Auditory Frequency Resolution in Human Infancy

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SPETNER, NANCY BENSON, and OLSHO, LYNNE WERNER. *Auditory Frequency Resolution in Human Infancy.* CHILD DEVELOPMENT, 1990, 61, 632–652. Frequency resolution is a fundamental capacity of the auditory system that underlies the perception of all complex sounds. The development of this capacity has not been well characterized in humans. This investigation used a nonsimultaneous pulsation threshold technique to examine the development of infant frequency resolution. Psychophysical tuning curves were obtained for 3- and 6-month-olds and for adults at either 500, 1,000, or 4,000 Hz. Both the sensation level and the sound pressure level of the stimulus were varied for adults to determine the contribution of stimulus intensity to age differences in frequency resolution. At 500 and 1,000 Hz, 3- and 6-month-olds' tuning curve widths were equivalent to adults'. At 4,000 Hz, the 3-month-olds' tuning curves were broader than those of 6-month-olds and adults, even when absolute sound pressure level was equivalent. The maturation of psychophysical frequency resolution in infants is discussed in terms of the general development of the auditory system and of nonsensory factors that might contribute to age differences in performance.

Auditory frequency resolution is the ability to respond to a single frequency in an acoustic stimulus when other frequencies are present. It is a fundamental auditory capacity underlying the perception of all naturally occurring sounds, including speech. However, little is known about the maturation of frequency resolution in humans. It is particularly important to examine the development of frequency resolution during infancy, a period when speech perception and production change dramatically.

The few behavioral studies of infant frequency resolution (described in detail below) do not include infants younger than approximately 6 months of age due to limitations of existing testing techniques. A few physiological studies of frequency resolution among infants younger than 6 months of age have been reported. Although physiological studies add to our understanding of frequency resolution, data from these studies cannot be interpreted in terms of the organism's ability to use acoustic information to guide behavior. Taken collectively, however, the behavioral and physiological findings suggest a progressive improvement in resolution with age (i.e., smaller differences in frequencies are resolved), and that 3-month-olds have more mature resolution at low than at high frequencies.

Masking is a commonly used technique for studying auditory frequency resolution. Masking occurs when the presence of a competing sound, the masker, reduces the audibility of, or otherwise affects the perception of, a sound called the signal or probe. There are many masking paradigms, and these vary in the information they can provide with respect to the development of frequency resolution. For example, among the behavioral studies, Nozza and Wilson (1984) obtained thresholds for 6- and 12-month-olds and adults for 1,000 or 4,000 Hz tones, masked by broadband noise presented simultaneously with the tone. This measure of frequency resolution is known as the critical ratio, and it was found to vary with frequency in the same way at each age. Infants' masked thresholds were 6 to 8 dB higher than were adults', im-

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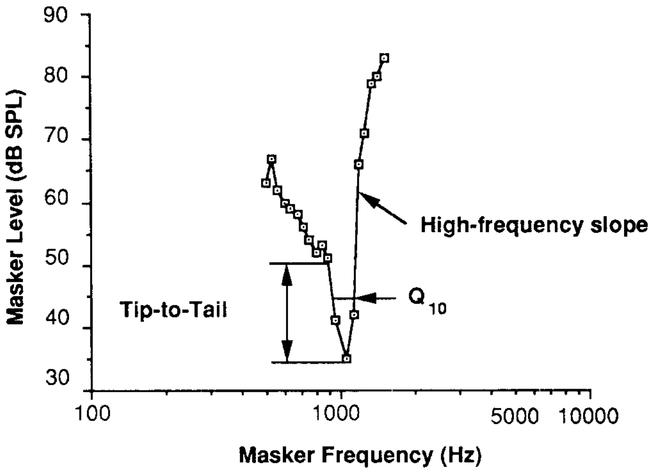

FIG. 1.—An example of a psychophysical tuning curve from a normal-hearing listener (from Carney & Nelson, 1982).

plying that infants have poorer resolution at both signal frequencies. However, this conclusion rests on the assumption that only frequency resolution affects performance. Performance would also be affected if infants are less "efficient" in detecting probes than adults are because, for instance, they are less attentive to the sounds, less motivated to detect probes, or require higher probe levels to respond. It is impossible to separate nonsensory (e.g., motivation, attention) from sensory contributions to performance in this task.

A relative measure of frequency resolution would eliminate the problem inherent in the critical ratio. In that case the differences between thresholds under different masking conditions provide the critical information. Thus, nonsensory factors can be effectively controlled because they would only be expected to affect the measurement of age differences in frequency resolution if they varied systematically with masking condition and if the systematic variation was different for infants and adults.

The tuning curve paradigm provides a relative measure of frequency resolution. A tuning curve describes frequency resolution by showing the intensity of one tone, the masker, necessary to affect the response to a second tone, the probe, by some amount. The greater the frequency difference between the two tones, the more intense the masker should have to be to affect the response to the probe. Conversely, when the masker and probe are identical in frequency, the masker should affect the response to the probe at a very low intensity. Thus, a tuning curve's lowest point, its tip, is generally at the probe frequency. The curve rises in either direction as the masker frequency progressively departs from the probe frequency, as shown in the example in Figure 1. A very narrow curve indicates good resolution ("tuning"), and a broad curve indicates poor resolution. The width of the tuning curve is generally measured by Q_{10}, its bandwidth 10 dB above the tip.

Physiological tuning curves indicate that frequency resolution at the most peripheral level of the auditory system may be mature very early in postnatal life. Bargones and Burns (1988) used spontaneous otoacoustic emissions (SOAEs) to obtain tuning curves. Otoacoustic emissions are sounds generated in the cochlea that can be recorded in the ear canal. Tuning curves were obtained by determining the level of a masker tone that reduced the amplitude of the SOAE by 5 dB for a variety of masker frequencies. Tuning curves were measured in 3-week-old to 6-month-old infants and in adults. Although there was a tendency for infants to exhibit emissions at higher frequencies than adults, the results revealed no age differences in tuning curve width for infants and adults whose SOAEs were in the same frequency range. Even among infants with higher frequency emissions (≥ 4,000 Hz), no sharpening of tuning was seen between 3 weeks and 6 months of age.

However, tuning curve measures of frequency resolution based on the central nervous system response suggest that immaturity persists for some months. Folsom and Wynne

(1987) obtained tuning curves by measuring wave V of the auditory brainstem response (ABR) in 3-month-olds and adults to 1,000, 4,000, and 8,000 Hz filtered clicks, simultaneously masked by pure tones varying in frequency and intensity. The width of the tuning curve was equivalent for infants and adults at 1,000 Hz, but it was broader for the infants at 4,000 and 8,000 Hz. Similarly, in an ABR masking profile study in which the response to the probe was measured in the presence of maskers of fixed intensity at various frequencies (Folsom, 1985), wave V latencies were longer and amplitudes were decreased for 3-month-olds compared to adults for maskers below the probe frequency, but only at 4,000 Hz.

The only infant behavioral tuning curves have been obtained from 6-month-olds. Olsho (1985) used simultaneous, pure-tone masking to explore the development of frequency resolution. The minimum masker level at which listeners would respond to the probe was determined for 500, 1,000, 2,000, and 4,000 Hz probes. The infants' and adults' tuning curves did not differ in width at any frequency. Thus, the 6-month-olds' average tuning curve does not show the apparently poor frequency resolution seen in the critical ratio. It should be noted that the relative position of the curves was lower for the infants: infants stopped responding to the probe at lower masker intensities than did adults. This was precisely Nozza and Wilson's (1984) observation in the critical ratio experiment and may, again, reflect the infant's inefficiency in detecting probes.

A hypothesis drawn from these studies is that frequency resolution matures early at a peripheral level but lags behind at neural levels. Immaturity in neural response may still be evident at 3 months of age. By 6 months of age, frequency resolution may be mature, although infants may still be less efficient in performance than are adults. This hypothesis predicts that a behavioral measure of frequency resolution for 3-month-olds would reflect the immaturity seen in the ABR. A major goal of this study was to test that prediction.

A further consideration is that no existing study has treated the development of so-called suppression. Suppression, a mechanism believed to sharpen auditory tuning, is the reduction of activity in neighboring nerve fibers as a result of excitation of a more strongly stimulated fiber. It has been argued that suppression can only be demonstrated psychophysically when the masker and the probe do not overlap in time (e.g., Duifhuis, 1980; Houtgast, 1972, 1977). Otherwise masker and probe exert mutual suppression, resulting in no net sharpening. Thus, the contribution of suppression to tuning is only included in measures of frequency resolution using nonsimultaneous masking techniques (Fastl & Bechly, 1981; Houtgast, 1972, 1977; Moore & O'Loughlin, 1986; Shannon, 1976). Since infant frequency resolution has only been measured using simultaneous masking, immaturity in suppression would not have been evident in previous studies. A second goal of this study was to examine frequency resolution at both 3 and 6 months using nonsimultaneous masking to assess possible immaturity in suppression.

The most commonly used nonsimultaneous masking techniques are forward masking and the pulsation threshold. In forward masking, the masker is presented and terminated before the probe is presented. The audibility of the probe is reduced despite the fact that the two stimuli do not overlap in time. In the pulsation threshold procedure, probe and masker alternate with no time interval between offset of the masker and onset of the probe. At low masker intensities, the probe is perceived as intermittent (pulsating). When the masker intensity increases beyond a certain point, the probe is perceived as continuous even though it is physically intermittent. The pulsation threshold is the point at which perception of the probe changes from intermittent to continuous.

The pulsation threshold technique was used here because pilot testing in our laboratory indicated that we could readily obtain pulsation thresholds from infants, whereas we have had difficulty obtaining forward masked thresholds from infants. Furthermore, it is often noted that adults tend to take longer to attain asymptotic performance in forward masking than in other psychophysical tasks, and that adult masked thresholds may be artifactually elevated because listeners confuse masker and probe under some conditions (e.g., Moore & Glasberg, 1983; Neff, 1985). These observations and our pilot testing of infants in forward masking suggested a strong influence of factors not related to frequency resolution, which, most importantly, appeared to vary with stimulus conditions. These factors could influence tuning curve width and could do so differentially for infants and adults. Thus, the pulsation threshold technique seemed more likely to provide useful information about infant frequency resolution.[1]

To summarize, the goal in the current study was to describe the development of human frequency resolution with a single behavioral technique from 3 months to 6 months postnatal age. To better separate sensory from nonsensory factors, a relative measure of frequency resolution, psychophysical tuning curve width, was used. To include the effects of suppression, a nonsimultaneous masking technique, the pulsation threshold, was used.

Method

Overview

As mentioned above, the width of the tuning curve, most commonly measured as Q_{10}, is one measure of frequency resolution. As shown in Figure 1, the slope of the high-frequency side, as well as the distance between the tip and the point where a decrease in tuning curve slope begins on the low-frequency side ("tip-to-tail" distance), can also be used to describe the tuning curve. We decided to concentrate on Q_{10}, however, because it is most frequently used, because it has been used in earlier infant studies, and—since it is difficult to obtain many data points from an infant—because its estimation requires fewer data points than other measures.

To obtain pulsation threshold tuning curve widths, four thresholds were obtained in a background of broadband noise from each subject. First, a detection threshold was estimated for the intermittent probe alone. For this task, the subject was required to discriminate trials on which a probe was presented from trials on which no probe was presented. This measure was used to set the level of the probe in the pulsation threshold tasks at the same relative level (sensation level, SL) for each subject. Next, a pulsation threshold was estimated at the tuning curve tip (i.e., when the masker frequency was set equal to the probe frequency). The subject's task was to discriminate trials on which an intermittent probe was presented with an intermittent masker from trials on which a continuous probe was presented with the intermittent masker. In this condition, masker *intensity* was varied to define pulsation threshold. Finally, two pulsation thresholds were estimated to define the tuning curve width, one for a masker frequency above and one for a masker frequency below the probe frequency. The subject's task was again to discriminate intermittent probe trials from continuous probe trials. The masker intensity was set 10 dB higher than the pulsation threshold at the tuning curve tip, and masker *frequency* was varied to define the pulsation threshold. Q_{10} would be defined, then, as the probe frequency divided by the difference between the pulsation threshold for a higher-frequency masker and the pulsation threshold for a lower-frequency masker.

The usual procedure for estimating pulsation thresholds for adults is to present the listener with two alternating tones, probe and masker, and to allow the listener to adjust the level of the masker until the probe just sounds continuous. Clearly, this is not a procedure that is readily adaptable for use with infants. Forced-choice procedures have been used to determine pulsation thresholds. For example, an alternating intermittent probe and masker could be presented on some trials, and an intermittent masker with a probe that is *physically* continuous during the presentations of the masker could be presented on other trials. When the level of the masker is above the pulsation threshold, these types of trials should sound the same to the subject. This technique was used by Dumond and Stern (1979) and by Ayres (1984) to estimate pulsa-

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[1] We do not intend to imply that pulsation threshold techniques are problem free. Moore and O'Loughlin (1986), for example, have argued that the listener's response bias changes on repeated testing. However, Escudier and Schwartz (1985) quantified such response biases and showed marginal effects when pulsation thresholds were determined for a single probe frequency with maskers that were relatively close to the probe in frequency. Moreover, while Escudier and Schwartz found that trained listeners became significantly more conservative in pulsation judgments, the net effect of this change was small, amounting to a 1 dB change in pulsation thresholds. Between-session variability was greater, but thresholds did not change in a systematic way. Although there are reports of high pulsation threshold variability with more complex listening conditions (e.g., Duifhuis, 1980; Houtgast, 1972; Shannon & Houtgast, 1980), psychophysical tuning curve studies tend to report low pulsation threshold variability (e.g., Vershuure, 1981). In pilot testing adults using the pulsation threshold technique, we found that well-trained listeners showed more pulsation threshold variability than naive listeners. Perhaps naive listeners are less likely to search for additional stimulus cues, and therefore maintain a more stable response criterion. In sum, it appears that stable pulsation thresholds can be obtained under conditions similar to those in the current experiment.

tion thresholds for adults. The problem with this approach is that when the continuous probe overlaps in time with the masker, additional sounds, known as distortion products, are generated in the ear, and these sounds could serve as a cue to the subject that a physically continuous probe is present. Thus, the subject could use these distortion products rather than probe continuity to distinguish between trial types. To avoid this difficulty in the current experiment, we masked distortion products by introducing a continuous low-level background noise during all testing.[2] The use of a broadband noise at a fixed intensity to prevent the listener from using information at frequencies other than the probe frequency is a commonly used procedure in psychoacoustics, although it is not without its problems (e.g., Green, Shelton, Picardi, & Hafter, 1981; Lutfi, 1983). The addition of such a background noise would not, however, be expected to differentially affect the frequency resolution measures of infants and adults.[3]

If Q_{10} is the measure of interest, the goal is to estimate the frequencies of the two points 10 dB above the tip. The typical procedure is to fix the masker frequency and vary its intensity to define masked threshold. However, it will rarely happen that the frequency chosen will fall exactly 10 dB above the tuning curve tip, and interpolating between points increases the variability in the estimate. In addition, because we are trying to estimate a point along a steep part of the curve near the tip, small errors in estimating masker intensity at threshold can produce large errors in estimating Q_{10}. To place the data points exactly where they are needed to estimate Q_{10}, in the current experiment we fixed the intensity of the masker and varied its frequency to define threshold. This procedure has been used in psychophysical studies of adults (e.g., Dreschler & Plomp, 1980). This approach also reduces the error due to estimating a point on a steep slope: by varying masker frequency, we are estimating a point on a very shallow slope (i.e., in intensity by frequency coordinates rather than in the frequency by intensity coordinates shown in Fig. 1).

Thus, although the current procedure was not the "standard" psychophysical task used with adults, the changes made in the procedures were expected to optimize the applicability to infant listeners and were not expected to affect the measures of frequency resolution obtained.

Subjects

Infants were recruited from a pool of families interested in participating in research at the University of Washington. Subjects had (1) no history of auditory pathology (including no more than two ear infections), (2) no family history of congenital hearing problems, (3) full-term birth, (4) no pre- or postnatal complications, and (5) no illness at time of testing.

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[2] Another possibility would be to present intermittent masker and probe on all trials, but on some trials to present the masker at an intensity high enough that the subject would always hear the probe as continuous. One difficulty with this technique is determining what that masker level should be for an infant, particularly when the infants are likely to have higher absolute thresholds for the probe alone. The crucial problem, however, would be that the subject would now always know which were "continuous" probe trials because the masker level would be higher. A more elaborate training procedure might direct the infant's attention toward probe continuity rather than masker intensity as the critical dimension, but would be likely to demand more time and, hence, provide too few data to obtain a frequency resolution measure. Soderquist, Swift, and Causey (1985) also described a two-alternative forced-choice procedure for estimating pulsation thresholds that involves using intermittent probe and masker on both trials but having the intensity of the masker on one trial always be slightly higher than that on the other. The subject is instructed to respond to the pulsating stimulus. As the intensity of the maskers on both trial types is varied, a point will be reached at which one masker is above the pulsation threshold while the other is below it. Performance on the task should only be above chance levels when this point is reached. While Soderquist et al. (1985) were successful at obtaining pulsation thresholds from at least one naive adult using this approach, we felt it would be extremely difficult to train infants in this task because for most of the run the stimuli cannot actually be discriminated on the basis of continuity of the probe.

[3] Several studies have examined infants' performance in the presence of noise (e.g., Bull, Schneider, & Trehub, 1981; Nozza & Wilson, 1974; Schneider, 1986; Trehub, Bull, & Schneider, 1981). In each study, infants' masked thresholds were found to be elevated relative to adults', but infants' masked thresholds increased 1 dB for every dB increase in masker level (Bull et al., 1981; Nozza & Wilson, 1984; Schneider, 1986) just as adults' do (Hawkins & Stevens, 1950). Furthermore, variation in infants' masked thresholds with probe frequency exactly paralleled that in adults' (Nozza & Wilson, 1984; Schneider, 1986). Thus, although infants do not, in general, detect sounds in noise well, the qualitative similiarity of their performance to that of adults suggests similar underlying processing.

TABLE 1

SESSIONS EXCLUDED BROKEN DOWN BY REASON FOR EXCLUSION AND AGE

	AGE	
REASON FOR EXCLUSION	3-Month-Olds	6-Month-Olds
Not trained	18	13
Not under stimulus control	35	65
Sleepy or fussy	12	2
Nonmonotonic function	2	5
Insufficient data	11	3
Error or equipment	2	4

NOTE.—Not trained = infant did not reach training criterion within 40 trials; Not under stimulus control = high false alarm rate or adaptive rule called for value beyond upper limit of masker or probe intensity; Nonmonotonic function = slope of best fitting psychometric function not greater than zero; Insufficient data = too few reversals, levels, trials, and/or sessions; Error or equipment = experimenter made error in setting up session or equipment malfunction.

The final sample consisted of 47 infants. Twenty-one 3-month-olds (*M* = 13 weeks 1 day, range = 11 weeks 4 days to 15 weeks 4 days) and 26 6-month-olds (*M* = 25 weeks 4 days, range = 23 weeks 3 days to 27 weeks 3 days) were tested. They were assigned randomly to one of three probe frequencies (seven 3-month-olds at each frequency; eight 6-month-olds at 500 Hz, and nine 6-month-olds each at 1,000 and 4,000 Hz). Thirty-six additional infants were eliminated from the final sample. Of 360 total sessions, 172 were excluded; these are broken down by age and reason for exclusion in Table 1. Thirty-six naive adults also served as listeners (*M* = 25 years, range = 21–31). The subjects had normal hearing and no history of auditory pathology determined by self-report.

Apparatus

Tones were generated by voltage-controlled oscillators (Coulbourn S24-05 and Wavetek 171), monitored by frequency counters (Simpson 710 and Hewlett Packard 5381A) throughout the experiment. White noise was produced by a noise generator (Coulbourn S81-02). Each of these signals was gated by an electronic switch (Coulbourn S85-08) and was routed to a programmable attenuator (Coulbourn S85-08), mixed and amplified (Coulbourn S85-24), and finally led through a manual step (impedance matching) attenuator (Coulbourn S85-02) to a small earphone (Sony, model MDR-E242). Stimulus frequency, amplitude, and duration were controlled by an Apple II Plus microcomputer and locally written software.

For each threshold task, the earphone, in a small foam cushion, was placed in the infant's right ear at the concha, and was secured with hypoallergenic micropore tape. The earphone wire was taped to the back of the infant's shirt to keep it out of reach. Infants were tested in an IAC sound-attenuated chamber.

At monthly intervals, the acoustic output of the earphone was calibrated using a Hewlett-Packard (model 3521A) real-time spectrum analyzer. The intensity of the acoustic output of the earphone (with the earphone cushion in place) was monitored by mounting the earphone in a Bruel & Kjaer (type 4152) 6-cc coupler. A Bruel & Kjaer (type 4132) 1-inch pressure microphone was used. The output from the miniature earphone was checked periodically with a Bruel & Kjaer (type 2203) sound-level meter with an octave filter network (type 1613).

Stimuli

The probe was a pure tone of 500, 1,000 or 4,000 Hz with a duration of 125-msec and 10-msec rise/fall. The masker was also a pure tone of 125-msec duration and 10-msec rise/fall. Masker frequency was variable. The level of the background noise was fixed at 20 dB pressure spectrum level for all conditions.[4]

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[4] Green et al. (1981) showed that tuning curve widths do not vary with probe intensity between 20 and 50 dB SPL for probe frequencies in the same range as those used in the current study with a background noise at a probe-to-noise ratio of 35 dB (e.g., a 1,000 Hz probe frequency at 50 dB SPL is presented in a noise background of 15 dB pressure spectrum level, or N_0). Pilot testing showed the youngest infants' average probe thresholds in noise to be approximately 45 dB SPL across the

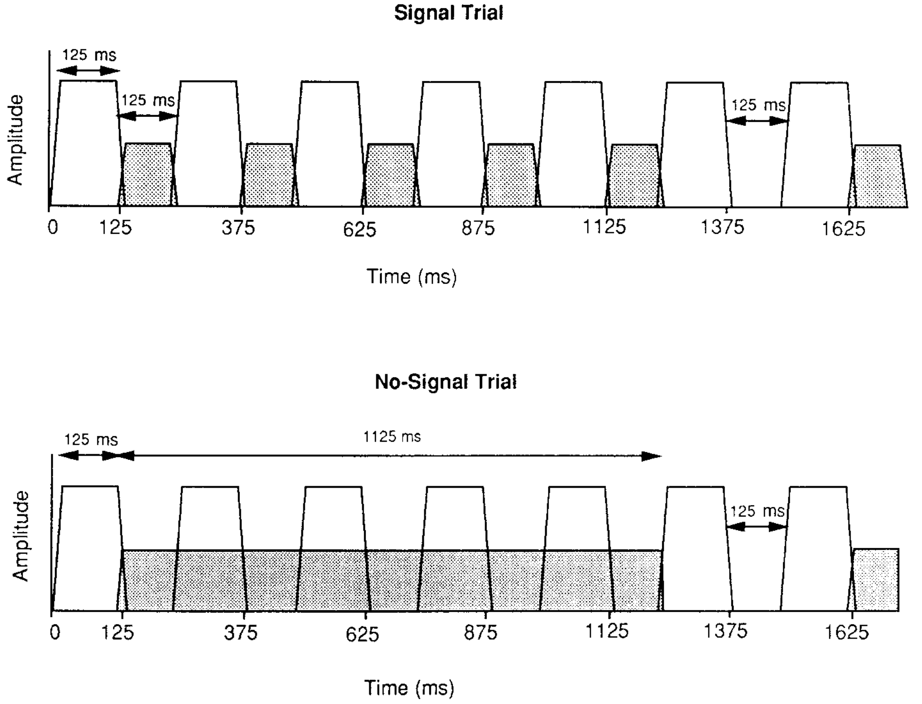

FIG. 2.—Stimulus configuration on signal and no-signal trials for pulsation threshold testing

For the probe detection threshold, the probe was presented in the noise background with 125 msec between tone bursts. The probe was repeated for a total trial duration of 7.5 sec (25 repetitions with every sixth probe omitted) on signal trials. On no-signal trials, the background noise alone was heard for 7.5 sec.

As shown in Figure 2, on signal trials during pulsation threshold testing, masker and probe tone bursts alternated, with no interstimulus interval (Houtgast, 1972, 1977). Every sixth probe pulse was omitted, producing different temporal patterns between the probe and masker to enhance the distinction between the two tones (Houtgast, 1972). On no-signal trials, a 1,375-msec tone, at the same frequency as the probe, with 10-msec rise/fall, was presented along with the masker tone bursts. The probe was gated on at the offset of the first masker burst and with every sixth masker burst thereafter. A 125-msec pause followed each sixth masker burst (i.e., after each 1,375-msec portion of the trial) to match the temporal pattern of signal trials. Both signal and no-signal trials were 7.5 sec in duration.

Psychophysical Method

Adaptive procedure.—An adaptive procedure was used to estimate thresholds in this study. In such a procedure, the stimulus is varied from trial to trial depending on the subject's performance on previous trials. The specific method used in this experiment was the hybrid technique developed by Hall (1981) in which the PEST rules (Parameter Estimation by Sequential Testing; Taylor & Creelman, 1967) determine stimulus conditions. Essentially these rules make a binary search for the threshold: if the subject was correct at the last stimulus value but incorrect at the current value, then the next value presented would be halfway between the last value and the current value. The rules include provisions for making larger changes, or steps, in stimulus value if the subject is performing either very well or very poorly. Unlike a simple PEST procedure, however, the

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frequencies tested here. Because the probes in the pulsation threshold tasks were to be presented at a 10 dB sensation level, we used a noise background of 20 dB N_0, thus preserving the 35 dB probe-to-noise ratio used by Green et al. (1981). Moreover, pilot testing of adults, both naive and trained, showed that distortion products were audible at lower noise levels, but not at 20 dB N_0.

hybrid technique estimates threshold by fitting a psychometric function (percent correct versus stimulus level) to all the data obtained in a run and picking the threshold from that function. Hall's method uses the maximum-likelihood criterion (Hall, 1968) for choosing the best-fitting psychometric function.

There are several advantages to this method of threshold estimation over others that have been used with infants. The technique converges on threshold relatively efficiently and concentrates observations around threshold, the data point of central concern. At the same time, as Hall (1981) and Shelton, Picardi, and Green (1982) point out, this technique is highly resistant to "lapses" on the subject's part because the threshold is based on the best fit to all the data, not just the trials around threshold. This is particularly important because infant performance can be quite variable when the stimulus is close to threshold. Furthermore, Olsho and Marean (1988) recently compared the modified hybrid method and the more commonly used one-up, two-down adaptive rule[5] (Levitt, 1971) and found that infant thresholds did not differ across methods in mean value or variability.

Hall's (1981) procedure was modified to fit the requirements of this experiment and the testing of infants generally. At least four signal trials were presented at a stimulus value before evaluating the subject's performance. The task was made more difficult if the subject got three or four correct. The stimulus value was maintained for another trial if the subject got two correct, and the task was made easier if the subject got one or none correct. This aspect of the procedure makes it less efficient in the sense that more trials are required to converge on threshold but produces much less variable infant performance than evaluating performance following every signal trial (Olsho, Koch, Carter, Halpin, & Spetner, 1988).

The application of the adaptive procedure in the current experiment meant that for probe detection thresholds, the probe intensity began at a clearly audible level, decreased at the beginning of the session, and then varied around threshold. For the pulsation threshold at the tuning curve tip, the masker level began at a low enough level that the probe was clearly intermittent. The masker intensity was then increased at the beginning of the session and varied around the pulsation threshold. For the pulsation threshold for masker frequency higher than the probe, the masker frequency was set well above the expected pulsation threshold, so that the probe was clearly intermittent and the masker frequency initially decreased. For the pulsation threshold for masker frequency lower than the probe, the masker frequency was set well below the expected pulsation threshold and masker frequency initially increased.

The specific starting values for the stimulus, the starting step size, the minimum step size, and initial slope and midpoint estimates for the function-fitting routine were chosen on the basis of extensive pilot testing of both adults and infants, following the general guidelines for the choice of these parameters discussed by Hall (1968, 1981) and by Levitt (1971). Criteria for acceptable values were that the test run converge relatively quickly on threshold for both infants and adults, and that the slope of the derived psychometric function be repeatable when an adult was retested in the same condition. The values are listed in Table 2 for each of the conditions in the experiment. Two trial-by-trial protocols are given in Figure 3 to demonstrate this application of the hybrid procedure. The reader is cautioned that while these values produced reasonable test results for this experiment, they cannot be assumed to be appropriate for other situations.

A cumulative normal form of the psychometric function was assumed, estimated by the logistic curve, following Hall (1981) and Taylor and Creelman (1967). The best-fitting function was found using an iterative procedure. The initial slope and position estimates for the fitting procedure were made from an unweighted linear fit of the data (transformed to z scores). The maximum and minimum values of the proportion of correct responses were also estimated from the data, since infants often did not achieve 100% correct and often responded on no-signal trials (false alarms). Threshold was defined as the 70% correct point.

Test method.—Infants were tested using the Observer-based Psychoacoustic Procedure (OPP; Olsho, Koch, Halpin, & Carter, 1987b), in which an observer, blind to the

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[5] In the one-up, two-down adaptive rule, a stimulus parameter is changed to make the task easier after one incorrect response is made and to make the task more difficult after two correct responses are made. Threshold is usually taken as the average of the reversal points.

TABLE 2

INITIAL VALUES OF STIMULUS PARAMETERS IN THE ADAPTIVE PROCEDURE FOR DETECTION THRESHOLDS AND PULSATION THRESHOLDS

	CONDITION											
	Probe Detection (dB)			Masker at Tip (dB)			High Masker (Hz)			Low Masker (Hz)		
FREQUENCY	Start	First Step	Min	Start	First Step	Min	Start	First Step	Min	Start	First Step	Min
500	70	10	1	23	10	1	750	60	1	300	60	1
1,000	70	10	1	25	10	1	1,250	120	2	750	120	2
4,000	70	10	1	27	10	1	4,800	240	8	3,000	240	8

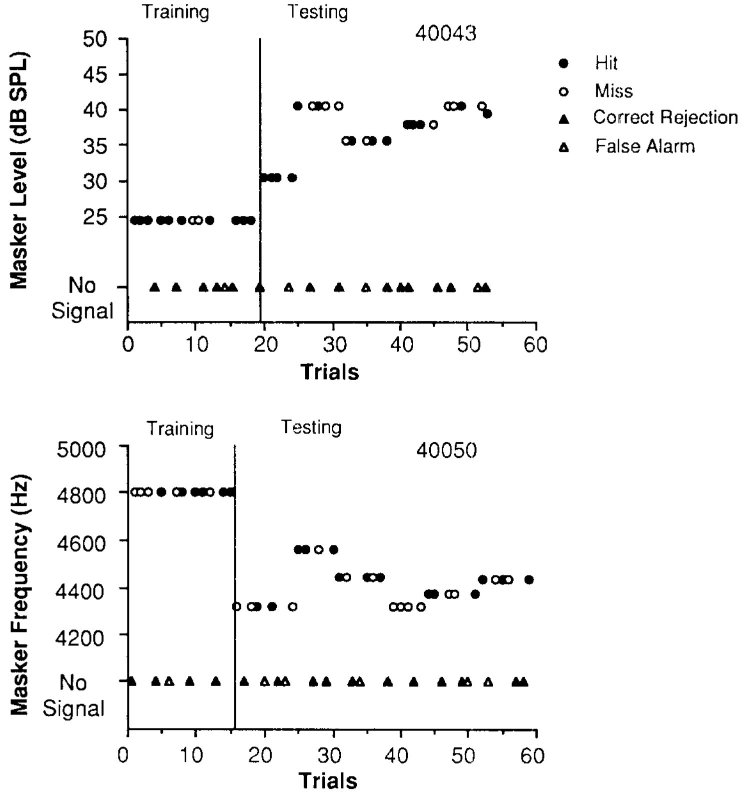

FIG. 3.—Examples of trial-by-trial protocols using the hybrid adaptive procedure to obtain pulsation thresholds for 3-month-old infants. The top panel shows a session in which masker frequency equaled probe frequency, 4,000 Hz, and masker level was manipulated. The bottom panel shows a session in which masker frequency was higher than probe frequency (4,000 Hz), and masker frequency was manipulated.

stimulus type, judges whether a signal or no-signal trial has occurred. The only information available to the observer during the trial is the infant's behavior, such as eye widening, brow raising, behavioral inhibition, or head-turning. The observer receives feedback after each trial. The infant is reinforced by the activation of a mechanical toy whenever the observer correctly identifies a signal trial. The definition of signal and no-signal trials depends on the experiment.

Three observers obtained the infant thresholds reported here. Each had been trained as described by Olsho et al. (1987b), and there was no significant difference between observers in the thresholds obtained in any condition. All observers were required to produce sessions meeting all conditions for inclusion in the final data set (false alarm rate, psychometric function slope, number of trials, number of levels—all discussed below) on a routine basis, and to obtain thresholds consistent with those obtained by other observers in previous studies in this laboratory (e.g., absolute thresholds or frequency discrimination thresholds).

For all tasks, the infant was seated on the parent's lap, at a table facing a half-silvered mirror adjoining the control booth. The assistant, seated to the infant's left, played with toys to engage the infant's attention at a midline position. A mechanical toy in a smoked Plexiglas box was situated to the infant's right at the infant's eye level. The toy was visible only when the box was illuminated. Both the parent and the assistant wore standard-sized headsets, and neither could hear the stimuli.

Each trial was initiated by the press of a computer key when the observer judged the infant to be quiet and facing midline. A flashing LED indicated to the observer that a trial was in progress. The occurrence of signal and no-signal trials was computer controlled. The probability that a signal occurred on any given trial was 0.65, with the restriction that no more than three signal or no-signal trials occurred consecutively.[6]

Four response outcomes were possible. If the observer decided that a signal occurred on a signal trial, a hit was recorded. If the observer decided that no signal was presented on a no-signal trial, a correct rejection was scored. An error was recorded when the observer either decided that a signal occurred on a no-signal trial (false alarm) or that no signal occurred on a signal trial (miss).

At the start of the session, during training, signal and no-signal trials were easily discriminable and stimulus parameters were not varied. The mechanical toy was activated as soon as the observer scored a hit or at the end of each signal trial, regardless of the observer's response. Training continued until the observer was correct on four of five consecutive signal trials and on four of five consecutive no-signal trials.

Once the training criteria were met, the testing phase began. In this phase, the adaptive procedure was used to estimate threshold. During testing, the reinforcer was activated only on correctly judged signal trials. If the false alarm rate from the previous four no-signal trials exceeded .25, testing was interrupted with a warning message displayed on the computer monitor. The observer opted either to proceed with the testing phase or to return to training until the original level of performance was re-established. The session continued until the infant fussed or fell asleep, until three false alarm warnings occurred, or until 50 signal trials, excluding training trials, were presented. A threshold was estimated if (1) at least 20 signal trials, (2) at least two reversals (changes from increasing to decreasing stimulus values), (3) at least four stimulus levels, (4) a psychometric function slope significantly greater than zero, and (5) a false alarm rate for the entire test phase of no greater than 0.35 were obtained. If the session did not meet these criteria, every effort was made to schedule an additional visit to obtain the data point.

Each session lasted for 20–30 min. Four to six sessions were generally required to obtain all the data necessary to estimate Q_{10} for an infant. The probe detection threshold was always obtained first, followed by the pulsation threshold at the tip of the tuning curve. The test order of the pulsation thresholds for maskers higher and lower than the probe was counterbalanced across subjects.

Adult Testing

The same apparatus and a similar procedure were used to test adults. The adults were told that the study was concerned with infant hearing, and that we were interested in testing adults in such a way as to make a fair comparison to infants. They were instructed to raise their hands when they heard "the sound that would make the mechanical toy come on." The adults listened alone in the test booth. In all other respects, the procedures were the same for the adults as de-

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[6] One concern about the practice of restricting the number of consecutive signal or no-signal trials is that the observer (and possibly the infant) could use knowledge of that rule to achieve better than chance performance in the absence of any information about the infant's response (or the stimulus). In general, this practice is probably not a good one for several reasons, but it does avoid problems associated with the infants becoming bored should a long string of no-signal trials occur in an unrestricted sequence. It has been our experience in OPP that the observer is concentrating quite hard on the infant's behavior throughout the session and has difficulty remembering even the recent history of signal and no-signal trials. Informal simulated sessions in which an observer attempts to obtain a threshold by counting trials alone suggest that it is extremely difficult to reach training criterion, let alone produce an acceptable threshold, under these conditions. Furthermore, we have checked for the possibility of counting directly, as suggested by Clarkson, Clifton, and Perris (1988), by comparing the rate of correct responses on the trial following a string of three consecutive trials of one type to the rate of correct responses for the entire test sequence. Repeated-measures 3 (age: 3 months, 6 months, adults) × 3 (frequency: 500, 1,000, 4,000 Hz) × 2 (trial position: unrestricted vs. trial following "three in a row") analyses of variance of arcsin proportion correct responses were conducted in each condition of the experiment. The effect of trial position was not significant in any of these analyses. Because most of the trials following "three in a row" were no-signal trials and because the effects of experimenter bias on these trials would be to include sessions that should have been excluded for high false alarm rate, the analysis of tuning curve width was repeated after excluding infants who had any session that did not meet the false alarm criterion when no-signal trials following three consecutive signal trials were excluded. The results of this analysis were no different from those reported for the entire sample. Thus, while we hesitate to condone the general practice of restricting the number of consecutive trials of a type, we conclude that it had no identifiable effect on the thresholds reported here, and we recognize that such restrictions may be useful in the psychophysical testing of infants.

scribed above for the infants. Three different groups of adults participated.

Equal sensation level condition.—Twenty-four adults, eight at each probe frequency, listened under the same listening conditions as the infants. A detection threshold for the probe was estimated, and the probe was set at 10 dB SL for the three pulsation threshold tasks. Preliminary results for the infants and adults at 10 dB SL suggested age differences in frequency resolution at 1,000 and 4,000 Hz. However, the infants' probe detection thresholds were worse than the adults': the mean difference between 3-month-olds and adults was about 24 dB. This may be because infants have poor auditory sensitivity or because infants simply stop responding to stimuli at low, yet audible, levels. Hence, two additional groups of adults were included.

Equal sound pressure level condition.—Consider the hypothesis that the infants are actually as sensitive as adults are, but that they produce higher thresholds as the result of inattentiveness or some other nonauditory factor. The result would be that the infants would be listening at a higher SL in the pulsation threshold task. To test this, tuning curves were obtained with probe intensity equal to the average probe intensity (or sound pressure level) for the 3-month-olds, for four adults at 1,000 Hz (44 dB SPL), and four adults at 4,000 Hz (57 dB SPL).

High noise level condition.—If the infants are actually as insensitive as their probe detection thresholds imply, then although they are listening at a higher SPL, their effective probe level, or SL, is still 10 dB. This situation is often simulated in normal-hearing adults by introducing a background noise at a level sufficient to raise thresholds to those of hearing-impaired listeners (e.g., Florentine, Fastl, & Buus, 1988). An adult listening to a probe at 10 dB SL in this "high noise" condition must process a high-SPL stimulus, even though the audibility of the sound is low. In the third adult listening condition, the level of the background noise was increased by 24 dB. The probe level for the pulsation threshold tasks was 10 dB above the detection threshold in this high-level noise. Four adults completed testing at 4,000 Hz only.

Results

Frequency Resolution

Average tuning curves for infant and adult listeners are shown in Figure 4. Each panel represents the data at a single probe frequency. In general, the tuning curves obtained from all listeners are sharper, on a log frequency scale, at higher probe frequencies, as is typically found (e.g., Carney & Nelson, 1982; Kiang, Watanabe, Thomas, & Clark, 1965). In addition, the curves are generally symmetric, as would be expected given that these measurements are made close to the tip of the tuning curve. Finally, raising the probe SPL for the adults, both with and without an accompanying increase in the background noise level, had the predicted effect of displacing the tuning curve upward. The effect of increasing the probe SPL at 4,000 Hz was, on the average, larger than expected, but not beyond the limits of normal variation between naive adult listeners.

To summarize the width of these tuning curves, the average Q_{10} for each age/condition is plotted as a function of probe frequency in Figure 5. The values of Q_{10} are reasonably consistent with those reported in earlier psychophysical tuning curve studies of adults using forward masking (e.g., Moore, 1978; Wightman, McGee, & Kramer, 1977) and using pulsation thresholds (e.g., Houtgast, 1972). If anything, these Q_{10}s are a little smaller than those typically reported for well-trained listeners (e.g., 6.5 at 1,000 Hz as opposed to 9.2 reported by Wightman et al., 1977); this might be expected if listeners in the current study are not pushed to the limits of their frequency-resolving capacity. However, the difference between the current Q_{10}s and those previously reported is not dramatic and could as easily be explained in terms of normal between-listener variability.

The general increase in Q_{10} with probe frequency quantifies the sharpening of tuning with increasing frequency that was noted in the tuning curves themselves. Three-month-olds appear to differ from the other groups, however, in that Q_{10} does not increase to the same extent with probe frequency. Moreover, increasing the SPL of the probe, whether or not accompanied by an increase in the background noise level, does not make the adults' Q_{10}s as low as the 3-month-olds'. A one-way analysis of variance was used at each probe frequency to examine the effects of age/condition (3 months, 6 months, three adult listening conditions) on Q_{10}. There was no difference between infants and adults tested at either 500 Hz or 1,000 Hz. However, the effect of age/condition was significant at 4,000 Hz, $F(4,26) = 5.60$, $p < .005$. Pairwise comparisons between means at 4,000 Hz, using separate variance estimates for each contrast, showed that 3-month-olds had significantly

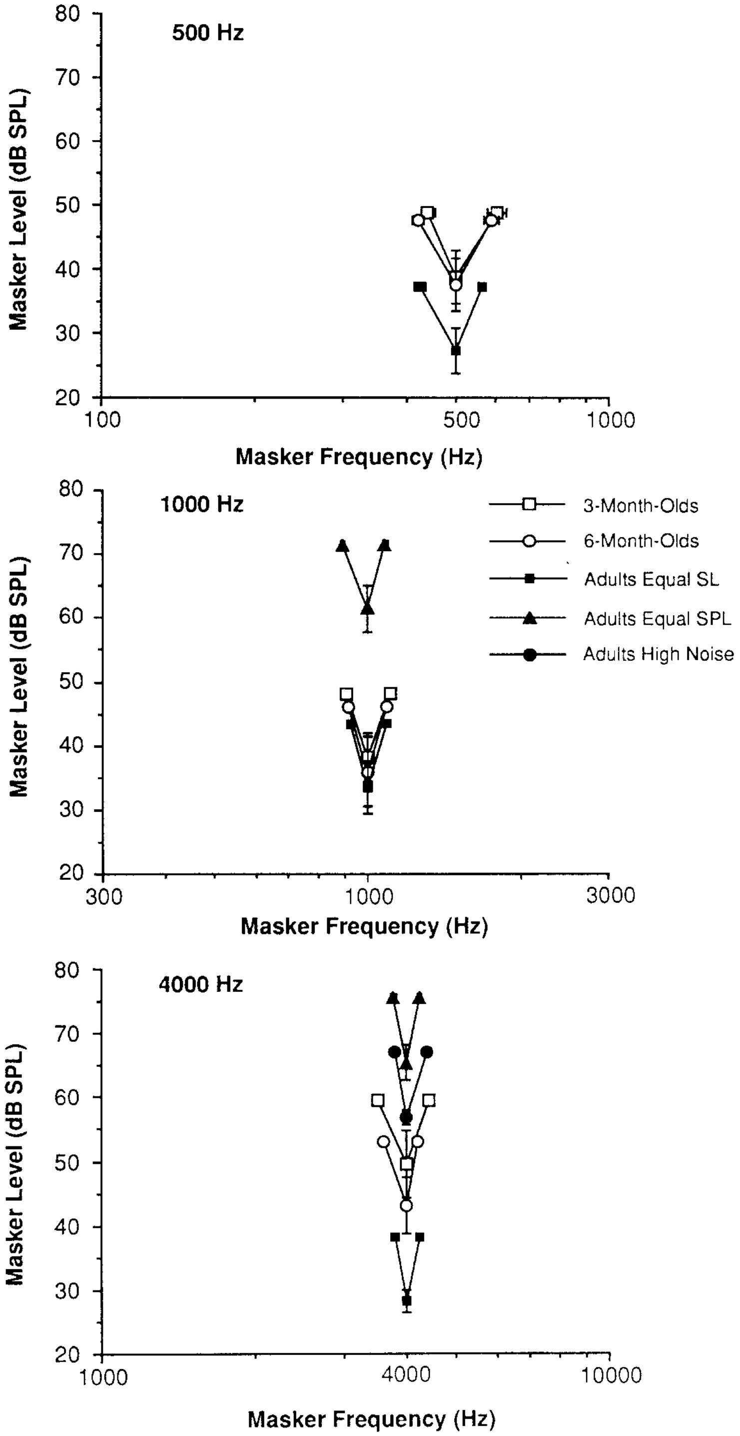

FIG. 4.—Psychophysical tuning curves at three probe frequencies. Each curve shows the pulsation threshold at a given masker frequency for one group of listeners. Error bars indicate ± 1 SE. Where error bars are not visible, they are smaller than the symbols. Only equal SL adults were tested at 500 Hz. Equal SL and equal SPL adults were tested at 1,000 Hz. All five groups shown were tested at 4,000 Hz.

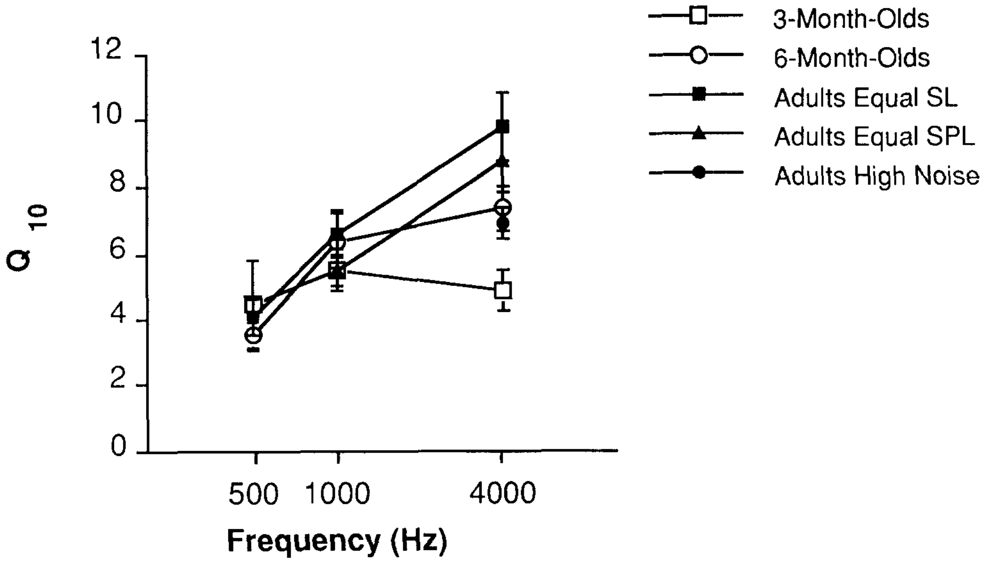

FIG. 5.—Average Q_{10} (± 1 SE) as a function of probe frequency for infants and adults in three listening conditions.

smaller Q_{10}s than 6-month-olds, $t(14) = -2.63$, $p < .05$, adults tested at equal SL, $t(12) = -4.06$, $p < .005$, adults tested at equal SPL, $t(9) = -3.48$, $p < .01$, and adults tested in a high-noise background, $t(9) = -2.49$, $p < .05$. By contrast, 6-month-olds' Q_{10}s did not differ from those of any of the adult groups. Comparisons among adult groups showed no difference between adults tested at equal SL and at equal SPL or between adults tested at equal SPL and adults tested in a high-level background noise. However, adults tested at equal SL in a low-level noise had significantly larger Q_{10}s than adults tested in a high-level background noise, $t(9) = 2.54$, $p < .05$. In other words, increasing the sound pressure level of the probe broadened the adult tuning curve, but only in the presence of the high-level broadband noise.

In summary, 6-month-olds seem essentially adultlike in tuning curve width at all three probe frequencies. Three-month-olds appear to have adultlike tuning at the lower frequencies, but poorer resolution at the highest frequency. This was true whether the adults were tested at the same SL, the same SPL, or the same SPL in a high level of background noise. Thus, differences in the level of the tones presented to the infants and adults cannot account for the observed difference in high-frequency tuning.

Since different mechanisms are believed to govern the shape of the tuning curve above and below its tip (e.g., Pickles, 1986), it is of interest whether the increase in tuning curve width is confined to the high- or low-frequency side. To examine this question, one-way analyses of variance were performed on the pulsation thresholds for higher- and lower-frequency maskers at 4,000 Hz. The effect of age/condition (3-month-olds, 6-month-olds, three adult listening conditions) was significant on the high-frequency side, $F(4,26) = 4.47$, $p < .01$. Pairwise comparisons between the 3-month-olds and the other groups of listeners, using separate variance estimates for each contrast, showed that the 3-month-olds had significantly higher thresholds (poorer resolution) than 6-month-olds, $t(14) = 2.75$, $p < .05$, adults at equal SL, $t(12) = 2.45$, $p < .05$, and adults tested at equal SPL, $t(9) = 2.21$, $p = .05$, but did not differ from adults tested in a high-noise background. On the low-frequency side, the effect of age/condition was not significant. Thus, the difference between 3-month-olds and older listeners in tuning curve width appears to result primarily from immaturity on the high-frequency side of the tuning curve.

Other Performance Measures

The infants tended to have higher pulsation thresholds at the tuning curve tip than did adults tested at equal SL, and this has the effect of displacing the entire infant tuning curve upward in level (Fig. 4). A 3 (age: 3-month-olds, 6-month-olds, adults tested at equal SL) × 3 (frequency: 500, 1,000, 4,000 Hz) analysis of variance of the pulsation thresholds at the tuning curve tip was used to examine this apparent age difference. This analysis revealed a significant effect of age, $F(2,62) = 5.81$, $p = .005$. Post hoc contrasts, using separate variance estimates in each case, showed that the 3- and 6-month-olds did not differ, but that both the 3-month-olds, $t(43) = 3.39$, $p < .005$, and 6-month-olds, $t(48) = 2.56$, $p < .05$, had significantly higher thresholds than adults tested at equal SL. Thus, higher masker levels were apparently required to induce a reliable "continuity effect" for infants, at least by this measure.

However, as is also apparent in Figure 4 and in the analysis of Q_{10} above, the infants' tuning curves are generally similar in shape to those of the adults. This means that once an effective level of pulsation masking has been achieved at the tuning curve tip, the infant's performance varies in a predictable and reasonable way with respect to that level.

As further evidence that the infant's behavior in the experiment is governed by stimulus conditions as one would expect, Figure 6 shows examples of infant and adult psychometric functions for pulsation thresholds. Each of these functions shows, for a typical individual subject, the proportion of "yes" or "signal" responses as a function of masker level (at the tuning curve tip) or masker frequency (above or below the tuning curve tip). For both infants and adults, performance tends to improve as the discontinuity of the probe on signal trials gets easier to detect (i.e., with decreasing masker level or as the masker frequency is moved away from the probe frequency).

The infants generally differed from the adults, however, in three respects (see Fig. 6). First, the infants' response rates on no-signal trials, or false alarm rates, tended to be higher than those of adults. A 3 (age: 3-month-olds, 6-month-olds and adults tested at equal SL) × 3 (frequency: 500, 1,000, 4,000 Hz) × 3 (pulsation threshold condition: at the tip, higher-frequency masker, lower-frequency masker) analysis of variance of the false alarm rates was used to examine the age difference in false alarm rate, and, in particular, to test for the possibility that interactions between age, frequency, and pulsation threshold condition may have influenced the tuning curve widths. While this analysis revealed a significant effect of age, as expected, $F(2,59) = 68.23$, $p < .001$, no other main effect or interaction was significant. The implication is that while elevated false alarm rates may have had a general effect on infant pulsation thresholds, they did not differentially change thresholds across conditions, and, thus, cannot account for the observed difference between 3-month-olds and older listeners in tuning curve width at 4,000 Hz.

The other two general differences in performance between infants and adults were that infant performance tended not to reach 100% correct, even in the easiest stimulus conditions, and that the slopes of the infant psychometric functions tended to be somewhat shallower than those of adults. Several previous investigations have noted both of these effects (e.g., Trehub, Schneider, & Endman, 1980; Olsho et al., 1987a, 1987b). We did not conduct specific analyses of these effects here, because these differences would affect the variability of the thresholds obtained but not the average threshold (McKee, Klein, & Teller, 1985).

To determine whether factors such as the infant's ability to understand the task could have affected tuning curve width, we compared infants and adults in the number of training trials required to reach the 80% correct criterion in the pulsation threshold conditions. A 3 (age: 3-month-olds, 6-month-olds, adults tested at equal SL) × 3 (frequency: 500, 1,000, 4,000 Hz) × 3 (pulsation threshold condition: at the tip, higher-frequency masker, lower-frequency masker) analysis of variance of trials to criterion was performed. It was not surprising that there was a significant effect of age on number of training trials, $F(2,57) = 8.71$, $p = .001$; pairwise comparisons, using separate variance estimates for each contrast, indicated that the 3-month-olds required significantly more trials to reach criterion than either the 6-month-olds, $F(1,57) = 8.23$, $p < .01$, or the adults, $F(1,57) = 7.70$, $p < .01$, and the 6-month-olds required more trials to reach training criterion than the adults, $F(1,57) = 17.97$, $p < .001$. However, no other main effect or interaction was significant. Thus, while infants tended to take longer than adults to learn the task, this tendency did not interact with other variables in such a way as to account for the differences in frequency resolution observed.

Thresholds for the Probe in Low-Level Background Noise

As discussed in the introduction to this article, the threshold of a narrow-band signal masked by a broadband noise, the critical ratio, has traditionally been considered a measure of frequency resolution. The critical ratio is limited as a measure of the development of frequency resolution because it does not allow the separation of sensory and nonsensory effects on performance (Banks & Dannemil-

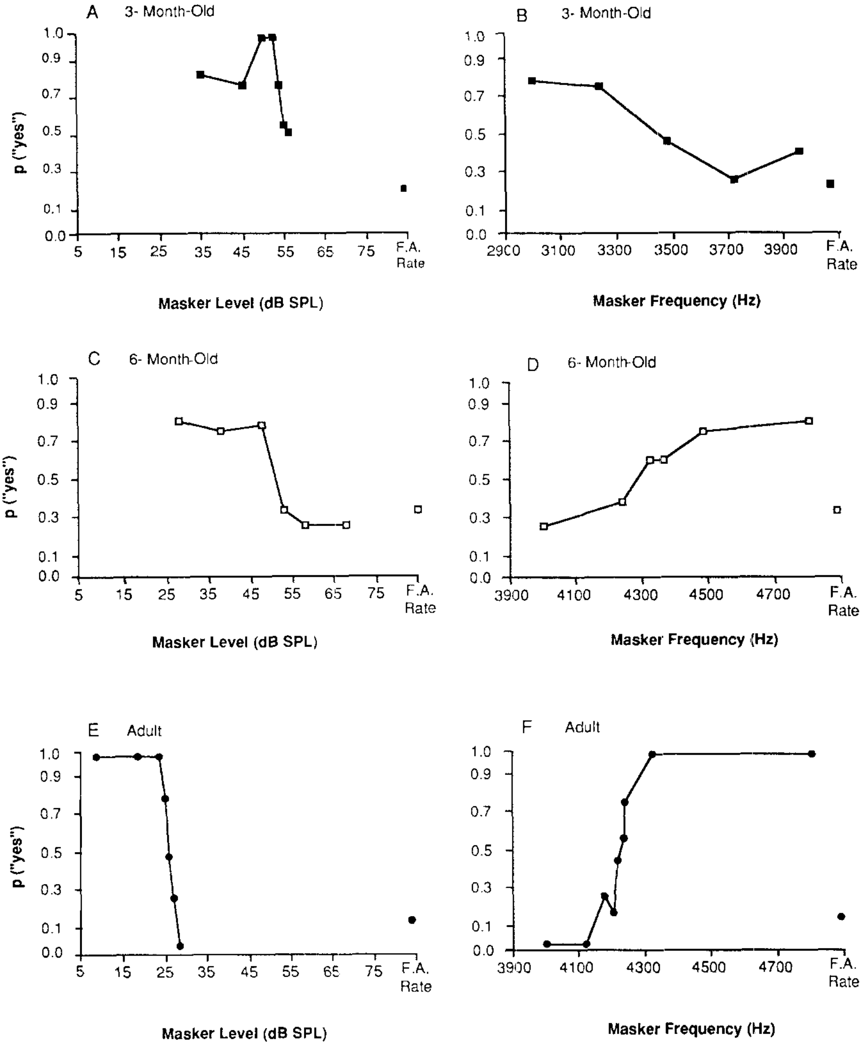

FIG. 6.—Examples of psychometric functions (proportion of "yes" responses as a function of stimulus level or frequency) obtained in pulsation threshold testing for two 3-month-olds, two 6-month-olds, and two adults. The probe frequency is 4,000 Hz in each case. The left-hand panels show data for the condition where the masker frequency equaled the probe frequency and masker level was varied. In the right-hand panel, the 3-month-old was tested with a masker frequency lower than the probe frequency, while both the 6-month-old and adult were tested with a masker frequency higher than the probe frequency. The point at the far right of each panel represents the false alarm rate (i.e., the proportion of no-signal trials on which a "yes" response was made).

ler, 1987; Olsho, 1986). However, it would be reasonable to predict that where deficits in frequency resolution are shown by other measures, one should see an increase in the critical ratio. The detection thresholds in the low-level background noise for infants and adults are plotted in Figure 7. Although we did not measure detection thresholds in quiet in this study, the thresholds reported here are higher than those obtained for infants in quiet in previous investigations (e.g., Olsho, 1985; Olsho et al., 1988), as would be expected from the addition of the background noise. Except at 1,000 Hz, the infant-adult differences in thresholds in noise are larger than those reported by Nozza and Wilson (1984) for 6-month-olds. Whether stimulus duration or other procedural variables account for this difference is not clear.

A 3 (age: 3-month-olds, 6-month-olds, adults tested at equal SL) × 3 (frequency: 500, 1,000, 4,000) analysis of variance indicated that the apparent interaction between

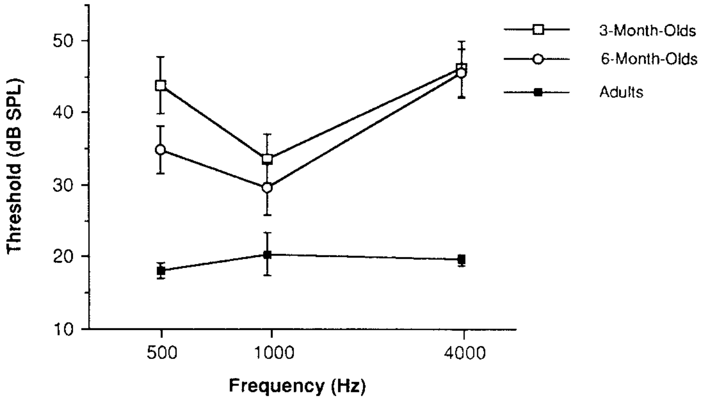

FIG. 7.—Average probe detection thresholds (± 1 SE) in 20 dB pressure spectrum level broadband noise as a function of probe frequency for 3-month-olds, 6-month-olds, and adults.

age and frequency in Figure 7 was not statistically significant. The effect of age was significant, $F(2,62) = 34.05$, $p < .001$, as was the effect of frequency, $F(2,62) = 5.82$, $p = .005$. Thus, it appears that 3- and 6-month-olds have higher thresholds or critical ratios than adults at all frequencies.

It would be misleading to place too much emphasis on the detection thresholds in broadband noise for several reasons. First, given that detection thresholds in quiet were not measured for these subjects, it is difficult to know just how much masking was actually produced at each frequency. Second, there are simply too many uncontrolled factors contributing to a *single* threshold to be able to interpret an age difference in threshold as a reflection of an age difference in the underlying sensory process. It is widely recognized that both "filter width" and "efficiency" (signal-to-noise ratio within the filter at threshold) determine the critical ratio and similar measures (e.g., Patterson & Moore, 1986); these two general effects on the critical ratio cannot be separated solely on the basis of detection thresholds in broadband noise. Age-related changes in both filter width and efficiency have been reported among preschool children (Allen, Wightman, Kistler, & Dolan, 1989; Irwin, Stillman, & Schade, 1986). However, the fact that infants have adultlike tuning curve widths suggests that the infants' higher critical ratio does not result from immaturity of frequency resolution.

Discussion

This study marks the first attempt to measure frequency resolution behaviorally in infants younger than 6 months of age. Using the pulsation threshold technique, we have demonstrated that by 3 months of age, human frequency resolution is adultlike at low frequencies (500 and 1,000 Hz), but continues to develop at high frequencies (4,000 Hz). The immaturity in resolution arises primarily on the high-frequency side of the tuning curve.

These differences are difficult to explain in terms of nonsensory effects for two reasons. First, the estimates of tuning curve width were based on thresholds measured under conditions differing only in stimulus intensity and frequency. Assuming that nonsensory factors remained stable across conditions, differences between thresholds were likely due to sensory differences in response to the stimulus manipulation. The similarity in the psychometric functions, false alarm rates, and training trials required in each condition argue that nonsensory age differences did remain stable. Second, the infants showed adultlike tuning at 500 and 1,000 Hz. It is difficult to imagine how nonsensory factors would differentially affect infant performance only at 4,000 Hz, and then for maskers above the tuning curve tip but not below.

Furthermore, the effects of sound pressure level cannot account for the difference between 3-month-olds and adults in tuning curve width. Three-month-old infants have poorer high-frequency resolution than do adults, regardless of whether the adults listen at the infants' average sensation level or average sound pressure level. We would argue that the current results reflect immaturity of the auditory processes involved in frequency resolution at high frequencies in the 3-month-old infant.

Another hypothesis with respect to the difference between 3-month-olds and older listeners in tuning curve width might be that the background noise interacted with the pulsation masker to produce masking among the older listeners but not among the 3-month-olds. Green (1967), for example, showed that when a simultaneous masker consisted of a broadband noise combined with a pure tone, the amount of masking obtained was greater than the sum of the masking produced by the noise and the tone separately. Jesteadt and colleagues (Jesteadt, 1983; Jesteadt & Wilke, 1982) have shown similar interactions between a forward masker and a broadband noise. We know of no data suggesting that such interactions occur in the pulsation threshold paradigm. It is important to consider that masker interaction effects can often be accounted for in terms of what subjects "listen for" when confronted with different maskers, and the fact that the cues used to detect the probe in the presence of a single masker may be eliminated when two maskers are present (e.g., Neff & Jesteadt, 1983). The ability to detect *discontinuity* appears to be the same whether it is measured with complete gaps, or with "partially filled" gaps, analogous to the pulsation threshold in a background noise situation (Green & Forrest, 1986). This suggests that the presence of the background noise does not interfere with the perception of the cues for continuity of a signal. Thus, we believe that the type of cue disruption that can occur with multiple maskers is unlikely to account for the results here. Of course a mechanism besides cue disruption could be responsible for an interaction between maskers. However, if the mechanisms responsible for the interaction are similar to those operating in forward masking, then Jesteadt's (1983) data suggest that the conditions in the current experiment are not optimal for producing masker interactions. In sum, it seems unlikely that age differences in masker interactions explain the 3-month-olds' broader high-frequency tuning curve.

In mature mammals, the high-frequency slope and the sharp tip of the tuning curve are thought to reflect active sharpening mechanisms arising in the cochlea (e.g., Yates, 1986). Although retrocochlear sharpening mechanisms are unnecessary to account for psychoacoustic frequency selectivity in adults, in order for these characteristics of the tuning curve to be reflected in psychoacoustic measures, the response pattern established at the cochlea must be maintained in the nervous system. Thus, the existence of adultlike SOAE tuning curves prior to 3 months of age in infants whose SOAEs were in the same frequency range as adults' (Bargones & Burns, 1988) is not inconsistent with the present findings. It is likely that the age-related changes in psychophysical tuning curve width reported here reflect immaturities of the nervous system rather than of the cochlea. This argument is further supported by a variety of ABR studies which have shown that latency of wave I, the most peripheral ABR wave, matures earlier than latencies of waves III and V, which reflect activity in auditory brainstem nuclei (e.g., Gafni, Sohmer, Gross, Weizman, & Robinson, 1980; Hecox & Burkhard, 1982), suggesting a peripheral to central gradient of development. More specifically, Folsom and Wynne (1987) found broader ABR wave V tuning curves at 4,000 and 8,000 Hz, but not at 1,000 Hz, for 3-month-old infants compared to adults—a result quite similar to that reported here. Folsom and Wynne's results further parallel the current findings in that differences in the high-frequency slope of the tuning curves were found at 4,000 Hz. The similarity of our findings to those of Folsom and Wynne (1987) leads us to conclude, then, that broad psychophysical frequency resolution at 3 months could reflect immaturity at the level of the auditory brainstem. Whether immaturity at higher levels of the system also contributes to the psychophysical result remains to be determined.

A second important result of this study is that 6-month-old infants have essentially mature psychophysical tuning curve widths, even when these are measured using nonsimultaneous masking. If nonsimultaneous masking reflects the sharpening effects of suppression, as held by many investigators (e.g., Houtgast, 1972; Moore & O'Loughlin, 1986), this finding suggests that suppression is active and adultlike in humans by 6 months of age. In addition, this finding replicates that of Olsho (1985), who previously reported mature tuning curve widths in 6-month-olds, based on simultaneous masked thresholds. These two studies suggest that large critical ratios (i.e., detection thresholds for tones in broad band noise) cannot be interpreted to mean that infants have poor frequency resolution; the elevated masked thresholds are more likely due to other factors reducing the infant's "efficiency" either in extracting signals from noise or in responding consistently to signals.

Javel, Walsh, and McGee (1986) recently suggested an equation, supported by ABR data, that matches the time course of auditory development for humans and cats. If this equation is correct, then the final stages of the development of human frequency resolution, at the level of the cochlear nucleus, should be around 3 postnatal months (Brugge, Kitzes, & Javel, 1981). Thus, the results of the current study appear to be consistent with the general time course of mammalian auditory development and with Javel et al.'s (1986) model. However, it must be noted that while high frequency resolution has often been reported to mature first in other species (reviewed by Sanes & Rubel, 1988), it appears to mature last in humans.

Although frequency resolution was found to be immature in the current study, differences between the infants and the adults were small. Certainly these age-related differences in frequency resolution are not nearly as large as those reported between hearing-impaired and normal-hearing adult listeners (reviewed by Tyler, 1986). Moreover, deficits in frequency resolution of this magnitude probably do not interfere with the infant's ability to perceive speech sounds because most of the energy in speech falls below 5,000 Hz. On the basis of the present results, one might predict that frequency resolution would be poorer at frequencies below 4,000 Hz at younger ages. However, the existence and magnitude of such differences have yet to be evaluated.

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