duration of approximately 50 ms in the guinea pig and gerbil (Smith and Zwislocki, 1975; Westerman and Smith, 1984). This process is often called short-term adaptation, as opposed to rapid adaptation, which occurs within the first few milliseconds of stimulus onset. Thus the intensity of a continuous pedestal is coded by an adapted spike rate. On the other hand, the intensity of a stimulus just turned on--the increment in both pedestal conditions and the gated pedestal--could be coded by the onset response spike rate. Physiological data from guinea pig (Smith and Zwislocki, 1975) and gerbil (Smith, 1979) show that the onset response spike rate is the same for adapted and unadapted auditory nerve fibers. Therefore, in the continuous-pedestal paradigm, the auditory system would compare the adapted spike rate associated with the continuous pedestal with the onset spike rate of the increment. In the gated-pedestal paradigm, the auditory system would compare the onset spike rate of the pedestal with the onset spike rate of the increment. The difference between pedestal and increment spike rates would be larger in the continuous-pedestal paradigm, leading to better intensity discrimination performance.

2. Listening bands. Campbell (1966) proposed a drifting listening band hypothesis to account for the adult gated-continuous difference. According to Campbell's hypothesis, for a pure-tone stimulus, the center frequency of this listening band drifts between stimulus presentations during the gated-pedestal condition and is kept to the center frequency of the signal by the pedestal in the continuous-pedestal condition. Therefore, the listener would make more efficient use of the information in the continuous-pedestal condition, leading to better performance.

For a noise stimulus which is composed of a wide representation of frequencies, listening band placement or width is expected to make only a minor contribution to increased listening efficiency. Listening band effects are predicted to cause only a minimal, if any, gated-continuous pedestal difference for a noise stimulus in Campbell's model. The predictions have been partially substantiated by published data. As described in section III.A., the gated-continuous DL difference is around 1 dB for most pure-tone stimuli, while the difference is much smaller for a broadband noise stimulus. However, one study using a .5 kHz pure-tone stimulus reported a gated-continuous difference as small as that reported for the broadband stimulus.

Varying listening band width may also be involved in the overshoot phenomenon. Details are described in the following section.

3. Within- and across-channel mechanisms proposed to explain overshoot. Many investigators have reported that detection of a short signal delayed relative to the onset of a longer masker is better than detection of a short signal presented simultaneously with a masker of duration equal to that of the signal (*e.g.*, Bacon and Viemeister, 1985; Bacon, 1990; Carlyon and White, 1992; Wright and Dai, 1994; Wright, 1995). This phenomenon has been called "overshoot" or the " temporal effect." This detection difference is analogous to the gated-continuous difference in intensity discrimination: the condition in which there is a long delay in signal onset relative to the masker onset is like the continuous-pedestal paradigm while the simultaneous masker-signal onset condition is like the gated-pedestal paradigm. Wright has studied these effects extensively (Wright and Dai, 1994; Wright, 1995) and hypothesizes that two mechanisms contribute to the advantage in the long-delay signal onset (*i.e.*, continuous-pedestal) condition: a within-channel and an across-channel mechanism. The precise nature of these mechanisms is not well-understood. Within-channel mechanisms may include adaptation or referential coding or may be mediated by the optimal narrowing of a listening band to match the signal. Wright and Dai (1994) and Wright (1995) reported broader listening bands and higher thresholds in the simultaneous masker-signal onset (*i.e.*, gated-pedestal) condition than in the long-delay signal onset condition. For intensity discrimination, an optimum narrow listening band would be expected to improve performance for pure tones in the continuous-pedestal paradigm.

The results of Wright (1995) show an advantange in the long-delay signal onset (*i.e.*, continuous-pedestal) condition even when the broadband masker was notched and had no energy at the signal frequency. These results indicate that across-channel mechanisms also contribute to the advantage in the long-delay condition. Candidates for across-channel mechanisms are less clear. Wright hypothesizes that, in the long-delay condition, activity in channels responding to energy in the masker (pedestal) can increase activity in neighboring channels responding to the signal (increment) (Wright, personal communication). For intensity discrimination, this would mean that an advantage would be gained for broadband signals in the continuous-pedestal paradigm.

4. Off-frequency cues. Carlyon and Moore (1986) posit that off-frequency energy at increment onset may be present in the continuous-pedestal condition. This onset energy splatter may provide a cue, leading to better performance than in the gated-pedestal condition. However, it is unlikely that this mechanism is responsible for the gated-continuous difference. Viemeister and Bacon (1988) reported that increasing the increment rise/fall time to 100 ms, thereby eliminating the off-frequency cues associated with onset energy splatter did not change the gated-continuous difference they had obtained with much shorter rise/fall times.

5. Memory. Fastl and Schorn (1981) proposed that memory constraints may be responsible for the decreased performance in the gated-pedestal paradigm, relative to performance in the continuous-pedestal paradigm. When listening to a continuous pedestal, a subject can simply detect a change in the intensity. In the gated-pedestal paradigm, the pedestal intensity is separated from the pedestal-plus-increment by a silent interval, and the subject must "remember" the pedestal sensation and discriminate it from the pedestal-plus-increment sensation.

Durlach and Braida (1969) and Braida and Durlach (1988) have described a theory of intensity resolution based on adult intensity discrimination performance. Their theory includes a model for memory operation, detailing two memory mechanisms for comparing sound intensities: a context-coding mechanism and a trace maintenance mechanism. These two memory modes are assumed to operate in parallel and any memory noise associated with their operation would be added in parallel. In the context-coding mode of memory operation, it is assumed that the listener maintains a long-term memory reference of the pedestal intensity and compares the intensity in each interval to this reference. Supporting evidence for this long-term memory cue is found in the data of Pollack (1955), which showed only a small decrease in intensity discrimination performance when the interstimulus interval was as long as 24 hours. In context coding, it is assumed that the listener can also compare the stimulus relative to the context of the pedestal intensity or relative to internal "perceptual anchors" (Braida, Lim, Berliner, Durlach, Rabinowitz and Parks, 1984). Examples of perceptual anchors in an intensity discrimination experiment would be absolute threshold and the threshold of discomfort.

In the trace maintenance mode of memory operation, it is assumed that the listener stores short-term memory sensations or "traces" of the stimulus. The sensation of the stimulus decays as the interstimulus interval increases. When pedestal intensities are roved over a large range, making long-term memory comparison difficult, pure tone intensity discrimination decreases as the interstimulus interval increases from 250 ms to 8 s (Berliner and Durlach, 1973; Green, Kidd and Picardi, 1983).

Plack and Carlyon (1995) have hypothesized that memory noise may account for the midlevel bump in intensity discrimination functions obtained under nonsimultaneous masking. (The midlevel bump is reviewed in sections I.B. and I.C.3.). A group of experiments showed that the midlevel bump was present under conditions of both forward and backward masking (Plack and Viemeister, 1992 a,b; Zeng et al., 1991). Memory processes emerge as strong candidates to explain the midlevel bump, since adaptation and other peripheral physiological explanations cannot account for the effects of backward masking. Results of several studies suggested that the effects of forward and backward masking were to interfere with memory processes involved in intensity discrimination. For example, Plack and Viemeister (1992b) showed that the bump was eliminated by presenting a notched noise with the signal. One explanation is that the notched noise provided an intensity reference for the signal, eliminating the need to use the short-term memory trace which the maskers interfered with. Plack, Carlyon and Viemeister (1995) tested this idea directly by presenting a fixed-intensity tone burst just before or after the signal, reasoning that this tone burst would provide a direct intensity reference. As predicted, there was no midlevel bump when the proximal tone burst was present.

Listeners can use this sort of referential coding in intensity discrimination with a continuous pedestal, where the pedestal provides a constantly-present reference intensity. Consistent with this idea is the finding of no midlevel hump in continuous-pedestal intensity discrimination, while there is a midlevel hump in gated-pedestal discrimination (Carlyon and Moore, 1986). Thus, in continuous pedestal intensity discrimination, minimal demands are made on either short-term memory or long-term memory.

C. Models of gated- versus continuous-pedestal DLs: Effects of immaturity

While the mechanism underlying the adult gated-continuous DL difference is not proven, several candidates are at least partially supported, and have yet to be disproved, by current research. Adaptation is often mentioned, based on physiological studies of adaptation (Smith and Zwislocki, 1975; Smith, 1979). Although Campbell's wandering listening band model has not recently received attention as a mechanism contributing to the gated-continuous difference, neither has it been disproved. Within- and across-channel mechanisms contributing to overshoot (Wright and Dai, 1994; Wright, 1995) have become fashionable explanations for the gated-continuous DL difference. The effects of memory (Fastl and Schorn, 1981; Plack and Carlyon, 1995) have been proposed to explain the gated-continuous difference and such explanations are receiving considerable attention. It is possible to predict infant performance in gated- and continuous-pedestal intensity discrimination on the basis of models of immature infant auditory performance.

1. Immature adaptation. Trehub, Schneider and Henderson (1995) proposed that immature adaptation contributes to immature gap detection thresholds in 6.5- and 12-month-old infants. They suggest that adaptation is immature in two ways: a more profound adaptation and a slower recovery from an adapted firing rate. The first component, a more profound adaptation, could mean that the firing rate associated with short-term adaptation, which has a time constant of about 50 ms in nonhumans, (Westerman and Smith, 1984; Smith, 1988) is a smaller percentage of the onset firing rate compared with that of an adult. Single-unit data show that the amount of short-term adaptation and the poststimulus recovery time are directly related (Harris and Dallos, 1979). That is, the more profound the short-term adaptation, the longer it takes the neuron to recover its maximum onset firing rate in response to a stimulus following an adapting stimulus. While a typical interstimulus interval of 500 ms in human adult psychophysical experiments is sufficient to allow nearly full recovery from adaptation (extrapolation of Figure 9A, Harris and Dallos, 1979), infants may still be recovering from the adaptation past 500 ms if adaptation is immature.

If adaptation is immature in the developing auditory system, a more profound decay in firing rate and a longer poststimulus recovery might be expected. Both of these effects are expected to enhance the gated-continuous DL difference. A more profound adaptation is expected to enhance the difference between the adapted discharge rate associated with the continuous pedestal and the onset discharge rate associated with the increment to the continuous pedestal. This effect is expected to make the continuous-pedestal DL even better, thereby increasing the gated-continuous difference. A longer poststimulus recovery time is expected to lead to a decrease in the onset firing rate of the increment tone that follows the pedestal tone in the gated-pedestal paradigm. Thus, the difference between the onset spike rate associated with the pedestal and the increment is decreased. This would lead to an increased gated-pedestal DL and further enhancement of the gated-continuous difference. In summary, if infants exhibit immature adaptation, the predicted gated-continuous difference would be greater in infants than in adults and the effect would be similar for both pure tone and broadband noise stimuli. Predicted infant DLs will be better than adult DLs in the continuous-pedestal paradigms and worse than adult DLs in the gated-pedestal paradigms.

2. *Reduced growth of excitation.* In so far as resolution (change in spike rate/change in dB) is a measure of the growth of excitation with increasing intensity, nonhuman data provide supporting evidence for a reduced growth of excitation during development. Data from single units in the cochlear nucleus and lateral superior olive of the cat and gerbil show reduced response growth rate and reduced maximum driven spike rate (Brugge, Javel and Kitzes, 1978; Brugge, Kitzes and Javel, 1981; Woolf and Ryan, 1985; Sanes and Rubel, 1988). It is possible that this reduced growth of excitation is the result of synaptic inefficiency in the immature auditory system. The idea of synaptic inefficiency in the developing auditory system is supported by physiological data from the gerbil (Sanes, 1993) and indirectly by ABR and behavioral human data (Werner et al., 1994).

A reduced growth of excitation with increasing intensity is expected to decrease the amount of spike rate information for both continuous- and gated-pedestal paradigms and for pure tone and noise stimuli. The predicted gated-continuous difference for infants will parallel the adult differences for both tonal and noise stimuli. For each stimulus, the thresholds will show a substantial decrease in sensitivity relative to adult thresholds due to the decreased amount of information. Infant DLs will be worse than adults DLs for all conditions. The magnitude of the infant-adult DL difference is expected to be the same for both the pure tone and noise stimuli, in both the gated- and continuous-pedestal paradigms.

3. Neural variability. Increased neural variability in the representation of intensity in the developing auditory system would require a larger increment in intensity before it is recognized as an intensity change rather than a random neural variation. This increased neural variability is expected to have a similar effect in both the continuous- and gated-pedestal paradigms. Since amplitude fluctuations are present in noise stimuli, this source of stimulus variability combined with neural variability will make infant DLs worse for noise stimuli than for tonal stimuli.[3] The predicted gated-continuous difference for infants will parallel the adult differences for both tonal and noise stimuli, with all thresholds exhibiting decreased sensitivity (*i.e.*, higher DLs). Infant DLs obtained with noise stimuli are expected to be worse than those obtained with tonal stimuli.

4. Listening band effects. Campbell (1966) proposed that the listening band, kept centered on a pure tone signal by the constant presence of the pedestal during the continuous-pedestal paradigm, drifts between stimulus presentations in the gated-pedestal paradigm. Hence, performance is better in the continuous-pedestal paradigm where the most efficient listening occurs. This hypothesis is very similar to the single, wandering listening band modeled by Hubner (1993) for auditory detection. Hubner's model describes a single listening band that wanders in frequency placement from the signal frequency. As the band wanders farther and farther from the signal frequency, auditory detection becomes less and less efficient. Wright (1995) presents a similar model based on gating effects, in which a narrow listening band is associated with a continuous masker and

---

[3] This result will be seen only if the effects of stimulus and neural variability are multiplicative.

a broader listening band with a gated masker. Whether this broader band results from a single listening band that wanders in frequency placement or from broadband listening is not clear. In auditory detection experiments, there is evidence for a wandering listening band or broadband listening in infants (Bargones and Werner, 1994; Bargones et al., 1995) and in children (Allen and Wightman, 1994).

Let us assume that an infant's listening band does wander between presentations of the pedestal and the pedestal-plus-increment in the gated-pedestal paradigm, but is kept close to the signal frequency by the continuous spectral cue in the continuous-pedestal paradigm. In other words, the infant is able to make use of the spectral cue provided by the continuous pedestal. For pure tone stimuli, the predicted gated-continuous difference will be *greater* than that found in adults. The predicted infant DL will be worse than adults' in the gated-pedestal paradigm, but will be similar to adults' in the continuous-pedestal paradigm. For a broadband noise stimulus, energy is present across a wide range of frequencies, making a single-band spectral cue less important. An infant attending to a wandering listening band should do equally well in a gated-pedestal paradigm and a continuous-pedestal paradigm. In other words a small gated-continuous difference is predicted for broadband noise, as in adults (Green and Sewall, 1962). The predicted infant DLs for broadband noise will be similar to adult DLs in both the gated-pedestal and continuous-pedestal paradigms.

Now let us assume that an infant attends to a single,wandering listening band or a broad listening band and does not make use of spectral cues. For pure tone stimuli, infant performance would show a substantial decrease in sensitivity when compared with adult performance due to the wandering or broad listening band. However, there would be no infant gated-continuous difference, because the infant would not use a spectral cue to enhance performance in the continuous-pedestal paradigm. For pure tone stimuli, predicted infant DLs will be worse than adult DLs in both the gated- and continuous-pedestal paradigms, with no paradigm difference. Because a wandering or broad listening band and use of a spectral cue is irrelevant with a broadband noise stimulus, predicted infant performance is better than predicted infant performance for pure tone stimuli. Predicted infant DLs for broadband noise will be similar to adults DLs in both the gated- and continuous-pedestal paradigms.

5. General inattention. As previously described in section II.C.2., several investigators have proposed that general inattention may account for immature performance in auditory detection experiments (Viemeister and Schlauch, 1992; Wightman and Allen, 1992; Bargones et al., 1995). A simple model of general inattention hypothesizes that a listener 'doesn't pay attention' on a certain number of experimental trials. On those trials, the listener is expected to be correct on half of the trials, just by guessing. If inattention is the underlying mechanism of immature intensity discrimination performance, the rate of inattention should be similar in the gated- and continuous-pedestal paradigms. For both pure tone and noise stimuli, the predicted infant gated-continuous difference is expected to be the same as adults, but predicted infant absolute performance will be less sensitive than adult performance, owing to the inattention. Predicted infant DLs will be worse than adult DLs in all stimulus conditions.

6. Memory effects. Stated simply, adult listeners use trace maintenance in the gated-pedestal paradigm and referential coding in the continuous-pedestal paradigm. In the proposed gated- versus continuous-pedestal DL experiment, memory noise associated with the trace maintenance mechanism is expected to be minimized due to the short silent period (500 ms) between comparison intensities. Immaturity of the trace maintenance mechanism would degrade gated-pedestal performance and increase the gated-continuous DL difference in infants relative to adults. Immature referential coding would degrade continuous-pedestal performance and decrease the gated-continuous DL difference in infants relative to adults. Two studies of 2-month-old infants' speech perception provide some measure of infant trace maintenance memory. Results from backward-masked vowel discrimination experiments (Cowan, Suomi and Morse, 1982) suggested that there was no difference between infant and adult trace maintenance at interstimulus intervals similar to those proposed for the current experiment. On the other hand, Swoboda, Kass, Morse and Leavitt (1978) showed that infants' vowel discrimination decreased more rapidly than that of adults with increasing interstimulus intervals between 500 ms and 10 s. While trace maintenance may be immature in 2-month-old infants, it is not clear if it is expected to be immature for the 6- to 9-month-old infants in the current intensity discrimination experiment.

7. Across-channel mechanisms. Within- and across-channel mechanisms have been invoked to explain the overshoot phenomenon-- that is, the advantage in the detection condition analogous to the continuous-pedestal paradigm. All of the models described above are based on within-channel mechanisms. It may be important to consider whether within- and across-channel mechanisms develop along different time courses. If infants are able to use the across-channel but not the within-channel mechanisms for intensity discrimination, for example, a continuous-pedestal improvement will be seen for broadband noise DLs but not for the pure tone DLs.

D. Summary

Sensory and nonsensory models of auditory development predict specific patterns of results from experiments measuring intensity DLs in gated-pedestal and continuous-pedestal paradigms. Figures 2 - 10 are schematic representations of predicted infant and adult intensity DLs for each model. The predicted effects of immature adaptation on infant DLs are shown in Figure 2. This mechanism is expected to decrease performance in the gated-pedestal paradigm and enhance performance in the continuous-pedestal paradigm. For both tonal and noise stimuli, infant DLs are worse than adult DLs in the gated-pedestal paradigm while infant DLs are better than adults' in the continuous-pedestal paradigm.

A reduced growth of excitation translates into a loss of spike rate information across all experimental conditions. Figure 3 shows that predicted infant DLs are worse than adults' with the magnitude of the difference similar across all conditions.

Figure 4 diagrams the predicted effects of neural variability on infant DLs. Infant DLs are worse than adult DLs for all conditions. However, the greatest infant-adult DL difference is evident for those conditions using noise stimuli, since the internal neural variability is combined with the external variability inherent in the noise stimulus, assuming the combination is multiplicative.

Figure 5 shows the DLs expected if the infant listener attends to a wandering listening band but does make use of the spectral cue provided by the continuous pedestal. For tonal stimuli, infant DLs are worse than adult DLs with a greater infant-adult difference for the gated-pedestal paradigm. For noise stimuli, infant DLs are not different from adult DLs because a wandering listening band will have little, if any, effect on listening to a broad-frequency stimulus and a spectral cue is irrelevant for noise.

Figure 6 shows the DLs expected if the infant listener attends to a wandering or broad listening band and does not make use of the spectral cue provided by the continuous pedestal. For tonal stimuli, infant DLs are worse than adult DLs and there is no gated-continuous DL difference. For broadband stimuli, infants' predicted DLs are similar to those of adults.

Figure 7 shows the results predicted if general attention is the mechanism underlying immature intensity discrimination in infants. Inattention is expected to affect performance equally in the gated-pedestal and continuous-pedestal paradigms and for tonal and noise stimuli. Therefore, infant DLs are worse than adult DLs with a similar infant-adult DL difference in all conditions. This pattern of results is similar to the results predicted by the reduced growth of excitation model, except that inattention is expected to produce a smaller effect on the size of the DLs.

Figure 8 shows that immature sensory-trace or context coding produces infant DLs that are worse than adult DLs in the gated-pedestal paradigm, for both tonal and noise stimuli. Figure 9 diagrams the expected results if infants can use the across-channel mechanisms but not the within-channel mechanisms contributing to overshoot. Since both of these mechanisms make the continuous-pedestal DL better, an improvement in the continuous-pedestal DL will be seen for broadband noise but not for tonal stimuli. Therefore, no gated-continuous DL difference is predicted for infants for the 1-kHz tone, while an adultlike gated-continuous DL difference is predicted for the broadband noise stimulus.

IV. Statement of Purpose

The purpose of the two proposed experiments was to examine potential processes underlying immature intensity discrimination in 6- to 9-month-old infants. In the first experiment, psychometric functions for intensity discrimination were measured from infants and adults using a broadband noise stimulus in a continuous-pedestal paradigm. Models of sensory and nonsensory immaturity make specific predictions of the shape of the psychometric function. The results of the first experiment are examined in the framework of these models.

A different approach to the same question was taken in the second experiment. As another way of examining potential mechanisms of immaturity, adaptive DLs for intensity discrimination were obtained from infants and adults using both a continuous-pedestal paradigm and a gated-pedestal paradigm. Each subject contributed a gated-pedestal DL and a continuous-pedestal DL for either a broadband noise stimulus or a 1-kHz stimulus. In the adult literature, better DLs for intensity discrimination have been reported in experiments using a continuous-pedestal paradigm than the DLs reported in experiments using a gated-pedestal paradigm. A number of models have been proposed to explain the gated-continuous DL difference in adults, with some models predicting differential effects for broadband and pure tone stimuli. Many of the mechanisms proposed in these models are the same processes that have been proposed to account for immature intensity discrimination in infants. Thus, the measurement of gated-pedestal and continuous-pedestal intensity discrimination DLs provided another method for studying immature intensity discrimination in infants.

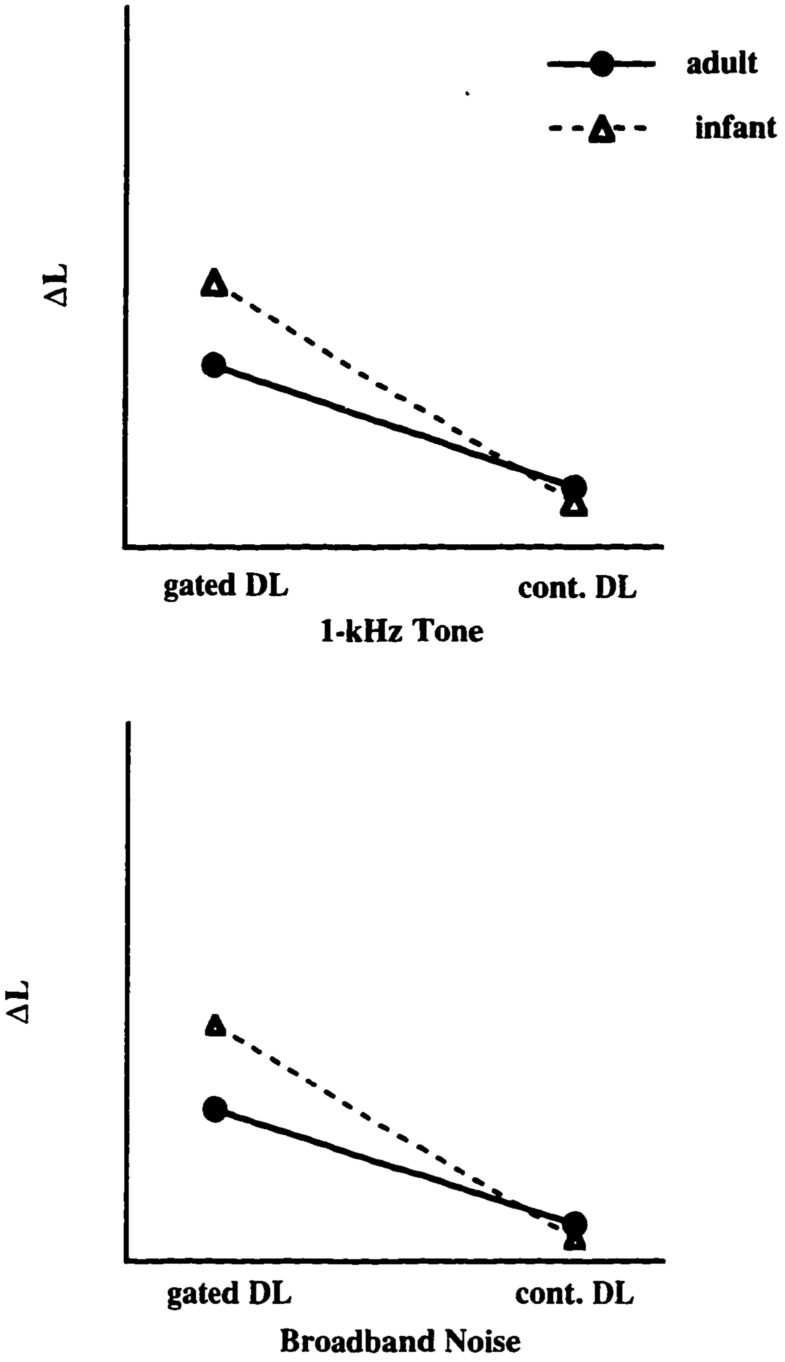

Figure 2. Predicted effect of immature adaptation on intensity DLs.

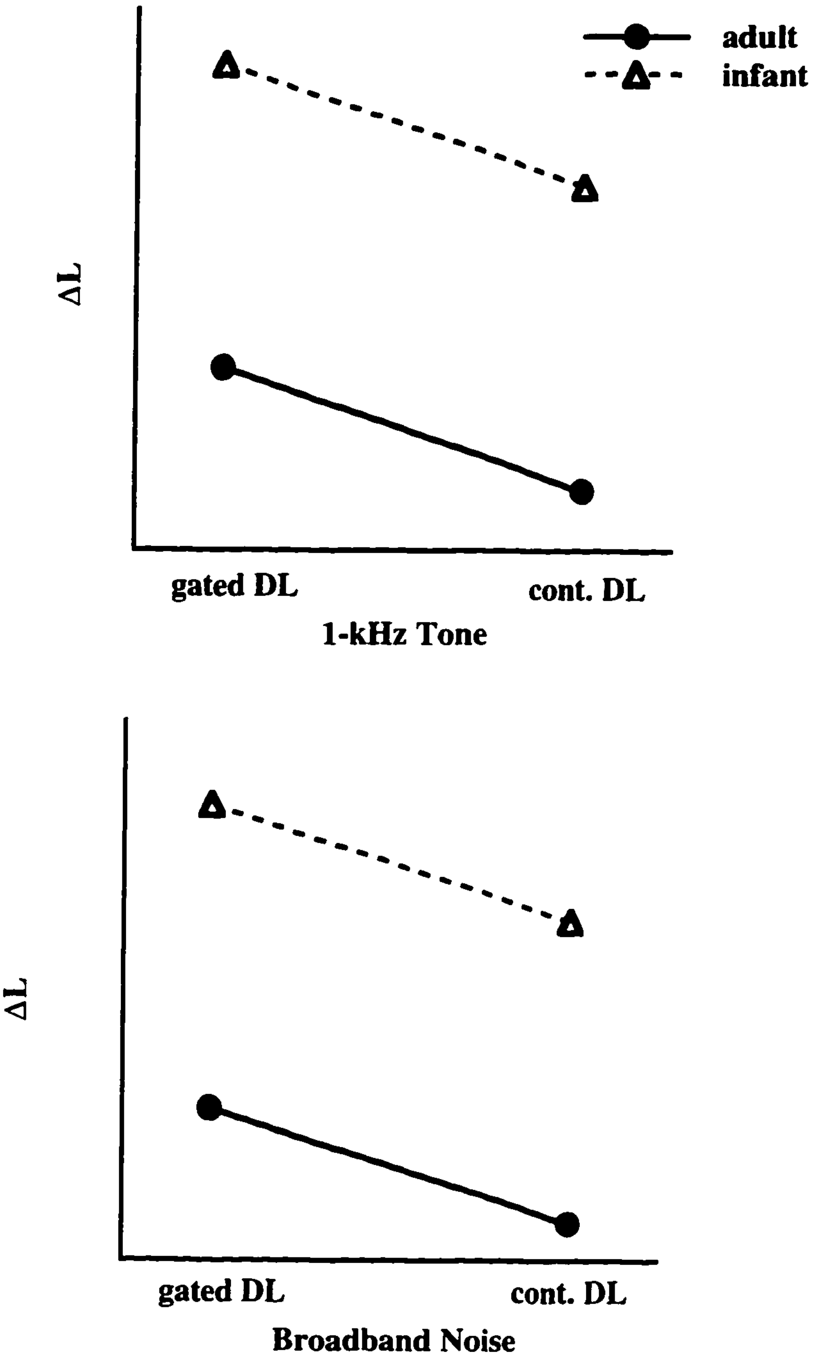

Figure 3. Predicted effect of reduced growth of excitation on intensity DLs.

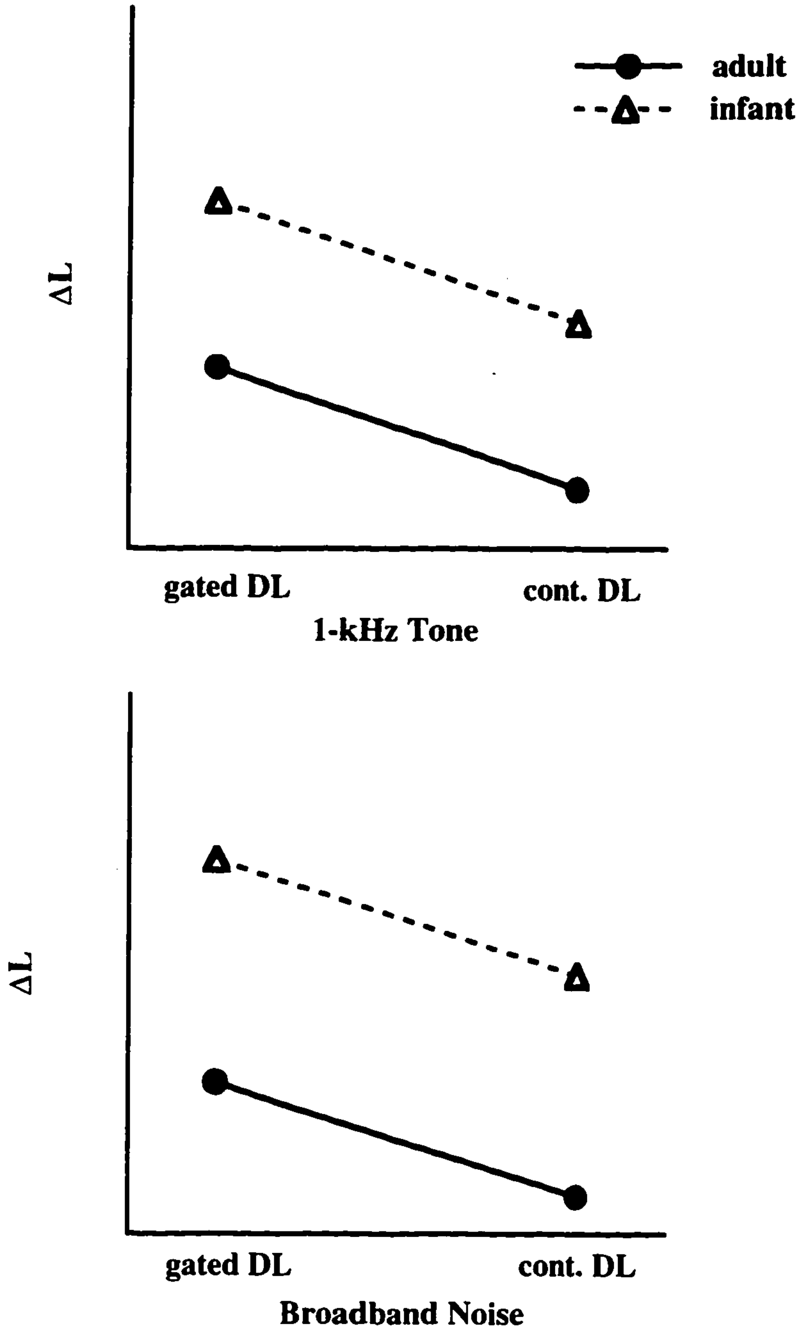

Figure 4. Predicted effect of neural variability on intensity DLs.

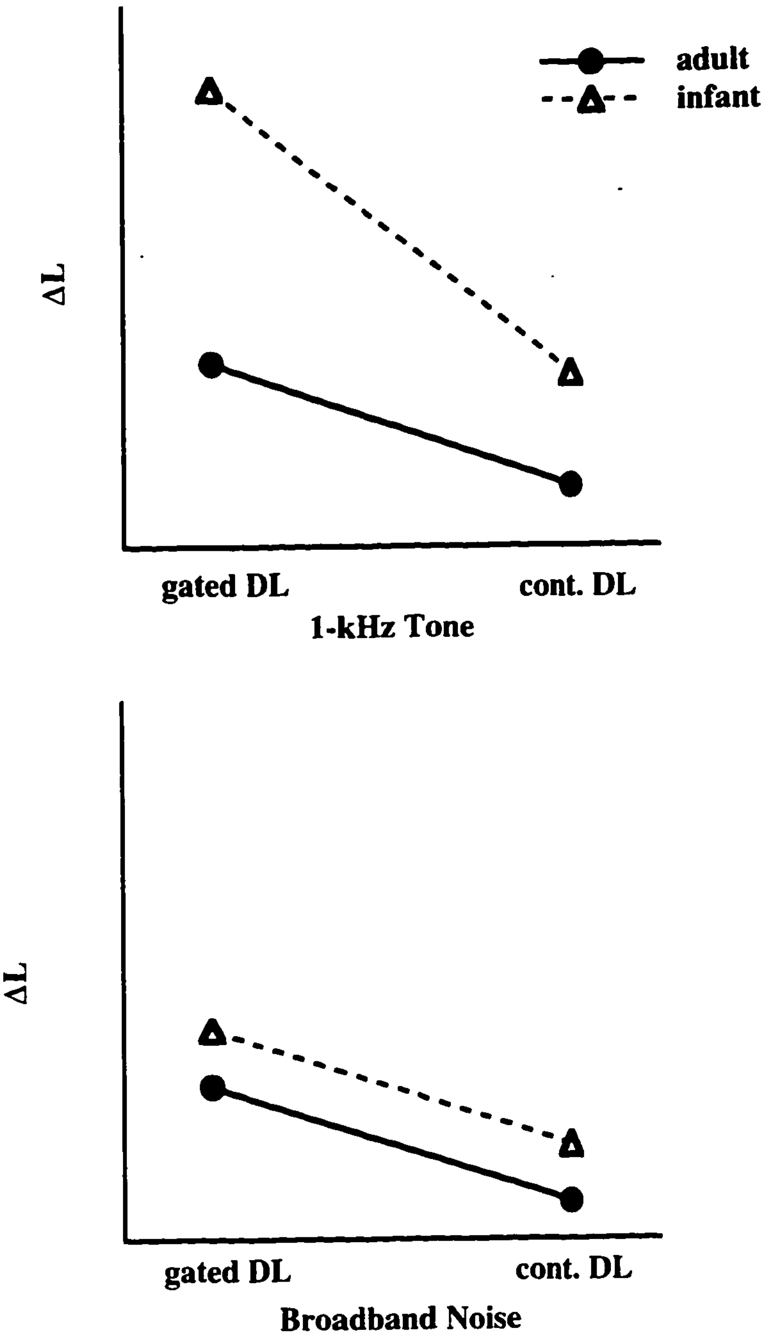

Figure 5. Predicted effect of wandering listening band (infant uses spectral cue) on intensity DLs.

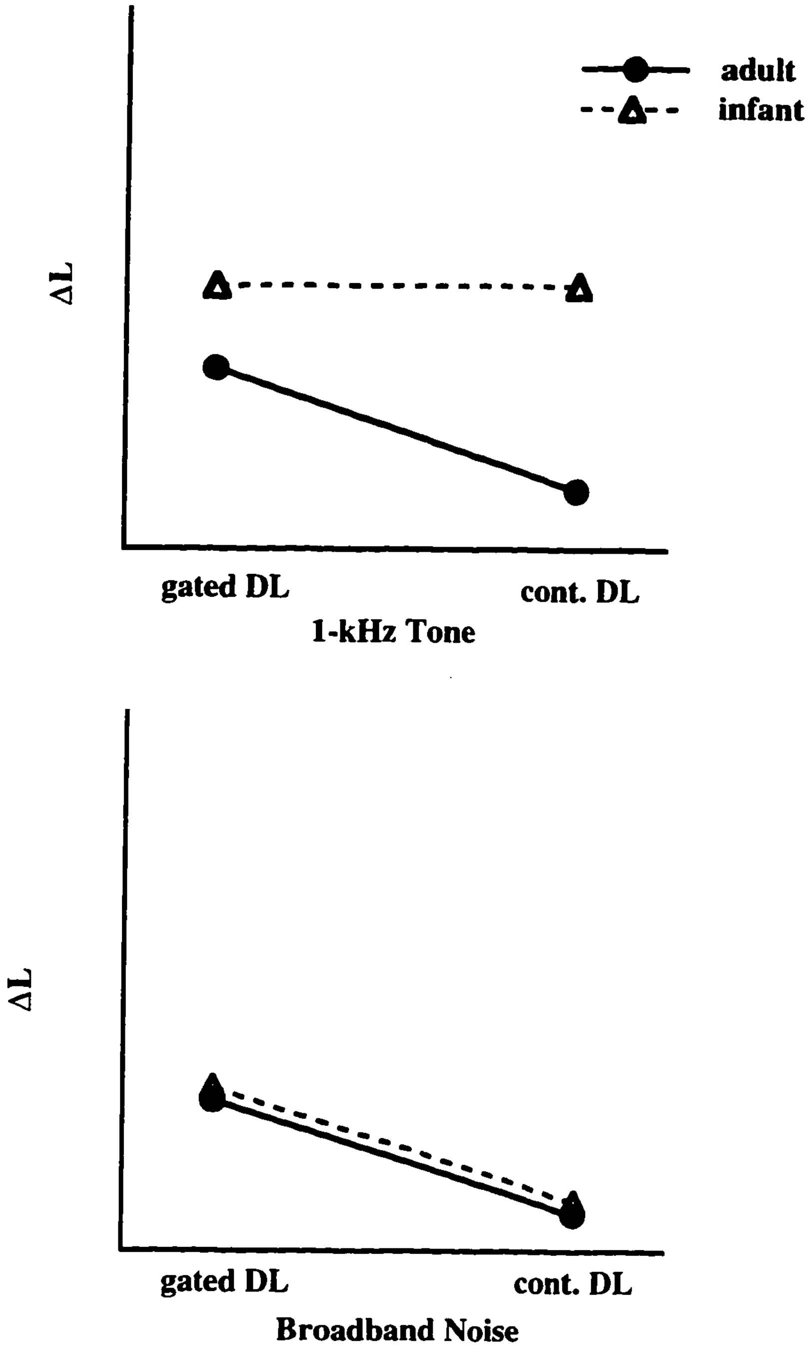

Figure 6. Predicted effect of wandering listening band (infant does not use spectral cue) or broadband listening on intensity DLs.

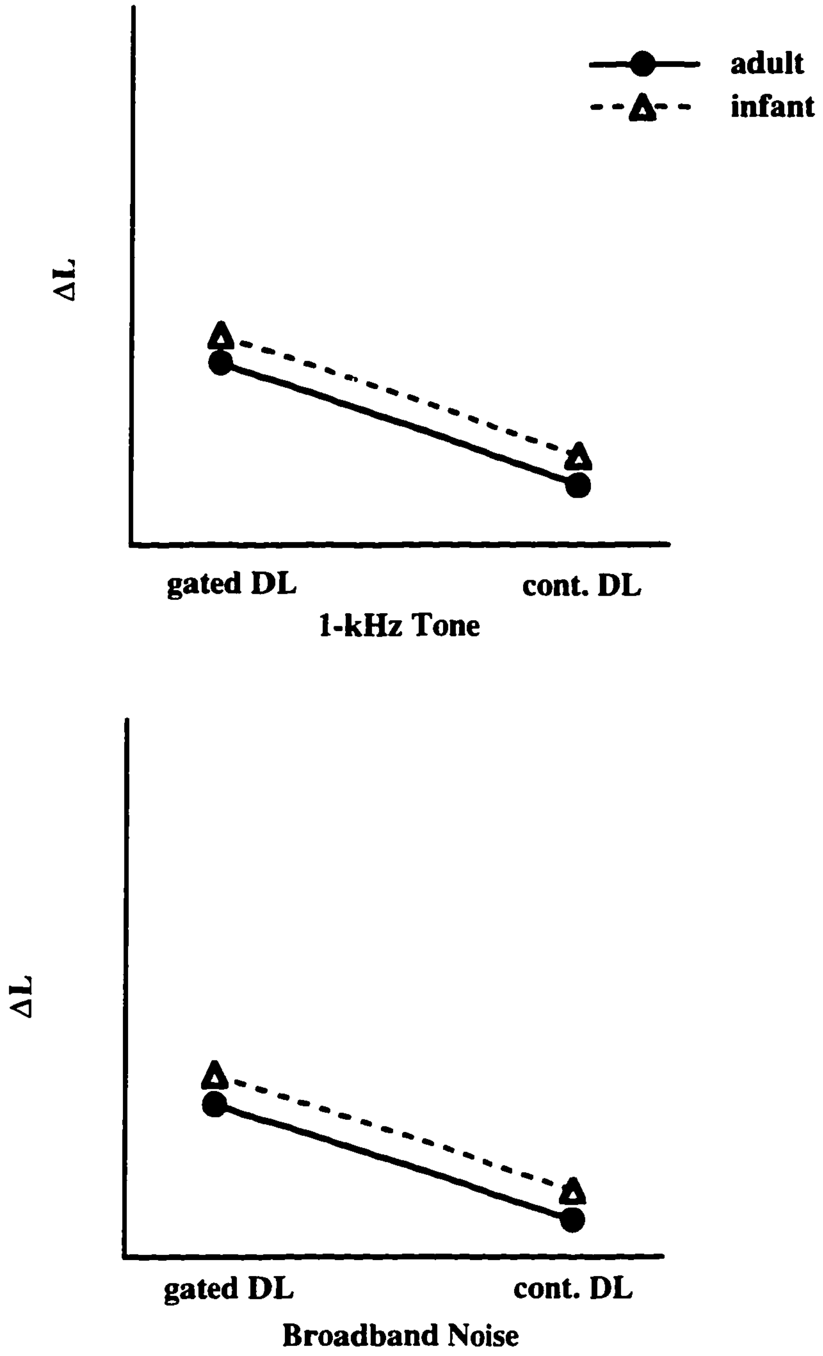

Figure 7. Predicted effect of general inattention on intensity DLs.

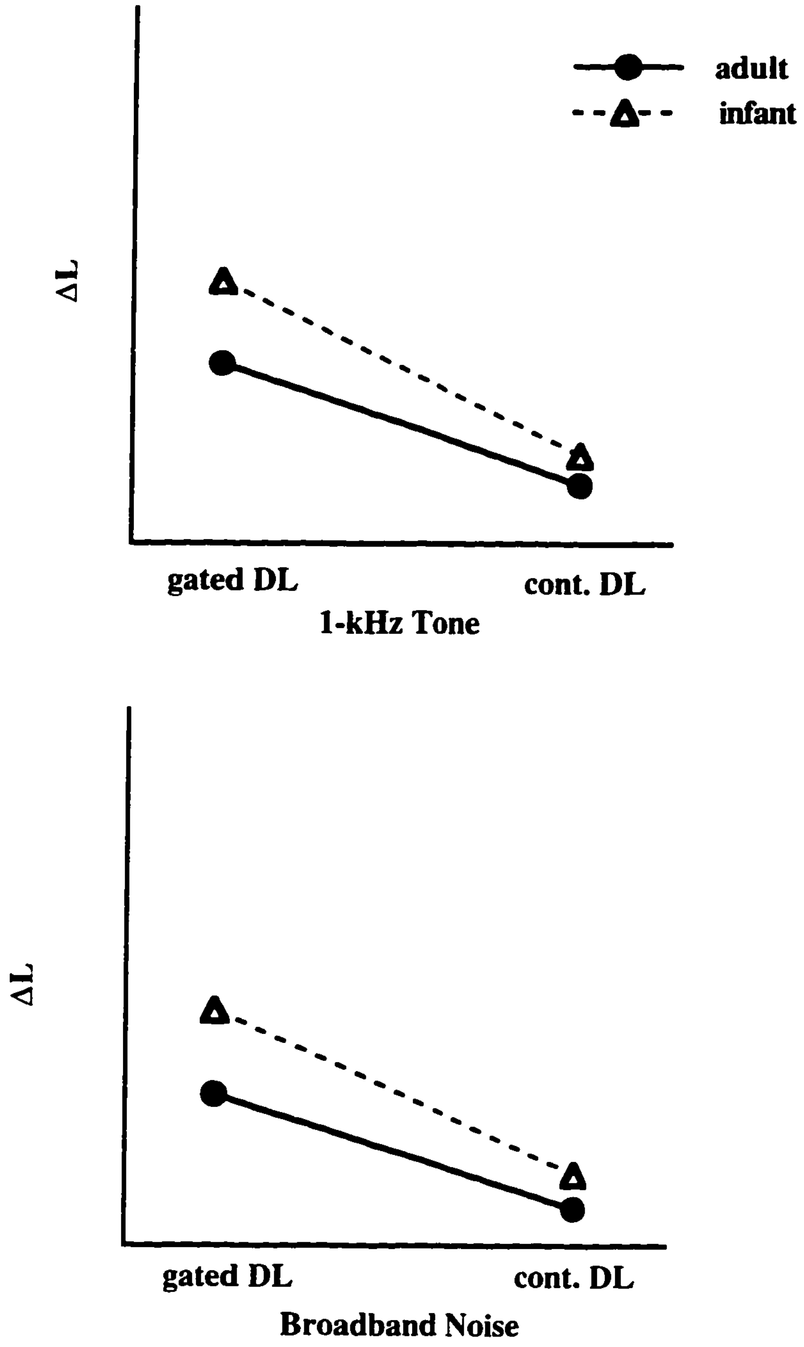

Figure 8. Predicted effect of immature memory on intensity DLs.

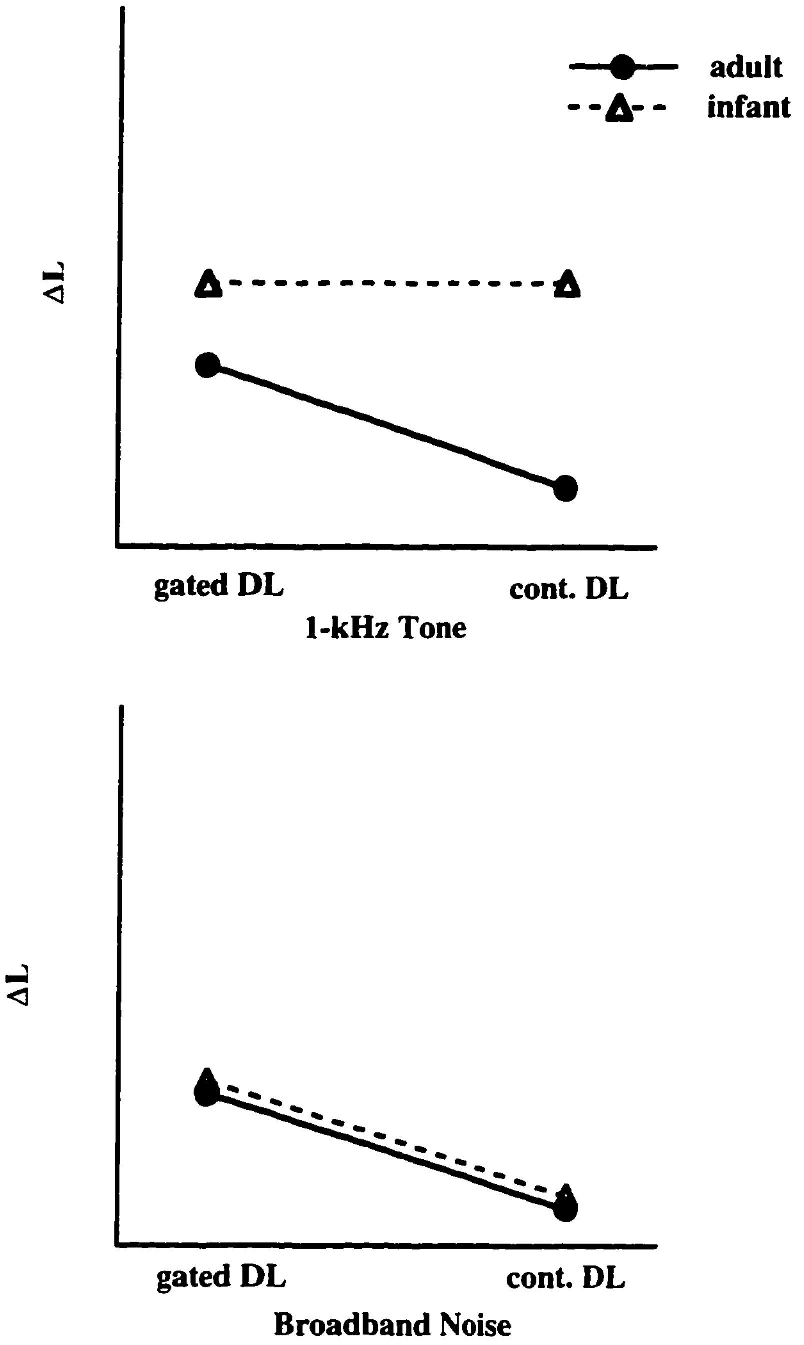

Figure 9. Predicted effect of mature across-channel mechanisms but immature within-channel mechanisms on intensity DLs.

Chapter 2.

General Methods

The general methods were the same for both experiments. Details specific to each experiment are explained in Chapters 3 and 4.

I. Subjects

Subjects were 6- to 9-month-old infants and young adults (19 years old to 29 years old). Infant subjects were recruited from the University of Washington Infant Studies Subject Pool, had no risk factors for hearing loss (Joint Committee on Infant Hearing, 1991) and were free of middle ear infections for at least a week by parental report.

Adult subjects were recruited by an advertisement in the daily student campus newspaper. By their own report, adult subjects had no risk factors for hearing loss, no known current hearing loss, were free of middle ear infections for at least a week, and were naive listeners. For this study, a naive listener was defined as a listener who has had less than 2 years of musical training and has not participated previously in a psychoacoustic experiment. All subjects were given a tympanometric screening at the end of each visit. Criteria for passing the screening was the presence of an admittance peak between +50 to -200 daPa with a peak height of ≥ .2 mmho.

II. Stimuli

The stimulus was either a pure tone of 1 kHz or a broadband noise. The subjects listened to all stimuli using an Etymotic ER-1 insert earphone fitted with either a standard-sized or custom-trimmed foam eartip. In the gated-pedestal, tone condition, 500-ms, 1-kHz tone bursts were generated digitally using a Data Translation (DT2821) D/A board. The 16-ms rise and fall was cosine-shaped. The signal was attenuated digitally (Wilsonics, PATT), passed through a dual filter (KEMO, VBF8; 45 dB/octave roll-off), mixed, amplified, impedance matched and sent to the listener's earphone. In the continuous-pedestal, tone condition the digitally generated, 1-kHz tonal signal was split at the output of the Data Translation (DT2821) D/A board. The pedestal tone was passed through the circuit described above. The 500-ms increments were gated (Colburn S84-04; set to 16 ms rise/fall), attenuated digitally (Wilsonics, PATT), passed through a dual filter (KEMO, VBF8; 60 dB/octave roll-off), mixed with the pedestal signal, amplified, impedance matched and sent to the ER-1 earphone.

In the gated-pedestal, noise condition, 500-ms noise bursts were produced by a General Radio, random noise generator (1381). The noise bursts were passed through an equalizer (Rane, PE15), attenuated digitally (Wilsonics, PATT),and low-pass filtered with a 12.75 kHz frequency cutoff (KEMO, VBF8; 60 dB/octave roll-off). The noise signals were then mixed, amplified, impedance matched and sent to the listener's earphone. In the continuous-pedestal, noise condition the pedestal noise signal passed through the circuit just described for the gated-pedestal, noise condition. Increments of 500 ms were produced by decreasing the attenuation of the noise pedestal.

Figure 10 shows signal and no-signal trials in the continuous-pedestal paradigm. For both the continuous-pedestal, noise and the continuous-pedestal, tone conditions, signal trials were 4 s in duration and were composed of: 3 repetitions of a 500-ms pedestal followed by a 500-ms increment; a 1000-ms pedestal ends the trial. No-signal trials were 4 s of the continuous pedestal. Figure 11 shows signal and no-signal trials in the gated-pedestal paradigm. For both the gated-pedestal, noise and the gated-pedestal, tone conditions, signal trials were 6 s in duration and were composed of 3 repetitions of a 500-ms pedestal and a 500-ms increment, each followed by 500 ms of silence. No-signal trials were a series of 6, 500-ms gated pedestals separated by 500-ms of silence. Trials in the gated-pedestal paradigm were longer than those in the continuous-pedestal paradigm due to the periods of silence between gated sound bursts. Prior to the experiment, it was decided to equalize the number of "looks" at the intensity changes rather than the length of trials. Therefore, both gated and continuous signal trials contained 3 intensity increments, but differed in length.

III. In-the-ear calibration

To ensure proper eartip placement, a calibration was performed using an Etymotic ER-7C probe microphone system. The level of a broadband noise, presented at 60 dB SPL as measured in a Zwislocki coupler, was measured in each subject's ear canal. This measurement was always taken at the beginning and end of the data collection session, any time the eartip was replaced, and whenever the experimenter questioned the eartip placement. If an age-appropriate level (based on lab norms) was not measured, the eartip was replaced.

IV. Procedure

All data were collected using the Observer-based Psychoacoustic Procedure (OPP; see complete description in Werner, 1995). In this procedure, an observer sits outside a soundproof test booth and watches the infant listener through a one-way window or on a video monitor. The infant sits on a parent's lap inside the test booth with the experimenter's assistant. Both the parent and the assistant wear earphones so they can't hear the infant's stimuli. The parent listens to music during the experimental session; the assistant listens to the observer announce the beginning of each trial and receives feedback after each trial ends. During the session, the assistant manipulates simple toys to bring the infant's gaze to midline and ready the infant for the start of a trial. When the infant is in a ready state (quiet and looking forward), the observer presses a switch to begin a trial. A trial was either a signal trial (3 increments added to the background or pedestal stimulus) or a no-signal trial (continuation of the background or pedestal stimulus). The observer, blind to trial type, decides whether a signal or a no-signal trial is occurring, based on the infant's response. The observer receives feedback after every trial and tries to learn the difference between a signal response and a no-signal response.

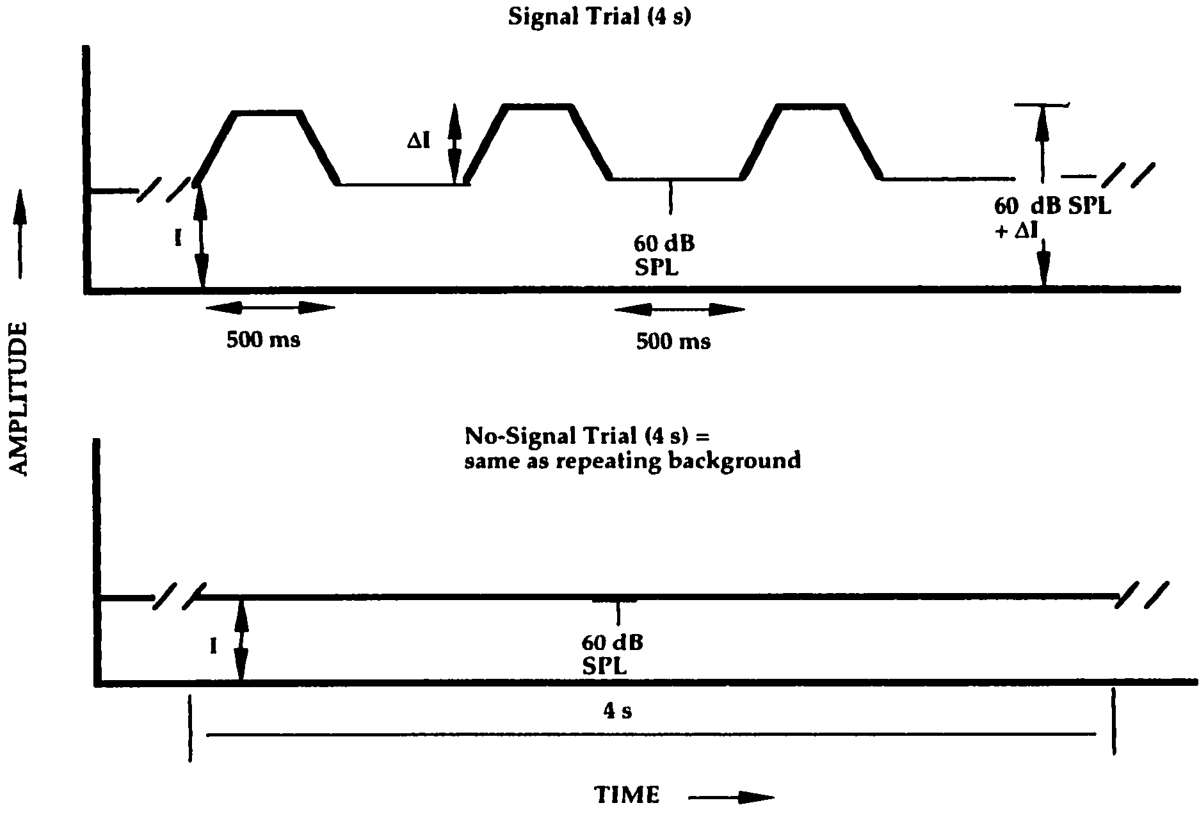

Figure 10. Signal and no-signal trials in the continuous-pedestal paradigm.

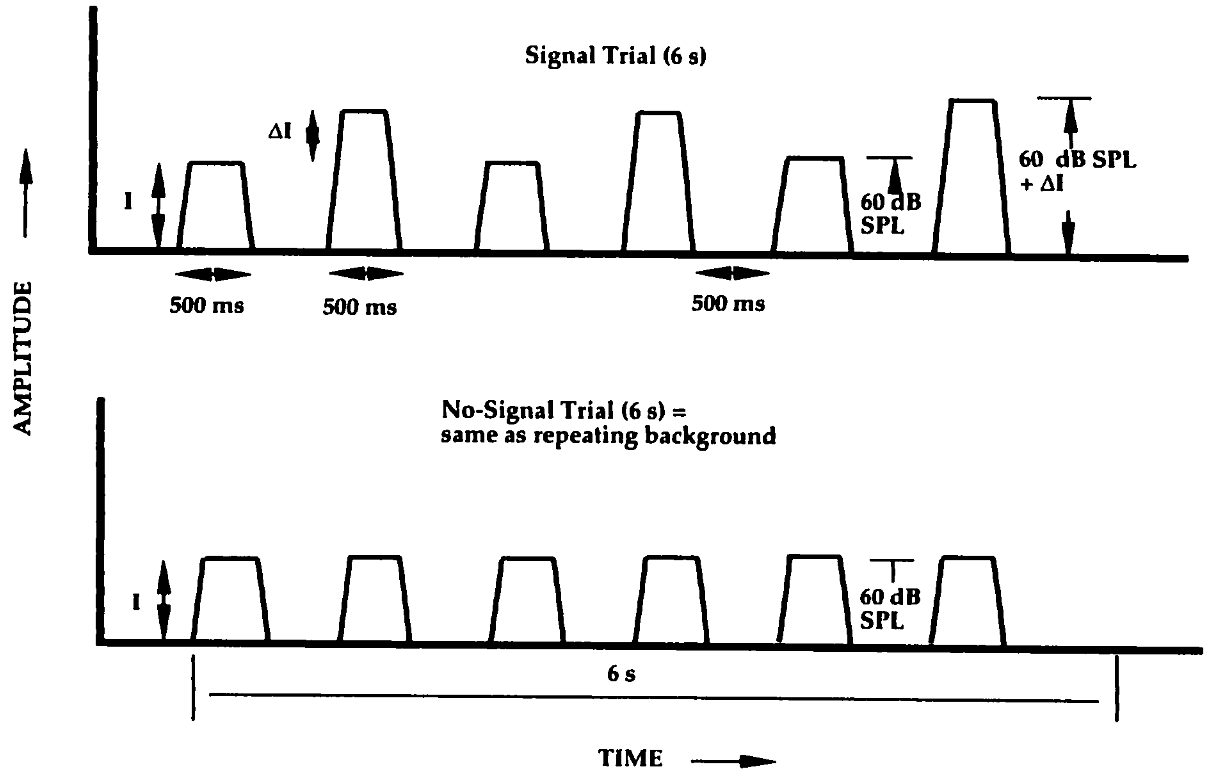

Figure 11. Signal and no-signal trials in the gated-pedestal paradigm.

A data collection session consists of two training phases, and if training criteria are met, a test phase. During the first training phase, a mechanical toy in a plexiglass box is activated at the end of every signal trial, regardless of the observer response. Pairing this reinforcer with each signal trial designates the signal stimulus. In the second training phase and in the test phase, the reinforcer is activated only when the observer correctly identifies a signal trial. Reinforcement begins as soon as the observer scores a hit (correctly identifies a signal trial) and lasts at least 2 s past the end of the trial. Since the observer begins a trial when the infant is in a ready state, the intertrial intervals are variable, with a minimum duration of about 1 or 2 s.

The pedestal was turned on after the earphone was inserted in the listener's ear and remained on throughout the session except during the in-the-ear calibration, between session phases and during any breaks that were taken.

Adult data collection sessions were conducted in a similar way to infant sessions. Adult subjects sat alone in the test booth and were instructed to respond when they "heard the sound or sounds that make the mechanical toy light up." Adult sessions were composed of two training phases and one test phase, identical to infant sessions.

Chapter 3.

Experiment 1. Individual psychometric functions for intensity discrimination

The purpose of this experiment was to measure psychometric functions for intensity discrimination of broadband noise from individual 6- to 9-month-old infants and from individual adults. Individual infant functions obtained with broadband stimuli have not been reported to date and are interesting for two reasons. First, the possible contributions of immature listening strategies have been indicated by, among other effects, the shallower slopes exhibited by psychometric functions for detection of narrowband signals in broadband noise. Immature listening strategies are not expected to produce shallower slopes when broadband stimuli are used. Thus, the results of psychometric functions obtained with broadband noise are expected to add evidence supporting or refuting the contribution of immature listening strategies in those previous experiments of narrowband signal detection in noise. Second, DL and slope information obtained from the psychometric functions were needed to specify the adaptive threshold rules in Experiment 2 (gated- versus continuous-pedestal DLs); no information about appropriate values for broadband noise are currently available for this age. In both experiments, adult psychometric functions were obtained in the same experimental paradigm as the infant functions. This provided proper adult-infant comparisons and insured that adult results were consistent with those obtained in other published experimental paradigms.

The pedestal level of 60 dB SPL for this experiment was well above the infant detection threshold for 1-kHz tones (Trehub, Schneider and Endman, 1980; Sinnott, Pisoni and Aslin, 1983; Nozza and Wilson, 1984; Olsho, Koch, Carter, Halpin and Spetner, 1988), was widely-represented in the adult literature (Campbell and Lasky, 1967; Florentine et al., 1987; Schlauch, 1994), and was in the vicinity of the level that produced the largest adult gated-continuous DL difference for a broadband noise stimulus (55 dB SPL, Green and Sewall, 1962).

I. Subjects

Infant subjects were scheduled for 3 - 7 visits; adult subjects were scheduled for 2 -3 visits. The objective was to measure intensity discrimination at 2 to 4 different ΔLs in order to construct a psychometric function. Initially, 13 infants and 9 adults were seen; complete psychometric functions were obtained from 9 infants and 8 adults (data from 1 adult were excluded due to equipment error). In an additional study to determine the upper asymptote of the infants' psychometric function, infant subjects were scheduled for 2 visits. A total of 21 infants participated, with data obtained from 11 of the infants. Infant data exclusions by category are listed in Table 1.[4] For all subjects, results from each visit were included if all 35 test trials were run and the hit rate on probe (easy) trials was 60% or better.

Table 1. Data exclusions from infant subjects in experiment 1

	psychometric function	upper asymptote
Nonmonotonic function	2	--
Incomplete data set	2	--
Not trained	--	4
Did not tolerate eartip	--	2
Incomplete test session	--	4

II. Method

Psychometric functions for intensity discrimination were obtained using a broadband noise stimulus in a continuous-pedestal paradigm with a pedestal level of 60 dB SPL.

---

[4] An additional 6 infants were scheduled for one or more visits to obtain a psychometric function. These infants did not complete the study due to failed tympanometry (5) and scheduling conflicts (1). An additional 4 infants who were scheduled for 2 visits to measure the upper asymptote failed tympanometry and did not complete the study.

After the subject met training criteria, a block of 35 trials was run and a measure of sensitivity, d ′, calculated. In each block, 15 signal trials (3 increments added to the continuous pedestal) and 15 no-signal trials (the continuous pedestal alone) occurred in pseudo-random order. The same increment size was used throughout a block. In addition, 5 probe trials--easily-detectable signal trials with increments of 10 or 15 dB--were interspersed throughout the block to assess whether the subject was attentive and under stimulus control. The probe trials were not used to calculate d ′.

Specific rules for obtaining the data points used to construct the psychometric functions were based on the results of pilot experiments. For infant subjects, the first two data points were obtained at ΔLs of 6 and 8, with the order of presentation counterbalanced across subjects. Depending on the d ′ s obtained, the next data point was run at a larger or smaller ΔL, increasing or decreasing in steps of 2 dB. For adult subjects, the first two data points were obtained at ΔLs of .6 and .8, with the order of presentation counterbalanced across subjects. Depending on the d ′ s obtained, the next data point was run at a larger or smaller ΔL, increasing or decreasing in steps of .2 dB. The objective was to obtain a data point at or near the upper asymptote, a data point near chance performance and at least one data point on the slope. If more than one point was measured on the upper asymptote[5], the d ′ s for the points were averaged and one point plotted corresponding to the lower ΔL. For example, a d ′ of 2.6 was obtained at a ΔL of 6 and a d ′ of 2.26 was obtained at a ΔL of 8 for one infant subject. The averaged d ′, 2.43, was plotted at a ΔL value of 6. If a psychometric function was not monotonic, an attempt was made to re-run the condition producing the nonmonotonicity. The best performance of the two runs was then included in the psychometric function.

---

[5] The data point corresponding to the best performance was plotted as the beginning of the upper asymptote. Any point that fell within the 95% confidence interval of this point in a binomial distribution was considered to be on the upper asymptote.

Since upper asymptotes were not obtained for most of the individual infant functions, upper asymptote data were obtained from a separate group of infants. A block of 30 trials, 15 signals and 15 no-signals was run at an increment size of 20 dB (ΔL), larger than the maximum increment used to obtain the individual psychometric functions.

III. Results

To this point, the size of the intensity increment has been described in units of ΔL, an intuitive metric for most readers. However, compared with other intensity metrics, the variance in ΔL measures increases with the magnitude of ΔL, compounding the heterogeneity of variance already present between infant and adult measures regardless of the metric. In addition, ΔL is a highly-compressive metric especially when plotted in log d'/log ΔL coordinates, as suggested by Buus and Florentine (1991). For these reasons, it was decided that the data would be analyzed and reported in units of $10 \log \Delta I/I$. To avoid confusion, data will also be described in units of ΔL.

In addition to d', subjects' performance will also be expressed in $p(C)_{max}$, which is the maximum percent-correct performance a subject can attain while using an unbiased criterion. Like d', $p(C)_{max}$ is an unbiased measure of sensitivity, but for most readers, $p(C)_{max}$ is a more intuitive measure of performance.

Individual psychometric functions for intensity discrimination are shown in Figure 12 for adults (left) and infants (right). It appears that infant slopes are more shallow than those of adults. The infant functions are all shifted to the right, indicating that infant DLs are worse than adult DLs.

The slope and DL were estimated for statistical analysis. It is apparent from Figure 12 that the infant psychometric functions exhibit greater DL variability than the adult functions. Across studies, infants' psychoacoustic performance is commonly more variable than adults' performance (*e.g.*, Sinnott and Aslin, 1985; Nozza, Miller, Rossman and Bond, 1991; Werner and Marean, 1991). Bartlett's test for homogeneity of variance was run prior to computing all statistics, and in cases of nonhomogeneity of variance, nonparametric statistics were used.

A. Slope

Individual slopes were estimated from the best linear fit to each subject's data, expressed as log d′ as a function of 10 log ΔI/I. In other words, there is a power function relationship between d′ and ΔI/I. For psychometric functions with an upper asymptote, only the data point at the beginning of the plateau (corresponding to the smallest value of 10 log ΔI/I on the asymptote) was used to calculate slope and DL information. If two points on the psychometric function were nonmonotonic, the d′s were averaged and the data point plotted at the corresponding average of the two values of 10 log ΔI/I.

In log d′ by 10 log ΔI/I coordinates, the average slope of infants' psychometric functions was .147 (S.D. = .074), while the average slope of adults' psychometric functions was .272 (S.D. = .143). The difference between infant and adult slopes was significant [$\underline{t}\,(15) = -2.313$, $p < .05$]. To give the reader a sense of the magnitude of the difference, around the midpoint of the psychometric function, infants' average slope in $p(C)_{max}$/dB (10 log ΔI/I) was 4.9%/dB while adults' average slope was 9.5%/dB.

B. Difference limen

Difference limens were extrapolated from the best linear fit to the psychometric function and were defined as the increment size (in 10 log ΔI/I) corresponding to a log d′ of 0 (*i.e.*, d′ = 1). Average DLs from individual infant and adult psychometric functions are shown in Table 2. Both the size of the infant DLs and the infant-adult DL difference are consistent with intensity DLs for tones reported for 7- to 9-month-old infants and adults (Sinnott and Aslin, 1985). Adult DLs were significantly better than infant DLs [Mann-Whitney $\underline{U} = 72$, $p < .001$], with an estimated infant-adult DL difference of 13.6 dB.

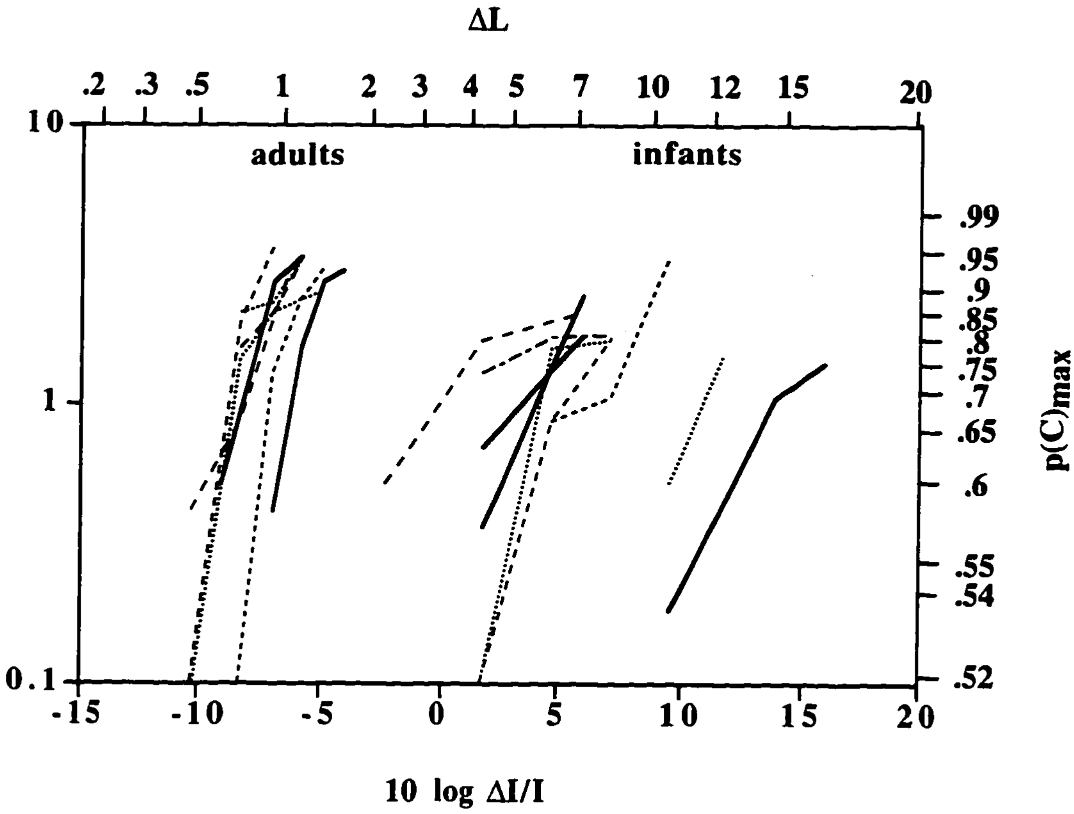

Figure 12. Individual psychometric functions for intensity discrimination from adults and infants.

A sequential look at DLs obtained in the current study indicates that the large DLs were obtained from the first infants run in the experiment while smaller DLs were obtained from infants run later. This observation of a possible order effect was confirmed by a significant correlation between order and DL [Spearman rank $\underline{r}_{\underline{s}} = -.917$, $p<.01$]. There was no order effect for slope [Spearman rank $\underline{r}_{\underline{s}} = -.467$, $p>.05$]. It is possible that with "practice", the observer became more sensitive and that the latter DLs obtained are more indicative of true infant performance. The average DL for the last 4 infants tested was 1.12 dB, which would make the infant-adult difference 9.5 dB. For this experiment, then, estimates of the infant-adult DL difference range from 9.5 to 13.6 dB.

Table 2. Average DLs obtained from individual psychometric functions in experiment 1

	DL (10 log ΔI/I)	DL (ΔL)
Adults	Mean = -8.40 S.D. = 2.00	Mean = 0.70 S.D. = 0.24
Infants	Mean = 5.20 S.D. = 5.26	Mean = 6.70 S.D. = 3.83

C. Upper Asymptote

Discriminating the large increment of 20 dB used to determine infant asymptote is an easy listening task for adults and it is assumed that adult listeners would achieve perfect performance. In another example of an easy auditory task for adults, Bargones (1992) reported that all adult listeners reached 100% correct at the highest levels tested in an experiment measuring psychometric functions for detection. The highest measure of sensitivity in this experiment, that which can be obtained with perfect performance in 30 trials, is a log d′ of .575, or equivalently, a $p(C)_{max}$ of .976[6]. Infants' upper asymptote, in log d′, averaged .463 (S.D. = .076) and, in $p(C)_{max}$, averaged .922 (S.D. = .036). A t-test determined that infants' asymptotic log d′ is significantly lower than .575 [$\underline{t}(10) = -4.87$, $p < .01$]. The average asymptote obtained from infants in this study is higher than upper asymptotes from individual infant psychometric functions (Bargones et al., 1995) but similar to upper asymptotes from individual children's psychometric functions (Allen and Wightman, 1994). Asymptotes from the current study are consistent with upper asymptotes from group infant psychometric functions, which range from .88 to .95 (Schneider et al., 1988; Schneider et al., 1989; Nozza et al., 1990).

---

[6] Because $p(C)_{max}$ is undefined for proportions of 0 and 1, hit or false alarm rates of 0 were changed to 1/2n and perfect hit or false alarm rates were changed to (1 - 1/2n), where n is the number of signal or no-signal trials in the given condition (Macmillan, 1985).

Chapter 4.

Experiment 2. Gated versus continuous intensity difference limens

The purpose of this experiment was to obtain intensity difference limens (DLs) from infants and adults using both a gated-pedestal paradigm and a continuous-pedestal paradigm for each subject. In published adult data, subjects' DLs are lower (i.e. performance is better) when a continuous-pedestal paradigm is used as compared to DLs obtained using a gated-pedestal paradigm. In this experiment, DLs were obtained from adults to verify the expected gated-continuous DL difference and to provide a comparison for infant results obtained in the same experimental conditions.

I. Subjects

Infant subjects were scheduled for 3 - 5 visits; adult subjects were scheduled for 1 visit. The objective was to obtain two thresholds from each subject: one in the continuous-pedestal paradigm and one in the gated-pedestal paradigm. Each subject listened to either a broadband noise or a 1-kHz tonal stimulus for both paradigms. A total of 74 infants and 39 adults participated in the study; 18 infants and 20 adults provided 2 acceptable DLs, 9 infants and 10 adults in each stimulus condition. In addition, 23 infants provided only one acceptable DL: 1 in the gated tone, 3 in the continuous tone, 0 in the gated noise and 19 in the continuous noise conditions. Data exclusions are shown in Table 3.[7]

Table 3. Data exclusions for infant and adult subjects in experiment 2

	Infants	Adults
Incomplete DL session	15	2
Not trained	8	2
Data inclusion criteria not met	10	9
Observer error	0	6

---

[7] An additional 38 infants were scheduled for 3 or more visits but did not complete the study due to failed tympanometry (21), illness (2), scheduling conflicts (11) and eartip intolerance (4).

II. Method

A DL for intensity discrimination was obtained from each subject using both a continuous-pedestal paradigm and a gated-pedestal paradigm with a pedestal level of 60 dB SPL. One group of subjects listened to broadband noise and a second group of subjects listened to a 1-kHz tone. Paradigm order was counterbalanced across subjects. The 1-kHz stimulus was chosen to facilitate comparison with published infant thresholds for intensity discrimination (Sinnott and Aslin, 1985) and because adult intensity discrimination data obtained with a 1-kHz stimulus has been well-characterized (Florentine et al., 1987; Rabinowitz et al., 1976; Jesteadt et al., 1977; Schlauch, 1994; Campbell and Lasky, 1967; Green et al., 1979; Campbell, 1966). The broadband noise stimulus was used because several models of the gated-continuous DL difference predict different results for pure tones and broadband noise.

After subjects successfully completed the training phases described in Experiment 1, they entered the testing phase. In this phase, a DL for intensity discrimination was estimated using a 1-up, 2-down adaptive procedure (Levitt, 1971) with the stimulus adjusted according to PEST rules (Taylor and Creelman, 1967). A total of eight reversals were obtained. The first two reversals were discarded and the last six reversal values averaged to calculate the DL. During the testing phase, in each block of 7 trials, 5 were signal trials, 1 was a no-signal trial and 1 was a probe trial. (See Figures 10 and 11 showing signal and no-signal trials for continuous- and gated-pedestal paradigms). Probe trials were easily-detectable signal trials with increments of 15 dB. Neither no-signal trials nor probe trials were used in the decision rules driving the adaptive staircase. No-signal trials were used to control for response bias: only DLs obtained in sessions with a false alarm rate $\leq .44$ were included in the data analysis. Probe trials were used to insure that the subject remained under stimulus control: only DLs obtained in sessions with a probe hit rate of at least .6 were included in the data analysis. The standard deviation of reversals had to be less than 1.51 for adults and 2.51 for infants. The data of 5 adults and 1 infant were discarded as outliers; their DLs were more than 2 standard deviations from the mean for their age group and condition.

III. Results

A. Gated and continuous DLs from infants and adults

Average DLs from infants and adults for a 1-kHz stimulus and a broadband noise stimulus are shown in Figure 13. Adults show the expected improvement in the continuous-pedestal DL for both stimuli, while infants' continuous-pedestal DL shows improvement for the broadband noise stimulus but not for the 1-kHz tone. In other words, the infant gated-continuous DL difference is similar to that of adults for the broadband noise stimulus, but apparently smaller than the adult DL difference for the 1-kHz stimulus. This observation was confirmed with separate, 2-way ANOVAs (age X paradigm) for 1-kHz and for broadband noise. An adjusted rank transform of the DLs (a nonparametric procedure, following Sawilowsky, 1990) was performed prior to the ANOVAs. The ANOVAs showed a significant interaction for the 1-kHz stimulus [F (1,17) = 7.09, p<.02] but not for the broadband noise stimulus [F (1,17) <1].[8] The main effect of paradigm was assessed using the Wilcoxon signed ranks test. For broadband noise, it was significant for both adults [T=-2.80, p<.01] and infants [T=-2.67, p<.01]. For the 1-kHz stimulus, the main effect of paradigm was significant for adults [T=-2.80, p<.01], but not for infants [T=-.533, p>.5].

To assess the main effects of age and stimulus, gated and continuous DLs were combined within each stimulus condition. Across all conditions, infant DLs were worse than adults DLs and this was confirmed by a significant main effect of age for the

---

[8] The Adjusted Rank Transform Test is a nonparametric technique for assessing an interaction effect. Sawilowksy advises against the analysis of main effects with this technique. Therefore, main effects were analyzed using nonparametric, pairwise comparisons.

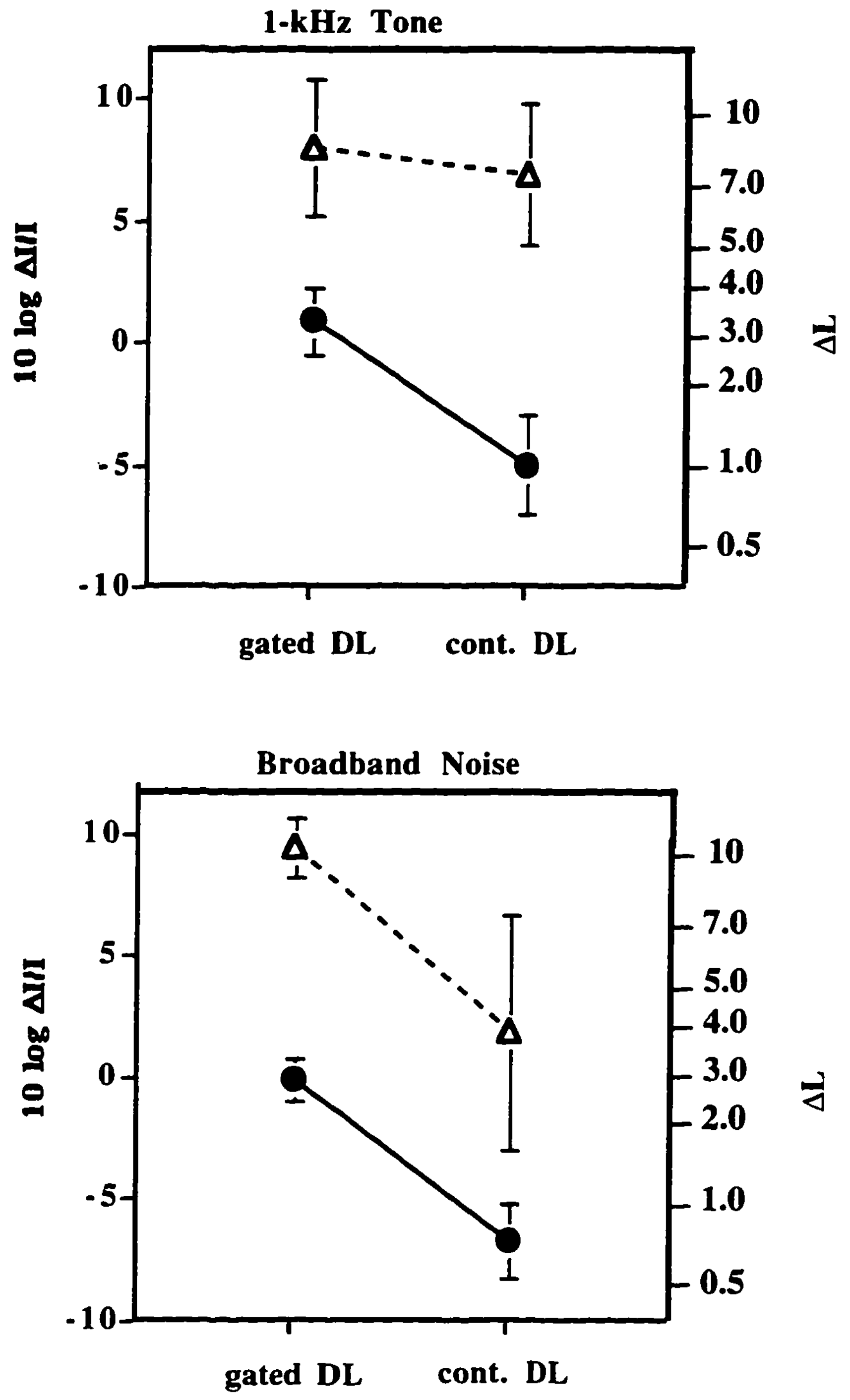

Figure 13. Average intensity DLs obtained in gated- and continuous-pedestal paradigms for 1-kHz tone and broadband noise. Data are from subjects who contributed a DL in both paradigms only. Infant results are indicated with open triangles; adult results are indicated with filled circles. Error bars are ± 1 S.D.

broadband noise stimulus [Mann-Whitney U = 322.5, p<.01] and the 1-kHz stimulus [Mann-Whitney U = 357.5, p<.01]. The finding of an age X paradigm interaction for the 1-kHz tone but not for broadband noise implies that the infant continuous-tone DL is worse than the infant continuous-noise DL. Therefore, the main effect of stimulus for infants was not tested because it is clear from the interaction results that the effect of stimulus depends on paradigm. However, the main effect of stimulus for adults was tested and found to be nonsignificant [Mann-Whitney U = 152.0, p>.1]. There was no significant difference between adult DLs obtained with a 1-kHz tone and a broadband noise.

The large amount of variability associated with the infant DL in the continuous noise condition is notable when compared with infant and adult DLs in the other stimulus and paradigm conditions. However, despite this variability, a significant interaction (age X paradigm as a function of stimulus) was found even using conservative nonparametric statistics.

B. Within and between-subject comparisons

A relatively small percentage of participating infant subjects contributed a DL in both paradigms. In an effort to evaluate whether this group of subjects is representative of the general infant population, their average DLs were compared with the average DLs calculated from all subjects who contributed data. Mean within-subject DL were calculated from the 18 infants who contributed a DL in both the gated- and the continuous-pedestal paradigms. Mean between-subject DLs included data from 23 infants who provided a DL in only one paradigm and the first DL obtained from the other 18 infants. The means are shown in Figure 14. Absolute DL values are nearly identical, and the pattern of results seen for the within-subject group is maintained in the between-subject group: no gated-continuous DL difference for 1-kHz and an adultlike gated-continuous DL difference for broadband noise. As mentioned above, the large amount of variability associated with the average DL for continuous noise obtained from the 2-DL group is striking. The large standard deviation for the gated-tone DL obtained from the 1-DL group is probably due to a small sample size (N = 3).

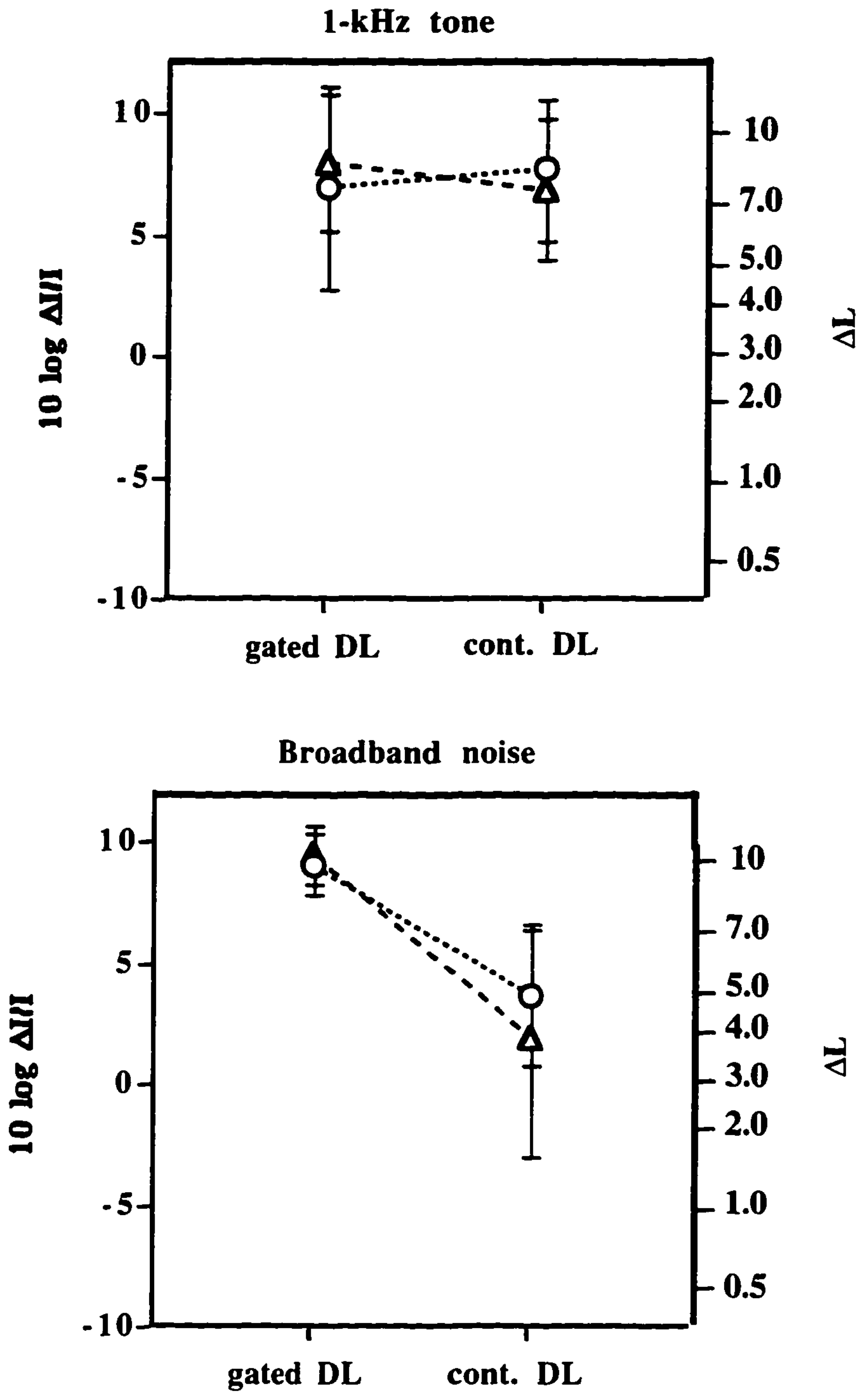

Figure 14. Average infant intensity DLs from two groups. Open triangles indicate average of infants who contributed 2 DLs. Open circles indicate average of all infants who contributed at least 1 DL. In cases where infants contributed more than 1 DL, only the first DL was used to calculate the average. Error bars are ± 1 S.D.

Chapter 5.

Discussion

I. Psychometric functions

Infants' individual psychometric functions for intensity discrimination of broadband noise stimuli exhibited higher DLs and shallower slopes compared with those of adults. The infant average upper asymptote was lower than presumed perfect adult performance. These results are qualitatively consistent with individual psychometric functions for detection of tones in noise from infants (Bargones et al., 1995) and from children (Allen and Wightman, 1994) and infant group psychometric functions for discrimination of speech syllables in noise (Nozza et al., 1990) and detection of octave-band signals in noise (Schneider et. al, 1992). Quantitatively, the infant upper asymptote is higher than upper asymptotes from individual infant psychometric functions (.92 compared to .83) but similar to those from individual psychometric functions from children (.92 compared to .93) (Bargones et al., 1995; Allen and Wightman, 1994). Data collection procedures and age of infants were similar in the current study and that of Bargones et al. (1995). However, differences in stimuli may account for the difference in upper asymptote: off-signal energy was present in the masker in the Bargones et al. (1995) study, and some immature listening strategies in such conditions would lead to an apparently lower asymptote (*e.g.*, Hubner, 1993). In the current study, the broadband noise contains signal energy across a wide range of channels, so listening strategy would not be expected to affect the slope, DL or upper asymptote of the psychometric function.

The average adult slope was steeper than slopes measured from trained adult listeners in a similar continuous-pedestal paradigm with broadband noise (Green and Sewall, 1962). The average slope from Green and Sewall's results, in log d' by 10 log $\Delta I/I$ coordinates, was .157 (S.D. = .016), compared to .272 (S.D. = .143) in this study. A difference in methodology that could account for the reduced adult slopes in the current study is obtaining data points in blocks of fixed increments rather than randomizing the increment within a block of trials. Buus (personal communication) has suggested that listeners will “slack off” in blocks of fixed, small increments thus making the psychometric function steeper. Randomizing the size of the increment would prevent this from happening.

To assess this possibility, psychometric functions were obtained for intensity discrimination from a small group of adult listeners (N = 3) using blocks of mixed increments. A block of 30 signal trials consisted of 15 no-signal trials and 15 signal trials in 5 increment sizes (in ΔL): .4, .6, .8, 1.0 and 1.2 dB. Each increment size appeared 3 times within a block and data were averaged over 5 blocks. Each point on the psychometric function was based on 30 (15 no-signal and 15 signal) trials, identical to psychometric functions obtained using blocks of fixed increments. The functions obtained are plotted in Figure 15, along with those obtained from the adults tested with fixed increments. The slope calculated from these functions averaged .119 (S.D. = .013), a closer approximation to Green and Sewall’s slope results. Thus, it appears that with a slight change in methodology, the adults’ results are consistent with published results.

How does this finding affect the interpretation of the difference in slope between infant and adult psychometric functions? Infants may be affected in the same way as adults by randomized versus fixed increments; that is, slopes of infants’ psychometric functions would become more shallow. This would maintain the infant-adult slope difference seen in the current results. Another possibility is that randomizing increments may have no effect on infant performance. In this case, the infant slope average would be similar to that obtained with fixed increments in the current experiment (.147 with S.D. = .074) and the adult slope average would approximate that obtained from the 3 adults listening to randomized increments (.119 with S.D. = .013) resulting in no infant-adult slope difference. Time constraints made it impossible to assess the effect of randomized increments on infant subjects. However, frequency discrimination results from infants

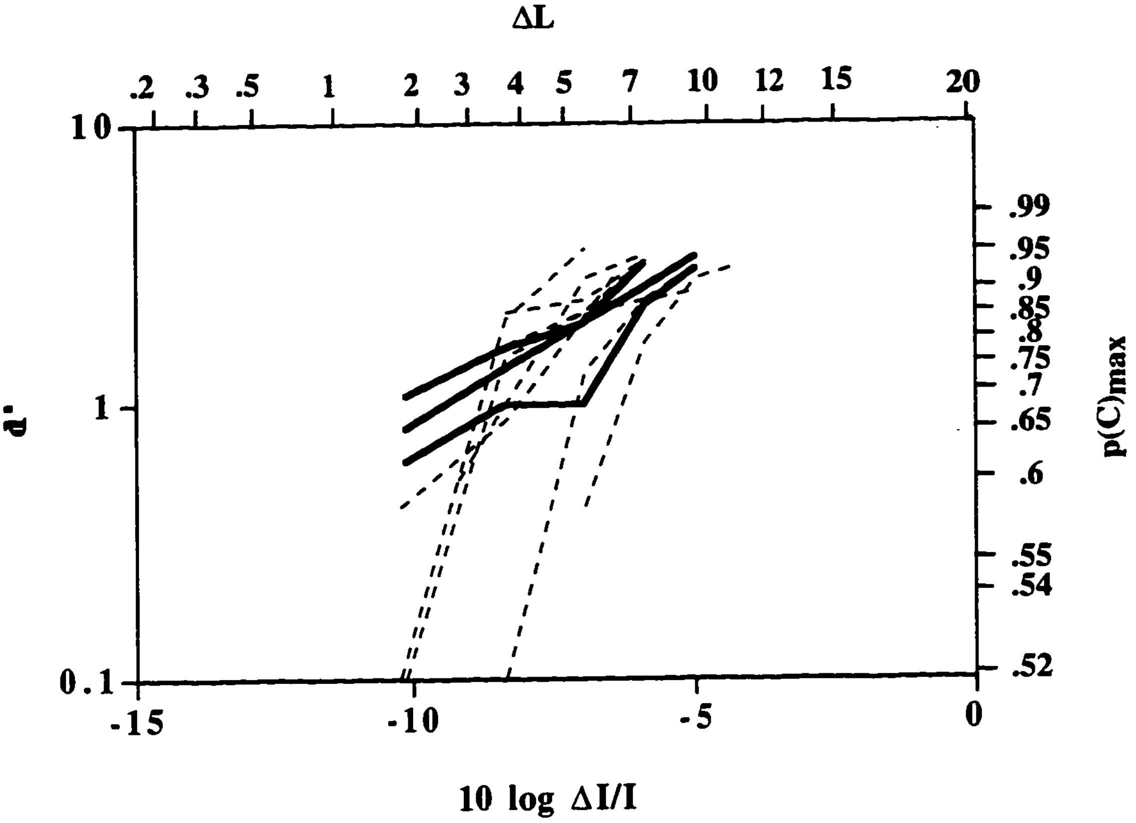

Figure 15. Individual adult psychometric functions for intensity discrimination obtained with random increments (solid line) and fixed increments (dashed line).

and adults using blocks of randomized frequency increments for all subjects showed that the slopes of infants' psychometric functions were still more shallow than those of adults (Olsho, Koch and Halpin, 1987). These results suggest that the infant-adult slope difference in the current experiment is not due to a lack of randomized increments.

The psychometric function slopes for intensity discrimination of broadband noise in the current study can be compared to the slopes for detection of a tone in noise (Bargones et al., 1995). To facilitate this comparison, the current results were plotted in $p(C)_{max}$ by 10 log $\Delta I/I$ coordinates in order to obtain an estimate of % performance change/dB. Infant average slope was 4.9%/dB, while the average adult slope was 9.6%/dB. Infant slopes are consistent with those reported by Bargones et al. (1995). Adult slopes are steeper than those reported by Green and Sewall (1962), as mentioned above.

Bargones et al. (1995) hypothesize that either a single, wandering listening band or inattention combined with either neural variability or reduced growth of excitation may account for their results. A wandering listening band is expected to make the slope of the psychometric function shallower for a pure tone stimulus but not for a broadband noise stimulus. There is no difference between infant slopes in the two studies, suggesting that a wandering listening band may not be contributing to immature infant detection in noise (Bargones et al., 1995), leaving a combination of inattention and neural variability or inattention and reduced growth of excitation as possible explanations.

Four models were proposed to account for the immature infant psychometric functions in Experiment 1: stimulus uncertainty, reduced growth of excitation with intensity increase, variability in the neural representation of intensity and general inattention. Because infant functions exhibited shallower slopes than adult functions, the two models that do not predict shallower slopes, reduced growth of excitation and stimulus uncertainty, can be eliminated as sole underlying mechanisms.

This leaves general inattention and neural variability as candidates for an exclusive underlying mechanism of immaturity. General inattention could explain the infant immaturities seen in the psychometric functions for intensity discrimination. The shape of the infant functions conforms to the predictions of the model: the slope is more shallow, the DL is increased and the upper asymptote is decreased as compared to adult functions. Reduced upper asymptotes attributed to general inattention are characteristic of infant psychometric functions for auditory detection (Schneider et al., 1989; Nozza et al., 1990; Bargones et al., 1995). If general inattention is the sole underlying mechanism of immaturity, it must be also be able to account for the magnitude of the infant-adult slope and DL differences. To assess this, infant functions were corrected for the presumed effects of inattention. In the current experiment, the rate of inattention estimated directly from the upper asymptote is 16%. The infant functions were adjusted (or rescaled) for this rate of inattention according to models of general inattention which define observed performance as 1 - (.5 x inattention rate) (*e.g.*, Wightman and Allen, 1992; Viemeister and Schlauch, 1992). Average slope and DL from infant functions rescaled for a .16 rate of inattention are shown in Table 4. Compared to the original data, the average slope from the rescaled infant functions is steeper and no longer different from the adult slope [$\underline{t}$ = 1.047, p>.3].

Thus it appears that inattention can account for the infant-adult slope difference. However, infant DLs from rescaled functions are still significantly worse than adult DLs [Mann-Whitney $\underline{U}$ = 71, p<.01]. The effect of general inattention can only account for .72 dB of the original 13.6 (or 9.5) dB infant-adult DL difference. Therefore, general inattention could contribute to, but cannot be the sole mechanism underlying immature infant intensity discrimination.

Another mechanism must be invoked to explain the magnitude of the DL increase. Correcting infant psychometric functions for inattention eliminates the infant-adult slope

Table 4. Average slopes and DLs from infant functions, adult functions and infant functions rescaled for inattention.

	Slope (log d′/10 log ΔI/I)	DL (10 log ΔI/I)
Infants	Mean = .147 S.D. = .074	Mean = 5.22 S.D. = 5.26
Adults	Mean = .272 S.D. = .143	Mean = -8.40 S.D. = 2.00
Infants (rescaled)	Mean = .198 S.D. = .150	Mean = 4.49 S.D. = 5.79

difference, so neural variability, which predicts a shallower slope, is no longer a possible underlying mechanism, exclusively or in combination with general inattention.

A combination of general inattention and reduced growth of excitation may explain the infant-adult intensity discrimination differences. Reduced growth of excitation predicts an increase in threshold. Reduced growth of excitation could result in a DL increase of approximately 10 dB (Schneider et al., 1989), which accounts for most of the 12.88 (or all of the 8.78) dB infant-adult difference remaining after correction for inattention. Some supporting evidence can be found in single-unit results from developing nonhumans (Brugge et al., 1978; Brugge et al., 1981; Woolf and Ryan, 1985; Sanes and Rubel, 1988) and evoked potential results from human infants (Werner et al., 1994) and children (Kraus et al., 1985) that reduced growth of excitation is characteristic of the immature auditory system.

A combined effect of general inattention and reduced growth of excitation was one explanation proposed by Bargones et al. (1995) to account for their immature infant psychometric functions for detection of a tone in noise. The infant-adult threshold difference was 8 dB for tone detection in noise, while it was between 9.5 and 13.6 dB in Experiment 1. In Experiment 2, the infant-adult DL difference was 8.6 dB for continuous broadband noise. A similar infant-adult difference would be expected if the same underlying mechanisms are to account for the results in both studies.

It is unlikely that differences between observers in judging infant responses will explain the threshold difference between the two experiments. An interobserver comparison of individual psychometric functions for infant visual acuity showed that functions obtained by one observer had shallower slopes and lower asymptotes than functions obtained by a second observer but there was no interobserver difference in threshold estimate (Teller, Mar and Preston, 1992). In contrast, an interobserver comparison between the Bargones et al. (1995) results and the current results shows no slope difference, a *higher* infant upper asymptote in the current study and a *lower* infant threshold estimate in the Bargones et al. (1995) study. Such a pattern is not consistent with the observer in this study being less sensitive than the observer in Bargones et al. (1995).

Although the combination of general inattention and reduced growth of excitation seems to explain the current results, it must be noted that there are other results that are inconsistent with that explanation. For example, Bargones and Werner (1994) showed that infants do not listen through a narrow, appropriately placed listening band. Such listening immaturity could easily produce immaturity of psychometric function slope and of threshold as observed by Bargones et al. (1995). Furthermore, immature listening for tones in noise can explain why infants' absolute thresholds for tones in noise are higher than their absolute threshold for broadband noise (Bargones et al., 1995; Boike and Werner, 1996). Reduced growth of excitation would not produce lower thresholds for noise than for pure tones. Thus, the current literature does not allow a straightforward choice between the explanations of immature listening strategies and inattention combined with reduced growth of excitation.

II. Gated versus continuous intensity DLs

Intensity DLs were obtained in a gated-pedestal paradigm and a continuous-pedestal paradigm from infants and adults for either a 1-kHz tone or a broadband noise stimulus. Adult continuous-pedestal DLs were better than their gated-pedestal DLs for both stimulus conditions. These results are consistent with previous reports (Green and Sewall, 1962; Campbell, 1966; Campbell and Lasky, 1967; Green et al., 1979; Viemeister and Bacon, 1983; Schlauch, 1994). Similar to adults, infant continuous-pedestal DLs were better than gated-pedestal DLs for the broadband noise stimulus. Infant continuous-pedestal DLs were not different from gated-pedestal DLs for the 1-kHz tone stimulus; in other words, there was no gated-continuous DL difference in the tone condition. The overall size of all infant DLs was much larger than adult DLs across all conditions.

The gated-continuous DL difference obtained from unpracticed adults in Experiment 2 was 6.63 dB (10 log $\Delta I/I$) for the broadband noise and 5.84 dB (10 log $\Delta I/I$) for the 1 kHz tone. This DL difference is larger than previously-reported DL differences from practiced adults. Table 5 shows the mean adult gated-continuous DL difference from this study compared with other previously published results. The DL difference is larger for the untrained adults in this study for the 1-kHz tone and especially larger for the broadband noise. Results from the studies reported in Table 5 were obtained from trained adult listeners who received many hours of practice over multiple visits. In the current study, untrained adult listeners participated in a single, one-hour session. To determine if additional practice might bring the DL difference in this experiment closer to other published results, DLs from 3 adult subjects were measured over 6 to 8 one-hour visits. One listener heard a 1-kHz tone; two listeners heard a broadband noise. Individual gated and continuous DLs obtained from these 3 listeners are shown in Figure 16. Overall, the DL difference for both stimuli decreased with practice, with most of the decrease due to an improvement in gated DLs. The DL difference from subject 1077 decreased from 6.72 in visit 1 to 3.77 in visit 8, approximating the DL difference reported by Green and Sewall (1962) for broadband noise. Subject 1040 and 1012 participated in fewer return visits, and although their DL differences steadily decreased, they were still slightly higher than those reported by previous investigators. It is possible that continuing improvement would be seen with additional practice. It was not feasible to evaluate the effects of practice on infants due to the prohibitive difficulty of obtaining such data. It is possible that practice would affect infants' performance in the same way as adult performance; that is, practice would decrease the gated-continuous DL difference for both the 1-kHz and the broadband noise stimulus. Conversely, practice may have no effect on infant performance. Either way, no change in the pattern of infant results would be expected: infants' continuous DL would still be better than their gated DL with a broadband noise but not with a pure-tone.

Table 5. Comparison of adult gated-continuous DL difference in experiment 2 with previous studies

Study	Stimulus	Gated-continuous DL difference (10 log ΔI/I)
Current	1-kHz tone	5.84
Campbell and Lasky (1967)	1-kHz tone	4.24
Schlauch (1994)	1-kHz tone	5.43
Current	Broadband noise	6.63
Green and Sewall (1962)	Broadband noise	3.10

Seven mechanisms were proposed as possible processes underlying infants' immature gated and continuous intensity DLs: immature adaptation, reduced growth of excitation, neural variability, listening band effects, general inattention, memory effects, and within- and across-channel mechanisms. Neural variability can be excluded as a possible mechanism, based on the results of Experiment 1. Models that predict a gated-continuous DL difference for the 1-kHz tone stimulus can be eliminated as sole explanations for the

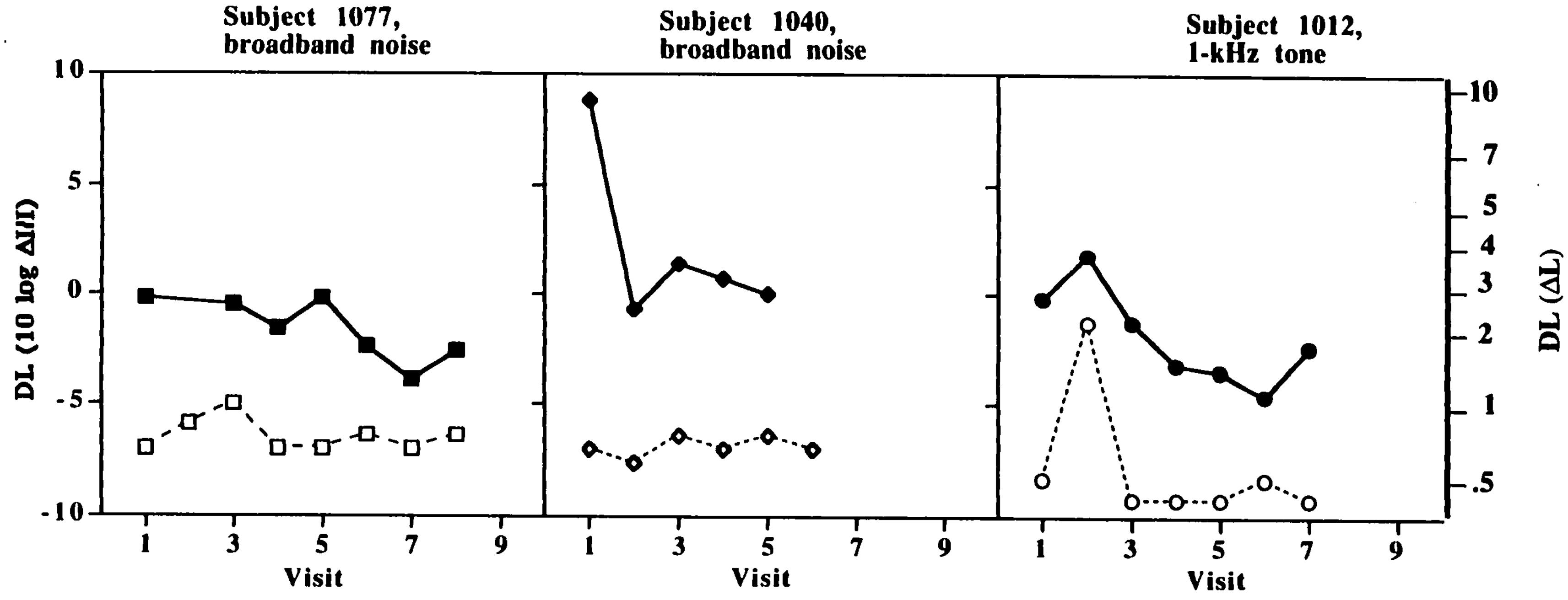

Figure 16. Individual gated and continuous DLs obtained from 3 adults over multiple visits.

results. These models are immature adaptation, reduced growth of excitation, wandering listening band with infant using spectral cue in the continuous-pedestal paradigm, general inattention, and immature memory.

This leaves listening band effects (immature listening strategies) and across-channel mechanisms that develop before within-channel mechanisms as possible sole underlying mechanisms. In fact, in Wright's (1995) model of within- or across-channel mechanisms in detection, listening band width is the within-channel mechanism mediating gating effects. Listening band effects will only be seen in pure tone or narrowband detection. If infants are able to use the across-channel, but not the within-channel mechanisms (*i.e.*, narrow listening bands) for intensity discrimination, a continuous-pedestal improvement will be seen for broadband noise DLs but not for the pure tone DLs. Listening band effects include the hypotheses that infants attend to a single, wandering listening band and don't use the spectral cue in the continuous-pedestal paradigm and/or that infants are broadband listeners. Infant results reporting more adultlike detection thresholds and intensity DLs from broadband noise than for pure tones (Sinnott and Aslin, 1985; Schneider et al., 1988; Werner and Boike, 1996) are consistent with a single, wandering listening band or a broad listening band model.

If infants attend to either a single, wandering listening band or a broad listening band for broadband stimuli, they will be able to make use of across-channel mechanisms when those mechanisms are active. The two listening models are not mutually exclusive: infants may be broadband listeners for broadband signals and try to narrow their listening band for pure-tone or narrowband signals but have drift or jitter in the frequency placement of the listening band. Infant psychometric functions and listening bands for detection of tones in noise support a wandering listening band model (Bargones, 1992; Bargones et al., 1995).

While the pattern of infant gated and continuous DLs is consistent with predictions of the listening band/within-channel mechanism models, the overall size of the infant DLs cannot be explained by these models. If immature listening was the only immaturity, then the infants' DLs for broadband noise would be adultlike. A combination of reduced growth of excitation and general inattention provided one possible explanation for the results of Experiment 1. For Experiment 2, these two models predicted an increase in the size of infant DLs across all conditions. It is possible that the effects of immature listening strategies and/or across-channel mechanisms developing before within-channel mechanisms, combined with reduced growth of excitation and general inattention may be responsible for immature infant gated-continuous intensity DLs. However, the combined effects of immature listening strategies and reduced growth of excitation would be expected to produce an infant-adult DL difference twice as large as that seen in the current results for pure tones.

Across studies, there are conflicting results regarding this possible combination of underlying mechanisms. Although infant psychometric functions with reduced upper asymptotes are the rule and provide support for general inattention, a listening band whose placement wanders far away from the signal frequency could also produce a reduced upper asymptote, at least for narrowband signals (Bargones et al., 1995). After correction for the effects of general inattention, a reduced growth of excitation can account for most of the remaining infant-adult differences from the current experiments and those of Bargones et al. (1995). On the other hand, a reduced growth of excitation is not consistent with better infant auditory detection for broadband noise (Werner and Boike, 1996) or better intensity discrimination of broadband stimuli versus pure tone stimuli (Schneider et al., 1988; Sinnott and Aslin, 1985).

Immature infant listening strategies have provided a partial or full explanation for infant-adult differences in previous experiments where the model is relevant (Bargones and

Werner, 1994; Bargones et al., 1995; Werner and Boike, 1996). However, immature listening strategies would be expected to produce a greater effect for pure-tone signals than broadband signals, and the infant-adult threshold difference for tone detection in noise (Bargones et al., 1995) is the same as the continuous noise DL difference from Experiment 2.

In summary, combined results from Experiments 1 and 2 and from infant auditory detection studies provide mixed support for a combination of general inattention and reduced growth of excitation. These mechanisms predict the similar effect on slope, threshold and upper asymptote that is seen when comparing psychometric functions for broadband noise (Experiment 1) with detection of a tone in noise (Bargones et al., 1995). However, they do not predict the better DLs reported for broadband noise than tones (Schneider et al., 1988; Sinnott and Aslin, 1985) or the better absolute thresholds reported for broadband noise than for tones (Werner and Boike, 1996).

On the other hand, the immature listening bands/within channel mechanism but mature across-channel mechanism model is also supported by the results of some studies but not others. Immature listening strategies can account for the infant-adult differences in psychometric function slope, threshold and upper asymptote seen for detection of a tone in noise (Bargones et al., 1995). Immature listening strategies are not expected to produce infant-adult differences for intensity discrimination for broadband noise. Consistent with this prediction, there are no infant-adult slope or upper asymptote differences for Experiment 1 results after correction for inattention. Immature listening strategies predict better absolute thresholds and intensity DLs for broadband noise than tones and this is borne out in the data (Werner and Boike, 1996; Schneider et al., 1988; Sinnott and Aslin, 1985). Immature within-channel mechanisms but mature across-channel mechanisms can explain a gated-continuous DL difference for broadband noise but not for tones, consistent with the results of Experiment 2. However, immature listening bands are expected to make intensity DLs worse for tones but not broadband noise and so cannot explain the infant-adult DL differences seen for broadband noise in Experiments 1 and 2.

Chapter 6.

Summary and Conclusions.

Mechanisms underlying immature infant intensity discrimination were examined in two experiments. In Experiment 1, psychometric functions were obtained from adults and infants for detection of increments in continuous, broadband noise. Infant functions exhibited shallower slopes and increased DLs compared to adult functions. The average infant upper asymptote did not quite reach adultlike performance. These results are consistent with the predictions of a combination of two immaturities: general inattention and reduced growth of excitation.

In Experiment 2, intensity DLs were obtained from adults and infants in both gated- and continuous-pedestal paradigms for either pure tone or broadband stimuli. Adults showed the expected performance improvement in the continuous-pedestal paradigm for both stimuli. While infants exhibited better continuous-pedestal DLs for the broadband noise stimulus, there was no gated-continuous DL difference for the pure tone stimulus. The pattern of infant results is consistent with the predictions of models positing immature listening band strategies but mature across-channel mechanisms. However, this model cannot account for the overall size of the infant DLs. At this time, no model consistently accounts for all observations on infants' detection of sound.

Results from Experiment 1 indicate that the effects of general inattention and reduced growth of excitation provide a reasonable explanation for immature intensity discrimination of broadband stimuli. However, this explanation is inconsistent with the results of Experiment 2 and several observations of infant detection that could be better explained by immature listening strategies.

References

Allen, P. and Wightman, F. (1994). Psychometric functions for children's detection of tones in noise. J. Speech Hear. Res. 37, 205-215.

Arehart, K.H., Burns, E.M. and Schlauch, R.S. (1990). A comparison of psychometric functions for detection in normal-hearing and hearing-impaired listeners. J. Speech Hear. Res. 33, 433-439.

Arthur, R.M., Pfeiffer, R.R. and Suga, N. (1971). Properties of "two-tone inhibition" in primary auditory neurones. J. Physiol. 212, 593-609.

Bacon, S.P. (1990). Effect of masker level on overshoot. J. Acoust. Soc. Am. 88, 698-702.

Bacon, S.P. and Viemeister, N.F. (1985). Simultaneous masking by gated and continuous sinusoidal maskers. J. Acoust. Soc. Am. 78, 1220-1230.

Bacon, S.P. and Viemeister, N.F. (1994). Intensity discrimination and increment detection at 16 kHz. J. Acoust. Soc. Am. 95, 2616-2621.

Bargones, J.Y. (1992). Selective attention to sound frequency by infants and adults. Unpublished doctoral dissertation, University of Washington, Seattle, WA.

Bargones, J.Y. and Werner, L.A. (1994). Adults listen selectively; Infants do not. Psychol. Science 5, 170-174.

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

Berliner, J.E. and Durlach, N.I. (1973). Intensity perception. IV. Resolution in roving-level discrimination. J. Acoust. Soc. Am. 53, 1270-1287.

Bos, C.E. and de Boer, E. (1966). Masking and discrimination. J. Acoust. Soc. Am. 39, 708-715.

Braida, L.D. and Durlach, N.I. (1988). Peripheral and central factors in intensity perception. In G.M. Edelman, W.E. Gall, and W. M. Cowan (eds.) Auditory function (pp. 559-583). New York: John Wiley & Sons.

Braida, L.D., Lim, J.S., Berliner, J.E., Durlach, N.I., Rabinowitz, W.M. and Purks, S.R. (1984). Intensity perception. XIII. Perceptual anchor model of context coding. J. Acoust. Soc. Am. 76, 722-731.

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

Brugge, J.F., Kitzes, L.M. and Javel, E. (1981). Postnatal development of frequency and intensity sensitivity of neurons in the anteroventral cochlear nucleus of kittens. Hear. Res. 5, 217-229.

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

Buus, S. and Florentine, M. (1991). Psychometric functions for level discrimination. J. Acoust. Soc. Am. 90, 1371-1380.

Campbell, R.A. (1966). Auditory intensity perception and neural coding. J. Acoust. Soc. Am. 39, 1030-1033.

Campbell, R.A. and Lasky, E.Z. (1967). Masker level and sinusoidal-signal detection. J. Acoust. Soc. Am. 42, 972-976.

Carlyon, R.P. and Moore, B.C.J. (1984). Intensity discrimination: A severe departure from Weber's law. J. Acoust. Soc. Am. 76, 1369-1376.

Carlyon, R.P. and Moore, B.C.J. (1986). Continuous versus gated pedestals and the "severe departure" from Weber's law. J. Acoust. Soc. Am. 79, 453-460.

Carlyon, R.P. and White, L.J. (1992). Effect of signal frequency and masker level on the frequency regions responsible for the overshoot effect. J. Acoust. Soc. Am. 91, 1034-1041.

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

Cowan, N., Suomi, K. and Morse, P.A. (1982). Echoic storage in infant perception. Child Devel. 53, 984-990.

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

Delgutte, B. (1987). Peripheral auditory processing of speech information: Implications from a physiological study of intensity discrimination. In M.E.H. Schouten (ed.), The psychophysics of speech perception, (pp. 333-353). Dordrecht: Nijhoff.

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

Durlach, N.I. and Braida, L.D. (1969). Intensity perception. I. Preliminary theory of intensity resolution. J. Acoust. Soc. Am. 46, 372-383.

Evans, E.F. and Palmer, A.R. (1980). Relationship between the dynamic range of cochlear nerve fibres and their spontaneous activity. Exp. Brain Res. 40, 115-118.

Fastl, H. and Schorn, K. (1981). Discrimination of level differences by hearing-impaired patients. Audiology 20, 488-502.

Florentine, M. (1986). Level discrimination of tones as a function of duration. J. Acoust. Soc. Am. 79, 792-798.

Florentine, M. and Buus, S. (1981). An excitation-pattern model for intensity discrimination. J. Acoust. Soc. Am. 70, 1646-1654.

Florentine, M., Buus, S. and Mason, C.R. (1987). Level discrimination as a function of level for tones from 0.25 to 16 kHz. J. Acoust. Soc. Am. 81, 1528-1541.

Graham, N.V.S. (1989). Visual pattern analyzers. New York: Oxford University Press.

Grantham, D.W. and Yost, W.A. (1982). Measures of intensity discrimination. J. Acoust. Soc. Am. 72, 406-410.

Green, D.M. (1961). Detection of auditory signals of uncertain frequency. J. Acoust. Soc. Am. 33, 897-903.

Green, D.M. and Sewall, S.T. (1962). Effects of background noise on auditory detection of noise bursts. J. Acoust. Soc. Am. 34, 1207-1216.

Green, D.M. and Swets, J.A. (1966). Signal detection theory and psychophysics. New York: John Wiley and Sons.

Green, D.M., Nachmias, J., Kearny, J.K. and Jeffress, L.A. (1979). Intensity discrimination with gated and continuous sinusoids. J. Acoust. Soc. Am. 66, 1051-1056.

Green, D.M., Kidd, G. and Picardi, M.C. (1983). Successive versus simultaneous comparison in auditory intensity discrimination. J. Acoust. Soc. Am. 73, 639-643.

Hanna, T.E., von Gierke, S.M. and Green, D.M. (1986). Detection and intensity discrimination of a sinusoid. J. Acoust. Soc. Am. 80, 1335-1340.

Harris, D.M. and Dallos, P. (1979). Forward masking of auditory nerve fiber responses. J. Neurophysiol. 42, 1083-1107.

Henning, G.B. (1970). Comparison of the effects of signal duration on frequency and amplitude discrimination. In R. Plomp and G.F. Smoorenburg (eds.), Frequency analysis and periodicity detection in hearing, (pp. 350-361). Leiden: A.W. Sijthoff.

Houtsma, A.J.M., Durlach, N.I. and Braida, L.D. (1980). Intensity perception. XI. Experimental results on the relation of intensity resolution to loudness matching. J. Acoust. Soc.Am. 68, 807-813.

Hubner, R. (1993). On possible models of attention in signal detection. J. Math. Psychol. 37, 266-281.

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

Jesteadt, W., Wier, C.C. and Green, D.M. (1977). Intensity discrimination as a function of frequency and sensation level. J. Acoust. Soc. Am. 61, 169-177.

Joint Committee on Infant Hearing. (1991). 1990 position statement. Asha 33 (Suppl. 5), 3-6.

Jusczyk, P.W., Cutler, A. and Redanz, N.J. (1993). Infants' preference for predominant stress patterns of English words. Child Devel. 64, 675-687.

Kiang, N.Y.S., Watanabe, T., Thomas, E.C. and Clark, L.F. (1965). Discharge patterns of single fibers in the cat's auditory nerve. MIT Research Monograph 35, MIT, Cambridge, Massachusetts.

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

Laming, D. (1986). Sensory analysis, (pp. 46-52). London: Academic Press.

Levitt, H. (1971). Transformed up-down methods in psychophysics. J. Acoust. Soc. Am. 49, 467-477.

Liberman, M.C. (1978). Auditory-nerve response from cats raised in a low-noise chamber. J. Acoust. Soc. Am. 63, 442-455.

Long, G.R. and Cullen, Jr., J.K. (1985). Intensity difference limens at high frequencies. J. Acoust. Soc. Am. 78, 507-513.

Macmillan, N.A. (1985). What sort of psychophysics is infant psychophysics? In S.E. Trehub and B.A. Schneider (eds.), Auditory development in infancy (pp. 231-240). New York: Plenum Press.

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

McGill, W.J. and Goldberg, J.P. (1968). Pure-tone intensity discrimination and energy detection. J. Acoust. Soc. Am. 44, 576-581.

Moore, B.C.J. and Raab, D.H. (1974). Pure-tone intensity discrimination: some experiments relating to the 'near-miss' to Weber's law. J. Acoust. Soc. Am. 55, 1049-1054.

Nozza, R.J., Rossman, R.N.F., Bond, L.C. and Miller, S.L. (1990). Infant speech-sound discrimination in noise. J. Acoust. Soc. Am. 87, 339-350.

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

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

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

Olsho, L.W., Koch, E.G., Halpin, C.F. and Carter, E.A. (1987). An observer-based psychoacoustic procedure for use with young infants. Devel. Psych. 23, 627-640.

Penner, M.J., Leshowitz, B., Cudahy, E. and Ricard, G. (1974). Intensity discrimination for pulsed sinusoids of various frequencies. Perception & Psychophysics 15, 568-570.

Penner, M.J. and Viemeister, N.F. (1973). Intensity discrimination of clicks: the effects of click bandwidth and background noise. J. Acoust. Soc. Am. 54, 1184-1188.

Plack, C.J. and Carlyon, R.P. (1995). Loudness perception and intensity coding. In B.J.M. Moore (ed.), Hearing (pp. 123-160). San Diego: Academic Press.

Plack, C.J. and Viemeister, N.F. (1992a). The effects of notched noise on intensity discrimination under forward masking. J. Acoust. Soc.Am. 92, 1902-1910.

Plack, C.J. and Viemeister, N.F. (1992b). Intensity discrimination under backward masking. J. Acoust. Soc. Am. 92, 3097-3101.

Plack, C.J., Carlyon, R.P. and Viemeister, N.F. (1995). Intensity discrimination under forward and backward masking: Role of referential coding. J. Acoust. Soc. Am. 97, 1141-1149.

Pollack, I. (1955). "Long-time" differential intensity sensitivity. J. Acoust. Soc.Am. 27, 380-381.

Raab, D.H. and Goldberg, I.A. (1975). Auditory intensity discrimination with bursts of reproducible noise. J. Acoust. Soc. Am. 57, 437-447.

Rabinowitz, W.M., Lim, J.S., Braida, L.D. and Durlach, N.I. (1976). Intensity perception. VI. Summary of recent data on deviations from Weber's law for 1000-Hz tone pulses. J. Acoust. Soc.Am. 59, 1506-1509.

Relkin, E.M. and Doucet, J.R. (1991). Recovery from prior stimulation. I. Relationship to spontaneous firing rates of primary auditory neurons. Hear. Res. 55, 215-222.

Sachs, M.B. and Abbas, P.J. (1974). Rate versus level functions for auditory-nerve fibers in cats: tone-burst stimuli. J. Acoust. Soc. Am. 56, 1835-1847.

Sanes, D.H. (1993). The development of synaptic function and integration in the central auditory system. J. Neuroscience 13, 2627-2637.

Sanes, D.H. and Rubel, E.W (1988). The ontogeny of inhibition and excitation in the gerbil lateral superior olive. J. Neuroscience 8, 682-700.

Sawilowsky, S.S. (1990). Nonparametric tests of interaction in experimental design. Rev. Education. Res. 60, 91-126.

Schalk, T.B. and Sachs, M.B. (1980). Nonlinearities in auditory-nerve fiber responses to bandlimited noise. J. Acoust. Soc. Am. 67, 903-913.

Schacknow, P.N. and Raab, D.H. (1973). Intensity discrimination of tone bursts and the form of the Weber function. Percept. Psychophys. 14, 449-450.

Schlauch, R.S. (1994). Intensity resolution and loudness in high-pass noise. J. Acoust. Soc. Am. 95, 2171-2179.

Schlauch, R.S. and Hafter, E.R. (1991). Listening bandwidths and frequency uncertainty in pure-tone signal detection. J. Acoust. Soc. Am. 90, 1332-1339.

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

Schneider, B.A., Bull, D. and Trehub, S.E. (1988). Binaural unmasking in infants. J. Acoust. Soc. Am. 83, 1124-1132.

Schneider, B.A., Trehub, S.E., Morrongiello, B.A. and Thorpe, L.A. (1989). Developmental changes in masked thresholds. J. Acoust. Soc. Am. 86, 1733-1741.

Sinnott, J.M. and Aslin, R.N. (1983). Auditory intensity discrimination in human infants. J. Acoust. Soc. Am. Suppl. 1 73, S104.

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

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

Smith, R.L. (1979). Adaptation, saturation, and physiological masking in single auditory-nerve fibers. J. Acoust. Soc. Am. 65, 166-178.

Smith, R.L. (1988). Encoding of sound intensity by auditory neurons. In G.M. Edelman, W.E. Gall, and W.M. Cowan (eds.), Auditory function (pp. 243-274). New York: John Wiley & Sons.

Smith, R.L. and Zwislocki, J. J. (1975). Short-term adaptation and incremental responses of single auditory-nerve fibers. Biol. Cybernet. 17, 169-182.

Spring, D. and Dale, P. (1977). The discrimination of linguistic stress in early infancy. J. Speech Hear. Res. 20, 224-231.

Swoboda, P.J., Kass, J., Morse, P.A. and Leavitt, L.A. (1978). Memory factors in vowel discrimination of normal and at-risk infants. Child Devel. 49, 332-339.

Tarquinio, N., Zelazo, P.R. and Weiss, M.J. (1990). Recovery of neonatal head turning to decreased sound pressure level. Devel. Psych. 26, 752-758.

Taylor, M.M. and Creelman, C.D. (1967). PEST: Efficient estimates on probability functions. J. Acoust. Soc. Am. 41, 782-787.

Teich, M.C. and Khanna, S.M. (1985). Pulse-number distributions for the neural spike train in the cat's auditory nerve. J. Acoust. Soc. Am. 77, 1110-1128.

Teller, D.Y., Mar, C. and Preston, K.L. (1992). Statistical properties of 500-trial infant psychometric functions. In L.A. Werner and E.W Rubel (eds.). Developmental psychoacoustics. (pp. 211-227). Washington, D.C.: American Psychological Association.

Trehub, S.E., Schneider, B.A. and Endman, M. (1980). Developmental changes in infants' sensitivity to octave-band noises. J. Exp. Child Psychol. 29, 283-293.

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

Turner, C.W., Horwitz, A.R. and Souza, P.E. (1994). Forward- and backward-masked intensity discrimination measured using forced-choice and adjustment procedures. J. Acoust. Soc. Am. 96, 2121-2126.

Turner, C.W., Zwislocki, J.J. and Filion, P.R. (1989). Intensity discrimination determined with two paradigms in normal and hearing-impaired subjects. J. Acoust. Soc. Am. 86, 109-115.

Viemeister, N. (1974). Detection of a noise signal: the effects of duration and masker level. J. Acoust. Soc. Am. Suppl. 1 56, S36.

Viemeister, N.F. (1983). Auditory intensity discrimination at high frequencies in the presence of noise. Science 221, 1206-1208.

Viemeister, N.F. (1988). Psychophysical aspects of auditory intensity coding. In G.M. Edelman, W.E. Gall, and W.M. Cowan (eds.), Auditory function (pp. 213-241). New York: John Wiley & Sons.

Viemeister, N.F. and Bacon, S.P. (1983). On the form of the masking function for intensity discrimination of pure-tones. J. Acoust. Soc. Am. 74(S1) , S34.

Viemeister, N.F. and Bacon, S.P. (1988). Intensity discrimination, increment detection, and magnitude estimation for 1-kHz tones. J. Acoust. Soc. Am. 84, 172-178.

Viemeister, N.F. and Schlauch, R.S. (1992). Issues in infant psychoacoustics. In L.A. Werner and E.W Rubel (eds.). Developmental psychoacoustics. (pp.191-209). Washington, D.C.: American Psychological Association.

Walsh, E.J. and McGee, J. (1986). The development of function in the auditory periphery. In R.A. Altschuler, D.W. Hoffman and R.P. Bobbin (eds.) Neurobiology of hearing: the cochlea (pp. 247-269). New York: Raven Press.

Walsh, E.J. and McGee, J. (1987). Postnatal development of auditory nerve and cochlear nucleus neuronal responses in kittens. Hear. Res. 28, 97-116.

Watson, C.S. and Gengel, R.W. (1969). Signal duration and signal frequency in relation to auditory sensitivity. J. Acoust. Soc. Am. 46, 989-996.

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

Werner, L.A. and Boike, K. (1996). Infants' sensitivity to broadband noise. J. Acoust. Soc. Am. 100, 2629.

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

Westerman, L.A. and Smith, R.L. (1984). Rapid and short-term adaptation in auditory nerve responses. Hear. Res. 15, 249-260.

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

Woolf, N.K. and Ryan, A.F. (1984). The development of auditory function in the cochlea of the mongolian gerbil. Hear. Res. 13, 277-283.

Woolf, N.K. and Ryan, A.F. (1985). Ontogeny of neural discharge patterns in the ventral cochlear nucleus of the mongolian gerbil. Devel. Brain Res. 17, 131-147.

Wright, B.A. (1995). Detectability of simultaneously masked signals as a function of signal bandwidth for different signal delays. J. Acoust. Soc. Am. 98, 2493-2503.

Wright, B.A. and Dai, H. (1994). Detection of unexpected tones in gated and continuous maskers. J. Acoust. Soc. Am. 95, 939-948.

Zeng, F.G., Turner, C.W. and Relkin, E.M. (1991). Recovery from prior stimulation. II: Effects upon intensity discrimination. Hear. Res. 55, 223-230.

Zeng, F.G. and Turner, C.W. (1992). Intensity discrimination in forward masking. J. Acoust.Soc. Am. 92, 782-787.

Zwicker, E. (1970). Masking and psychological excitation as consequences of the ear's frequency analysis. In R. Plomp and G.F. Smoorenburg (eds.). Frequency analysis and periodicity detection in hearing (pp. 376-396). Leiden: A.W. Sijthoff.

Vita

Beth Ann Kopyar

Education

1997, Ph.D., University of Washington, Seattle
Dissertation: Intensity discrimination abilities of infants and adults: Implications for underlying processes

1985, M.A., Kent State University, Ohio
Thesis: Intertester Reliability of Acoustic Reflex Thresholds

1982, B.S., Miami University, Ohio

PROFESSIONAL EXPERIENCE

1991-1997	Research Assistant Department of Speech & Hearing Sciences University of Washington, Seattle, Washington
1996-1997	Clinical Audiologist Puget Sound Otolaryngology, P.S., Inc. Edmonds, Washington
1992-1996	Clinical Audiologist Agnes Yue, M.D. Private Practice in Otolaryngology, Seattle, Washington
1990-1991	Teaching Assistant Department of Speech & Hearing Sciences University of Washington, Seattle, Washington
1984-1990	Educational Audiologist Fort Mill School District #4 Fort Mill, South Carolina

Certification

1985, Certificate of Clinical Competence, Audiology
American Speech-Language-Hearing Association

Presentations

Werner, L.A., Kopyar, B.A., and Bargones, J.Y. (1993). *Psychophysical measures of auditory sensitivity in human infants.* Poster presented at the Midwinter Research Meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, FL.

Werner, L.A. and Kopyar, B.A. (1994). *A procedure for developing effective visual reinforcers for infant psychoacoustics.* Poster presented at the Midwinter Research Meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, FL.

Kopyar, B.A. and Werner, L.A. (1995). *Intensity discrimination abilities of infants and adults: Implications for underlying processes.* Poster presented at the Midwinter Research Meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, FL.

Kopyar, B.A. and Werner, L.A. (1996). *Infant psychometric functions for intensity discrimination: Implications for underlying processes.* Poster presented at the Midwinter Research Meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, FL.

Kopyar, B.A. and Werner, L.A. (1996). *Intensity DLs from infants and adults: Implications for underlying mechanisms of immaturity.* Paper presented to the American Speech-Language-Hearing Association, Seattle, WA.