Assessment: Scientific Foundation

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There are a number of factors currently influencing pediatric hearing assessment. The trend toward universal newborn hearing screening and very early identification suggests that we will be assessing hearing of young infants in larger numbers than ever before. As a result, there will be an increasing need for reliable and valid assessment methods for infants. In particular, it is important that we have the means for estimating frequency-specific and ear-specific thresholds. In addition, there is a need to gather information on other aspects of auditory processing in infants to help us in making our amplification and management decisions. This article focuses on issues not only related to scientific foundations of current hearing assessment methods, but also on research that can impact our understanding of the relationship between assessment data and the ability to process meaningful auditory information in the environment.

There are several issues to consider in the relationship between research and clinical practice as they relate to assessment and to the link between assessment measures and the process of evaluating and fitting amplification. First, it is important that our clinical assessment measures be supported by normative data. For example, interpreting thresholds of infants and young children in the clinic depends on an understanding of the thresholds that are provided by infants and children with normal hearing. Infants and young children undergo developmental changes in several dimensions of the sensori-perceptual process, any of which can affect the outcome of an audiological assessment.

Second, to make better decisions regarding management of hearing impairment, we need to know something about how infants and children use auditory information at various stages of development and what impact reduced hearing sensitivity

has on that process. For example, how does an infant with normal hearing process speech and what happens to that capability when the signal is degraded by hearing impairment? Consider the procedures we use for fitting amplification. They are primarily threshold-based prescriptive procedures. Obviously, the greater the reliability and validity of the thresholds obtained, the better the chance that the prescriptive fitting will be appropriate. But threshold-based prescriptive procedures were not developed based on threshold data alone. They are based on a relationship between thresholds and some measure of, or some assumptions about, suprathreshold processing of speech. There are different assumptions underlying different prescriptive procedures, but all of them have as an objective to amplify speech to a level that is comfortable and/or that produces the greatest intelligibility for the listener. Given the number of different threshold-based procedures, it is easy to see that there is no consensus on how thresholds relate to what hearing impaired ears require in terms of amplified speech. Further, most prescriptions are not based on data from infants or very young children. Answering questions related to more complex auditory processes in infants, and the effect of hearing impairment on those processes, almost necessitates laboratory research.

Third, in the laboratory setting, variables can be controlled that cannot be controlled easily in a clinical setting. Tracking and/or manipulation of test variables such as trial interval duration, step size, and trial type (stimulus versus control trial) can be done easily in a laboratory setting. As a result, information on the methods used can be gathered in a systematic way. The work done in the laboratory can and should contribute to the development and improvement of our clinical methods.

Finally, work that goes on in the laboratory should force us to question some of our assump-

tions. Hopefully, the following discussion will stimulate us to think differently about some of the issues that are raised. We should never become complacent and assume that we have all of the knowledge and information that we need. Ideally, the relationship between the clinical process and the work that goes on in the laboratory is synergistic. There are different objectives for work in the laboratory and for work in the clinic. However, in the field of audiology, the best work in the laboratory is driven by clinical questions and the best work in the clinic makes use of knowledge that is gained in the laboratory.

In cooperative adults and older children, the assessment stage and the beginning of the management and follow-up stage are somewhat distinct. Typically, the assessment stage is complete before the initiation of the hearing aid fitting process, except, of course, for regular follow-up evaluations and/or examinations to evaluate perceived changes in function. However, in the younger child and infant, the process of selecting and fitting hearing aids often must begin before the assessment stage is complete. Development of a complete and valid audiogram of an infant occurs over a period of time. Introduction of amplification can be deemed necessary long before the assessment is complete, so there is an overlapping, highly inter-related process that goes on and it should not be viewed as two separate and distinct processes. Assessment then becomes part of the intervention. This is important because it may impact the choice of assessment method at various points in the clinical process.

The four basic assessment methods used with infants and children are auditory brainstem response (ABR), otoacoustic emissions (OAE), aural acoustic immittance and behavioral test methods. After just a brief overview of some recent work in ABR and OAEs, the discussion will focus on acoustic immittance testing and behavioral measures of hearing. (See Sabo, in this issue, for more information on ABR and OAE measures in the clinic.)

ABR

Research has played an important role in development of the ABR as an assessment tool. Research has been influential in three areas that are of particular interest to the pediatric audiologist: Development of stimuli that are capable of generating a frequency specific ABR for clinical application, measures of developmental change in the

ABR and the correspondence between the ABR and behavioral measures of hearing.

The inadequacy of the transient, or click, stimulus to provide frequency specific information that correlates with behavioral thresholds in various configurations of hearing loss has led to attempts in clinical research laboratories to determine stimulus configurations that would best provide a frequency specific ABR. Gorga et al (1989) provided data on normal patterns of responses for the ABR in infants. Stapells and Oaks (1997) studied several methods for improving the frequency-specificity of the ABR and the degree to which the methods produce results that are predictive of behavioral thresholds. In spite of some reports that tone-burst ABRs are not as good as stimulus arrangements using various gating functions or high-pass or notched-noise masking, Stapells et al (1995) have shown excellent results using tone bursts alone as well.

With respect to developmental changes, there have been many studies examining changes in latency of the ABR with age early in life. Using ABR waveforms to predict threshold, however, reveals that by 3-to-6 months of age, ABR thresholds are similar to those of adults. This is not consistent with changes in behavioral thresholds during infancy and will be discussed further in the section on behavioral testing.

Agreement between ABR thresholds and behavioral thresholds can be quite good when proper stimulus conditions are used. Stapells, et al (1995) have been able to demonstrate good agreement between tone burst ABR thresholds and behavioral thresholds in both normal and impaired ears.

OAE

Otoacoustic emissions (OAE) testing has provided us with important new information about processes within the ear. OAEs have become an integral part of the test battery, especially with infants and other difficult to test individuals. The ability of OAEs to predict thresholds in a frequency specific way is still not strong, although the work of researchers like Gorga and colleagues (1997) and Prievé and others (1997a, b), has been encouraging. Recently, Gorga et al (1997) reported distortion product otoacoustic emission (DPOAE) responses at various frequencies for a variety of different hearing thresholds. Although there is still significant variability, and the OAE response is limited to hearing losses less than about 50-60 dB HL, the data reveal a relationship

between the OAE and audiometric thresholds that suggests that we can separate normal from abnormal ears with a high degree of accuracy. These data indicate that the OAE may be fairly predictive of the degree of hearing loss in impaired ears, at least up to 50-60 dB HL. As our understanding of this phenomenon grows, the work of researchers in this area will translate into improved clinical assessment methods. The development of a condition that was unheard of before the discovery and clinical implementation of OAEs, auditory neuropathy, has caused us to view individuals with sensori-neural hearing loss in a different light, as well.

ACOUSTIC IMMITTANCE

As part of the pediatric assessment battery, especially as pertains to the ongoing management of an infant or child with hearing loss, acoustic immittance testing serves to alert us to changes in middle ear status. This is critical for a child wearing hearing aids for which gain/frequency response has been determined with a healthy middle ear. Research over the past decade or so has altered the way we measure and interpret acoustic immittance information. Incorporation of the new data into clinical practice has been slow, however.

One event that has changed the way we interpret acoustic immittance information was the development of an ANSI standard (S3.39, 1987) for aural acoustic immittance measures. This standard calls for use of absolute physical quantities in specifying middle ear function. This development made obsolete instruments that used what are referred to as arbitrary compliance units rather than units of admittance (mmhos) or units of impedance (ohms). It also encouraged investigation into quantitative analyses of immittance data as opposed to the pattern classification scheme made popular by Jerger (1970).

Pattern classification has been most successful when the pattern is flat. The flat pattern indicates middle ear effusion a high percentage of the time. However, only a fraction of ears with effusion produce a flat tympanogram. In addition, very few ears with middle ear effusion (MEE) produce a tympanogram with peak immittance and tympanometric peak pressure (TPP) within the normal range. The bulk of ears with fluid behind the tympanic membrane produce tympanograms that are classified as type C (i.e., peak immittance within a normal range, but with high negative TPP). Unfortunately, many ears without MEE produce

type C tympanograms as well. Even with subclassification of the type C, the ability of pattern classification of tympanograms to identify MEE is limited. In attempts to improve diagnostic performance, the pattern classification system has been taken to extremes and has resulted in schemes with as many as 15 different patterns (Cantekin et al, 1979), with no real improvement in performance with respect to identification of MEE.

Along with the change to absolute physical units of measure for the tympanogram, attention has been brought back to the value of tympanogram shape in the diagnosis of MEE. In the A,B,C scheme, tympanogram shape is largely ignored. Except for peak versus no peak, there is no use of information related to the rate of change in immittance near the peak as a function of ear canal pressure. The notion that tympanogram shape, or gradient, contains valuable information with respect to the presence or absence of middle ear fluid is not a new one (Brooks, 1968, 1969). However, the use of the arbitrary compliance units in clinical instruments made the gradient measure difficult to apply. In 1986, de Jonge published a paper that examined normal properties of different gradient measures, one of which was called tympanometric width, using tympanograms that were based on absolute physical units rather than arbitrary compliance units. Subsequently, Koebse and Margolis (1986) and Margolis and Heller (1987) investigated the use of tympanometric width for identification of MEE with young children and found the results to be encouraging. In 1990, in a revision of the ASHA guidelines for screening for middle ear disease, a cutoff based on tympanometric width was included, along with one for peak compensated static acoustic admittance, as independent criteria for referral for middle ear disease. Both are quantitative measures and contribute to the description of important characteristics of the tympanogram. The use of quantitative analysis of tympanograms in identification of MEE was further supported in new ASHA (1997) guidelines and in a position statement on screening by the American Academy of Audiology (1997).

In spite of several studies that have been published regarding the clinical application of the admittance criteria based on absolute physical quantities (Karzon, 1991; Roush et al, 1992; Silman et al, 1992; Nozza et al, 1992, 1994), and the publication of the recent guidelines and position statement, there seems to be a persistent use of the pattern classification scheme for characterizing

tympanograms in clinical practice. Because tympanograms now are not based on arbitrary units of compliance and they must conform to standards with respect to aspect ratio, the relationship between the scale for immittance (admittance in mmhos or impedance in ohms) on the y-axis versus the scale for pressure (in daPa) on the x-axis, their appearance is slightly different from those that were based on arbitrary units. Clinicians and investigators have been forced to establish their own criteria for a flat, or type B, tympanogram, and many have still not incorporated the information on tympanogram shape. Of course, gradient or tympanometric width information is available now on many commercial immittance instruments.

In recent years, there has been research to examine the properties of acoustic immittance measures in the ears of infants and young children. Several investigators have reported on normal values for peak admittance (the immittance measure most commonly found on commercial instruments) and for tympanometric width for infants at very young ages. The research is consistent in finding developmental change in peak admittance and in tympanometric width from early infancy (Roush et al, 1995; De Chicchis et al, 1997). Clearly, tympanograms of normally developing young infants are lower in admittance and have greater tympanometric width than those of older infants and children. Table 1 displays data from studies that measured tympanograms on infants and children who were free of middle ear disorder or were considered to have normal middle ears, even excluding abnormalities that were clinically insignificant (De Chicchis et al, 1997). The table illustrates the age effect for both peak compensated static acoustic admittance and tympanometric width.

Distributions of values for peak admittance and for tympanometric width were determined in a study of admittance values in children with history of chronic or recurrent MEE who were scheduled for myringotomy and tube surgery (Nozza et al, 1992, 1994). Immittance testing was done immediately before surgery and the determination of the presence or absence of MEE was made by the surgeon at the time of the myringotomy. Values of tympanometric peak pressure (TPP) and peak admittance (Nozza et al, 1992, 1994) and tympanometric width (Nozza et al, 1994) were evaluated, alone and in combination, for their ability to separate ears with MEE from ears without MEE. Peak admittance and tympanometric width were much better at identifying

MEE than was TPP. Even in combinations, TPP added almost nothing to the ability of the other variables to identify ears with MEE.

The data from the ears of children undergoing surgery also were compared to those of children drawn from a group unselected with respect to their ears or ear history and who were without middle ear disorders by otoscopic exam at the time of testing. The sensitivity and specificity for identification of MEE in the children undergoing tube surgery were determined so that different criteria for identification of MEE could be examined (Table 2). The performance of tympanometry in identifying MEE in children, using a quantitative classification scheme, is quite good and is more objective than pattern classification schemes that have been used in the past.

BEHAVIORAL TESTING

A primary goal of diagnostic audiological assessment is to develop a complete and valid audiogram. The behavioral audiogram is the cornerstone of the diagnostic evaluation and is critical to the development of a strategy for intervention. It is understood that it may take time to establish a valid audiogram for an infant or young child; repeated testing is not unusual. For infants, when thresholds are obtained, they are often considered to be biased by inability of the infant to maintain attention to the task. The term minimum response levels (MRL) is often used for estimates of hearing sensitivity in infants because they are not considered to be thresholds in the same sense as those determined for older, more cooperative individuals. However, in spite of the developments in ABR and OAE testing, behavioral testing still has an important role. The behavioral test is especially important with respect to the infant with a hearing aid for whom the ability to process auditory information and then to use it in a meaningful way are the ultimate objectives.

Research in auditory behavior of infants has provided much in the way of an understanding of normal hearing sensitivity in infants. It also has contributed to our understanding of the ability of infants to process speech and to our notions of the impact hearing loss might have on speech perception. Finally, behavioral studies of infant auditory function have provided us with information about methodological issues that is important to understand if we are to improve our techniques in the clinical setting.

Table 1. Tympanometric variables as a function of age.

1a: Peak compensated static acoustic admittance (mmho) as a function of age for normal ears of children.					
Age	Mean (mmho)	SD	90% Range	Reference	Comments
6–30 months	0.45	0.19	0.20–0.70	Roush et al, 1995	Ear canal volume est. at +200 daPa. Normal by otoscopy
6–36 months	0.41	0.23	0.20–0.90	De Chicchis et al, 1997	Ear canal volume est. at +200 daPa. Ears with any sign of middle ear disease or TM abnormality excluded
4–6 years	0.50	0.19	0.22–0.81	Margolis and Heller, 1987	Ear canal volume est. at +200 daPa. No ear disease by otoscopic exam and no recent history
3–6 years	0.67	0.22	NA	Koebseil and Margolis, 1986	Ear canal volume est. at +200 daPa
5–10 years	0.93	0.52	0.4–2.3	Nozza et al, 1997	Ear canal volume est. at +400 daPa. Normal by otoscopy. Ears included unless pediatrician thought a medical referral necessary
3–16 years	0.78	0.31	0.4–1.4	Nozza et al, 1992	Ear canal volume est. at +400 daPa. Normal by otoscopy. Ears included unless diagnosis of OME
1b: Tympanometric width (daPa) as a function of age.					
Age	Mean (daPa)	SD	90% Range	Reference	Comments
6–30 months	148	40	102–204	Roush et al, 1995	Ear canal volume est. at +200 daPa. Normal by otoscopy
6–36 months	140	42	80–220	De Chicchis et al, 1997	Ear canal volume est. at +200 daPa. Ears with any sign of middle ear disease or TM abnormality excluded
4–6 years	100	NA	59–151	Margolis and Heller, 1987	Ear canal volume est. at +200 daPa. No ear disease by otoscopic exam and no recent history
3–6 years	124	33	68–187	Koebseil and Margolis, 1986	Ear canal volume est. using MAX/MIN
5–10 years	137	78	46–289	Nozza et al, 1997	Ear canal volume est. at +400 daPa. Normal by otoscopy. Ears included unless pediatrician thought a medical referral necessary
3–16 years	104	32	60–168	Nozza et al, 1994	Ear canal volume est. at +400 daPa. Normal by otoscopy. Ears included unless diagnosis of OME

Normal Thresholds

Over the years, visual reinforcement audiometry (VRA) has been used to obtain thresholds of infants from about five or six months of age. With the use of earphones in experimental studies using VRA, ear-specific and frequency-specific thresholds have been measured in infants as young as six months of age. A consistent finding has been that thresholds of infants with normal hearing improve with age and that there is greater developmental change in the low frequencies than in the high frequencies (Nozza and Wilson, 1984; Olsho et al, 1988). That is, infant hearing is more adult-like in

the high frequencies than in the low frequencies, at least over the range of 500 to 4000 Hz. This has been of great interest for several reasons. First, some studies of developmental change in ABR suggest that, in contrast to the behavioral data, infant hearing develops first in the low frequencies and later in the higher frequencies (e.g., Folsom and Wynn, 1986). Second, the notion that the inner ear is mature at birth would argue against a developmental change in sensitivity such as is observed in the behavioral data of infants. These facts have contributed to the notion that the thresholds of infants are MRLs and not thresh-

Table 2. Performance of selected tympanometric criteria in screening for middle ear effusion based on otoscopic diagnosis (Nozza et al, 1994).

General Population					
Variables	Criterion	Sens (%) (N = 9)	Spec (%) (N = 135)	PPV (%)	NPV (%)
TW	>150	89	93	44	99
	>200	78	99	78	99
	>250	78	100	100	99
TW or Y _{tm}	TW > 150 or Y _{tm} < .2*	89	93	44	99
	TW > 200 or Y _{tm} < .3 ⁺	78	98	70	99
	TW > 250 or Y _{tm} < .2 [@]	78	99	88	99
<p>*Interim norms from ASHA (1990) guidelines, which were superseded by new guidelines (ASHA, 1997). ⁺ Criteria for screening children 1–6 years using immittance (ASHA, 1997) [@] Criteria for screening pre-school and school age children using immittance (AAA, 1997). Sens = Sensitivity; Spec = Specificity; PPV = Positive Predictive Value; NPV = Negative Predictive Value; TW = tympanometric width; Y_{tm} = peak compensated static acoustic admittance.</p>					

olds as we think of them when testing an adult or cooperative older child. MRLs are considered to be influenced by nonsensory factors such as attention, motivation, response criteria and biases. Further, it is suggested that non-sensory factors must operate more on low-frequency signals than on high-frequency signals to explain the infant-adult differences across frequency.

Why is the issue of sensory versus nonsensory limits on threshold estimates important in the context of assessment of hearing-impaired infants? Before we can estimate degree of impairment, we must understand the capabilities of the infant with a normal auditory system. Currently, audiometric data obtained on an infant are plotted on the audiogram that uses audiometric reference values based on adult hearing. If there are developmental differences in hearing, we need to know the magnitude of such differences, as a function of frequency, so we can interpret more properly thresholds obtained on infants with hearing impairment.

That there is a different estimate of hearing when using ABR than when testing with a behavioral technique also is important to consider. ABR thresholds of six-month-old infants with normal hearing are much like those of adults, while the behavioral thresholds are elevated.

Does this mean one is correct and one is not correct? Does this prove that infant hearing does not undergo developmental change?

Behavioral thresholds, more so than ABR thresholds, reflect the infant's ability to process an auditory signal at the peripheral level and provide an indication of the level of a signal that is required to motivate a response from an infant. Implicit in the behavioral test is the concept that the intensity level necessary to elicit a reliable behavioral response from the infant is the same intensity level necessary for the infant to process an auditory signal in a way that permits a meaningful response such as might be necessary for appropriate development of speech and language. In other words, although some exposure to sound in infancy may trigger passive activity within the central nervous system, at least some of what infants learn from auditory input is an active process. Looking at it another way, if an infant is exposed to an auditory stimulus that is of sufficient intensity to generate an observable ABR waveform, but is not sufficient to motivate a behavioral response, to what degree has the signal been processed (i.e., been influential in the development of the infant's ability to process auditory information in a meaningful way)? Making it into an even more direct clinical question in the context of am-

plification, if an infant ABR reveals thresholds that are 15 dB better than behavioral thresholds, which thresholds do you use in your prescription for setting the gain of a hearing aid? Is it the one based on an identifiable waveform or the one that indicates the ability of the infant to respond in a meaningful way?

Comparisons of infant behavioral thresholds in quiet versus conditions of masking may shed some light on the degree to which infant threshold estimates can be influenced by nonsensory factors. In a number of studies designed to measure infant and adult behavioral thresholds, in quiet and/or in noise, infant-adult differences in masked thresholds have been much more consistent across stimulus conditions than have the infant-adult differences in thresholds in quiet (Table 3). Why would thresholds in quiet vary widely with the stimulus conditions (e.g., tone frequency or speech-sound discrimination task) at the same time that thresholds for the same stimulus conditions in the presence of a masking noise vary little?

While some have proposed that the greater difference in unmasked threshold between infants and adults in the low frequencies is due to nonsensory factors such as listed above, it may be reasonable to assume that the differences in thresholds between infants and adults may be due, at least to some degree, to true differences in sensory processes. For example, in a study to investigate the minimum masking level (MML) for infants and adults for a tone of 1000 Hz, thresholds were estimated in quiet and at increasing levels of

masking noise (Nozza, 1995). The group difference between infants and adults was about 12 dB for unmasked thresholds. If infants were biased against responding to a 1000 Hz tone relative to the adults, the introduction of masking noise should not alter the infant-adult difference. However, if infants truly have a poorer sensitivity than adults, then as the masking noise reaches and exceeds the MML, the difference between infants and adults should diminish or disappear in much the same way as an increase in masking intensity level would shrink the difference in thresholds between a listener with normal hearing and one with a hearing impairment. That is, under this assumption, we can view the infant as having a hearing loss relative to the adult. Figure 1 illustrates the change in thresholds of infants and adults as masking intensity increases. The difference between infants and adults in threshold for the masker at +10 and at 0 dB SPL per cycle is about 5 dB compared to 12 dB in the unmasked condition. If there were nonsensory factors accounting for the entire 12 dB difference between infants and adults for the unmasked thresholds, one would expect those same factors to operate in the masking condition. Clearly, the infant-adult difference shrinks considerably with the introduction of the masker and the difference of about 5 dB with masking probably represents the most that nonsensory factors contribute.

Preliminary analysis of the results of a recently completed study in my laboratory indicates that infant-adult differences in unmasked thresholds

Table 3. Differences between infants (6–12 months) and adults in thresholds, determined in quiet and in the presence of masking noise, using pure tones greater than 250 ms in duration and using earphone presentation.

Infant-adult differences for thresholds determined in noise vary much less across stimuli than do those determined in quiet. Some values are averages.

Stimulus	Difference in threshold in quiet	Difference in threshold in noise	References
500 Hz	15 dB	4 dB	Hesketh, 1983 (quiet; monaural); Nozza, 1987b (noise; binaural); Estimated based on work in progress (quiet and noise; Nozza).
1000 Hz	12–13 dB	5–7 dB	Nozza and Wilson, 1984 Nozza, 1995 Olsho et al, 1988
2000 Hz	4 dB	4 dB	Estimated based on work in progress (Nozza).
4000 Hz	6 dB	7 dB	Nozza and Wilson, 1984
/ba/	17 dB	6 dB	Nozza et al, 1988
/ba/ vs /ga/ discrimination threshold	25 dB	6–7 dB	Nozza et al, 1991b (quiet) Nozza et al, 1990 (noise) Nozza et al, 1991a (noise)

Figure 1. Thresholds of infants and adults for a 1000 Hz pure tone, presented through an insert earphone, in quiet (Q) and in different intensity levels of masking noise using an octave band masker centered at the test frequency. Data taken from Nozza (1995).

get smaller with increasing frequency (500 to 2000 Hz) and are consistent with data from other studies (Werner, 1992). However, in the same study, the infant-adult differences in thresholds under conditions of masking are quite similar across the two frequencies. That is, the results are consistent with earlier studies (Table 3) that suggest wide variability in unmasked thresholds as a function of frequency and little variability when masking is employed.

Given the evidence that the inner ear is mature at birth and that infants have normal abilities with respect to frequency analysis (Werner, 1992), what sensory factor(s) might explain the differences between infants and adults in unmasked thresholds as a function of frequency? One possible factor is developmental change in transfer characteristics of the middle ear. There are changes in middle ear admittance in early life (Table 1) and data are emerging on developmental changes in middle ear reflectance (Keefe et al, 1993). Such changes are consistent with greater stiffness and poorer transmission of low frequencies. Another factor that must be considered is that of physiological noise. Greater self-generated noise in infants is likely to occur in the behavioral test setting and such noise is typically greater in the low frequencies than in the high frequencies. That would suggest that, at least in part, the greater infant-adult differences in unmasked thresholds in the lower frequencies could be due to greater low-pass internal noise in the infants. This would be a limit on the sensory process that is not related to the nonsensory factors such as attention, motivation, etc. Of course, we know little about the role that the central nervous system might

play in the limits on sensory processing in the developing infant, even with respect to sensitivity and in spite of infant ABR thresholds, so this must be included in our thinking. For all measures of sensitivity, and especially when thinking about the similarity between ABR thresholds of infants and adults, we must keep in mind that the SPL at the tympanic membrane of an infant is greater, by substantial amounts at some frequencies, than at the tympanic membrane of an adult for the same output at the earphone (Feigin et al, 1989). So even when threshold estimates for infants and adults are similar, the infant is working with greater intensity at the input to the system, suggesting that there are differences in transmission and/or processing beginning at the tympanic membrane between the two age groups.

Suprathreshold Processing

How do these different theories about the origin of infant-adult differences in behavioral thresholds affect our thinking with regard to suprathreshold processes such as speech perception? If differences in threshold are due to greater internal noise in the infants, tasks performed at levels 30-50 dB above threshold would be unaffected. This has been tested in a study of the effects of intensity on infant speech perception (Nozza, 1987a). Infants revealed optimal performance in a speech-sound discrimination task at levels (about 50-60 dB HL) that are consistent with normal conversational speech. However, at around 40 dB HL, within 20 dB of typical speech, infant performance was reduced (Nozza, 1987a, 1994). Adults were able to perform the task down to around 10 or 15 dB HL. There are several possible explanations for the breakdown in infant performance with only slight reduction in intensity of the stimuli, including the greater complexity of the discrimination task relative to a detection task, acoustic filtering of the stimuli due to a different audibility curve, and possibly others.

The important point to consider is that infants demonstrated a reduction in processing ability for speech sounds at levels well above those that would cause a similar reduction in adults and well above levels that would be influenced by the suggested internal noise hypothesis. The move from a task to measure detection thresholds, which could be limited by some level of internal noise, to a suprathreshold speech discrimination task did not eliminate the difference between infants and adults that is seen in unmasked detection thresh-

olds. That is, internal noise might explain a difference in threshold responses but cannot explain infant-adult differences in speech processing at levels well above threshold. As with detection, testing with masking noise revealed that infant performance on a speech-sound discrimination task was much more similar to that of adults than when testing was done in quiet (Nozza et al, 1990).

The speech-sound discrimination task was modified so that intensity thresholds could be determined in much the same way as they are in a detection task. The purpose of developing a threshold of discrimination was to make more efficient the process of getting a measure of speech sound discrimination for the infants. Using the standard one up, one down adaptive protocol, the 50% point on the psychometric function was estimated for discrimination of speech sounds in noise (Nozza et al, 1990, 1991a) and in quiet (Table 4; Nozza et al, 1991b). The differences in thresholds between infants and adults were 25-28 dB in quiet, but were small (6-7 dB) when masking noise was included. Again, the evidence suggests that infants can perform much more like adults when masking noise is used to equalize the background for infants and adults. However, in the absence of an external masker, infant performance is far inferior to that of adults, suggesting that the greater part of the infant-adult difference is not due to nonsensory or task-related variables, but to some limitation in the sensory process.

When considering amplification for infants, we worry about over-amplification; and this is an appropriate concern. However, data suggest that infants with normal hearing cannot perform simple auditory tasks unless stimuli are at intensities above those at which adults can perform the same tasks. Does this mean the infant with hearing impairment has need for greater sensation level

also? We don't know, but this is something we must consider. Determining gain based on prescriptive procedures that assume infants have the same auditory requirements as adults may be less than optimal. Research that demonstrates how infants really do perform important speech perception tasks must be incorporated into our thinking about and management of hearing impairment in infants.

Methodological Improvements

Of course, in the laboratory study of auditory behavior, we can track variables that might affect infant performance or that might affect the way we estimate infant performance. We study the infant's behavior and the methods we use in a controlled setting so that we can better understand how to improve our clinical methods. For example, one of the features of the laboratory version of VRA that has not been incorporated to any great degree in the clinic is the computer control of specific aspects of the protocol. In behavioral testing, experimenter bias or error can influence outcome. With the computer, some decisions can be removed from the experimenter's control, such as duration of the stimulus presentation or response interval, information about whether a trial contains a signal or is a control trial, the intensity level of a given signal in the adaptive protocol, and others. This kind of computer control prevents the experimenter from extending or reducing the duration of a signal based on knowledge of the stimulus intensity (and the assumptions about whether the infant can hear it), or changing the time following a signal during which the reinforcer will be available. With the computer, experimenter involvement is limited. We know in clinical behavioral testing with any age group that these things can and do come into play and can bias our estimate of hearing.

An example of how the computer can assist us in understanding what we are doing in the behavioral test situation involves measuring the latency of response. In experimental VRA, the computer is programmed to determine, based on a set of predetermined rules, whether to present a signal or to have a control, or blank, trial when the trial is initiated. The experimenter who is observing the infant is not aware of the trial type and so, once initiating a trial, simply observes the infant and judges whether a head-turn response occurs. The infant, of course, is not informed that a signal is starting in much the same way as an adult tak-

Table 4. Thresholds (dB SPL) for discrimination of two consonant-vowel syllable pairs, /ba/ vs /da/ and /ba/ vs /ga/ for infants and adults (Nozza, 1991b).

Age group		Stimulus pair	
		/ba/ vs /da/	/ba/ vs /ga/
Infants	Mean (sd)	39.3 (6.5)	35.1 (5.6)
Adults	Mean (sd)	11.8 (5.1)	9.7 (3.7)
Difference between infants and adults		27.5	25.4

ing a hearing test is not told when to listen for the signal. If a criterion head turn occurs, the experimenter presses a response button that is interfaced with the computer. If the trial is a stimulus trial and if the response button is pressed during the response interval, the computer scores a hit, activates the visual reinforcer and steps the attenuator according to the tracking algorithm. However, if the button is pressed and it is NOT a stimulus trial (i.e., it is a control or blank trial), it is recorded as a false positive and no reinforcement is provided. Also, if it is a stimulus trial but the button is pressed outside the response interval, no reinforcement is given. The inclusion of computer-selected control trials helps to keep the experimenter objective in making decisions about starting trials and in judging responses.

In one experiment (Nozza, 1987a), the time interval from the onset of each trial to the time of the first head-turn response, for both stimulus and control trials, was recorded to chart the infant's tendency to respond as a function of stimulus condition. The data were collected to permit analysis of the relationship between responses to trials in which the stimulus was present versus when it was not present as a function of the time following trial onset. In the example from one typical subject (Figure 2), it is evident that the infant made a high percentage of responses in the first four seconds following the onset of stimulus trials. However, notice that there is also a cluster of responses that were made within the first four seconds following initiation of control trials. Con-

trol trials, in theory, provide no information regarding the stimulus, so why would the infant respond so often within four seconds of the start of a control trial? One thing we can derive from data like these is that the infant is predisposed to respond at certain times during the session, independent of whether the stimulus is present or not. This can happen easily if the experimenter is starting trials with a constant inter-trial interval and the infant has developed a timing response. This can happen also if the experimenter in the room with the infant has certain behaviors that occur at the time he or she is initiating a trial, signaling to the infant that the probability of seeing the toy reinforcer is greater than at other times. Things such as cessation of movement, introduction of a new distracting toy, or making eye contact with the infant just as a trial is initiated could inform the infant. Data on the frequency and timing of false responses are very useful for estimating the reliability of an infant's performance. An infant who responds only when the stimulus is present and never when it is absent would provide a more reliable estimate of auditory function than one who responds as often when the signal is absent as when it is present. Such knowledge is useful in helping us understand the infant's behavior in the stimulus-response paradigm and can help us to minimize biases that we, as the audiologists, might introduce into the testing.

CONCLUSIONS

Audiological research related to assessment of hearing in children has provided us with great new knowledge and new methodologies. From the development of objective procedures such as ABR and OAE testing to changes in the way we record immittance data, our ability to evaluate hearing in the young has improved tremendously in the last two decades. Research related to behavioral testing has been slower and has not moved into general clinical practice, but will be more important as we move towards early identification and intervention in the very young. Besides the research data that provide norms to support our clinical test methods and our interpretation of clinical data, research on the normal development of speech perception and on the effects of degrading speech stimuli (through reduced intensity or through noise) on infant speech perception also has great relevance to our approach to clinical questions. Knowledge about how infants with hearing loss perceive speech and

Figure 2. Percent of head-turn responses as a function of time following onset of the trial for an infant subject in a speech-sound discrimination task (from Nozza, 1987a). The response latencies represent the time from trial onset to the first head-turn response following the start of the trial.

what amplification strategies are optimal will ultimately depend on behavioral research with infants rather than on data from studies of adults. Finally, data on infant performance in behavioral test settings, which is most easily derived from laboratory studies, should be used to better understand and improve the methods we use in the clinic.

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