Level and age effects in infant frequency discrimination

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Frequency difference limens (FDLs) were estimated for 3-, 6-, and 12-month-old infants and for adults using pure tones at 500, 1000, and 4000 Hz. Each listener provided an FDL at 40 dB and at a higher (80 dB, in most cases) sensation level (SL). An observer-based behavioral testing technique was used. The FDLs of 3-month-olds were worse than those of adults at all three frequencies, and increased with increasing frequency. The FDLs of 6- and 12-month-olds were worse than those of adults at 500 and 1000 Hz, but not at 4000 Hz. Decreasing the SL led to an increase in the FDL of about the same magnitude at all ages, and the same age differences were found at both SLs. Thus infant–adult differences in FDL are not a simple consequence of differences in absolute sensitivity. Infant FDLs at one SL were also found to be significantly correlated with the FDL at the other SL. The FDLs at one age were, in general, predictive of the FDL at a later age in a longitudinal sample of infants. Models that might account for these age-related differences are discussed.

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INTRODUCTION

The development and refinement of a conditioning procedure appropriate for use with human infants (Moore *et al.*, 1975) led to the recent publication of three estimates of the frequency difference limen (FDL) in 5- to 9-month-olds. Olsho *et al.* (1982a,b), Olsho (1984), and Sinnott and Aslin (1985) estimated infant FDLs using a conditioned head-turn technique in which infants were trained to make a head turn when the frequency of a pure tone changed. Infants were reinforced for turning by the activation of a mechanical toy. The results of the Olsho *et al.* (1982a,b) and Sinnott and Aslin (1985) studies are in agreement insofar as the FDL at 1000 Hz was found to be about 21 Hz. Olsho (1984) reported infant thresholds to be about 10 Hz at 1000 Hz. Given variation in method and stimuli among the three studies, this difference may not be important, but it would be helpful if the discrepancy could be resolved.

A more interesting finding by Olsho (1984) was that, while infants' FDLs were significantly worse than adults' at 250, 500, 1000, and 2000 Hz, their performance was as good as that of adults at 4000 and 8000 Hz.[1] This finding can be explained in several ways. One obvious hypothesis is that the auditory mechanism underlying frequency discrimination matures first at high frequencies. Olsho (1985) found no evidence that psychophysical tuning curves obtained in simultaneous masking were broader in infants at this age than in adults. However, given that models of frequency selectivity based on peripheral spectral analysis alone have difficulty accounting for the adult frequency discrimination data (e.g., Wier *et al.*, 1977), infant psychophysical tuning curves may not be relevant to infant frequency discrimination.

Another explanation has been suggested, however. At each of the frequencies employed in the study, Olsho (1984) presented the stimulus at 70 dB above average adult absolute threshold at that frequency. Several laboratories have reported elevated detection thresholds for infants at this age (Trehub *et al.*, 1980; Schneider *et al.*, 1980; Berg and Smith, 1983; Sinnott *et al.*, 1983). Moreover, Trehub *et al.* (1980) found that infant thresholds were 20–25 dB higher than those of adults at 400 Hz, but only about 15 dB higher at 10 000 Hz. The suggestion is that infant FDLs were larger at lower frequencies in the Olsho (1984) study because they were actually presented at a lower sensation level (SL) for the infants. It should be noted, however, that, if this explanation is correct, infant frequency discrimination would have to be extremely sensitive to changes in level. Wier *et al.* (1977) report that a change from 80 to 40 dB SL results in approximately a 50% increase in FDL at 1000 Hz. Here, it is being suggested that a 20-dB decrease in SL produces a doubling of the FDL for infants relative to adults tested using a similar procedure.

In the present study, absolute thresholds were estimated for both infants and adults. The FDLs were then estimated at two sensation levels for each subject to examine the contribution of sensation level to the previously reported age differences in FDLs.

The conditioned head-turn technique does not yield reliable thresholds for infants younger than 5–6 months (Moore *et al.*, 1975). Consequently, one limitation of all of the studies described above was that the youngest infant tested was about 5 months of age. We have recently made substantial changes in methodology that permit testing of infants as young as 3 months of age (Olsho *et al.*, in press). The FDLs for infants at 3, 6, and 12 months are reported here.

I. METHOD

A. Subjects

Families of all "normal newborns" in Charlottesville, VA, were contacted by letter soliciting participants for the study. Thirty 3-month-old infants were participants in the longitudinal portion of the study and were tested at 3, 6, and 12 months. Of the original 30 infants, 24 were tested at all three ages; 21 of these had complete data sets. Twenty-three additional infants completed testing at one or two ages. The addition of these subjects brought the minimum number of infants providing an FDL at each frequency and sensation level to 10. There were 23 males and 30 females in the entire group of participating infants, distributed approximately equally over conditions. Twelve other infants were tested but provided no data, either because they became fussy or sleepy during one session and failed to return for additional testing or because they failed to train in one session and did not return for additional testing.

All infants met the following criteria for inclusion, as reported by their parents: (1) products of full-term uncomplicated deliveries and perinatal course; (2) healthy and developing normally; (3) never diagnosed as having hearing loss; (4) free of colds; (5) without occurrence of middle ear infection within 3 weeks prior to testing and had no more than two prior occurrences of ear infections; and (6) without familial history of congenital hearing loss. Infants were tested within 2 weeks of their birthday.

Adult listeners were 12 undergraduate and graduate students (7 female, 5 male) without prior experience as listeners in psychoacoustic experiments. Four adults listened at each frequency. Their ages ranged from 20 to 30 years. None reported any hearing difficulties; the absolute thresholds obtained as part of this study were all well within normal limits.

B. Stimuli and apparatus

The stimuli were pure tones generated using a Wavetek (model 171) voltage-controlled oscillator. Tones were switched by a Coulbourn (S84-04) rise–fall gate and attenuated by a Coulbourn (S85-08) programmable attenuator and a Coulbourn (S85-02) manual attenuator. These devices were controlled by an Apple II Plus microcomputer, which also performed all timing and recorded observer judgments.

The tones were delivered to the right ear using a Toshiba RM-3 or Sony MDR-E242 earphone. These are "walkman"-style earphones, which were used because the infants were extremely tolerant of them. The earphones were calibrated using a Bruel & Kjaer (type 2031) spectrum analyzer and a 6-cc coupler (Bruel & Kjaer type 4152) with a 1/2-in. microphone (type 4144). The response of the earphone was relatively flat (within 4 dB) over the range from 500 to 4000 Hz. At 500 Hz, which was the worst case, the amplitude of the second harmonic was 60 dB below that of the fundamental. This harmonic may have been audible at 500 Hz, particularly to the adults, at the higher SL. However, even if the adults listened exclusively to the second harmonic in this condition, performance would only be expected to improve by a few Hz—a small difference, given the magnitude of infant–adult differences typically observed. During testing, the earphone was held firmly in place in the infant's ear with hypoallergenic micropore tape; the earphone cord was taped to the back of the infant's shirt to keep it out of the baby's reach and to reduce any tension on the cord that might displace the earphone.

TABLE I. Average stimulus sound-pressure level at absolute threshold and at 40 and 80 dB SL for frequency discrimination for 4 age groups at 3 frequencies.

	Frequency								
	500 Hz			1000 Hz			4000 Hz		
Age	Abs	40 dB	80 dB	Abs	40 dB	80 dB	Abs	40 dB	80 dB
3 months	25	65	95	29	69	96	26	66	99
6 months	36	76	93	19	59	98	14	54	94
12 months	34	74	97	24	64	91	30	70	99
Adult	6	46	86	7	47	87	10	50	90

The stimuli were 500-ms tone bursts, with 500 ms between bursts. The rise and fall times of each burst were 10 ms. Stimuli were presented in trains of ten bursts/trial. Stimulus level for frequency discrimination was set at either 40 or 80 dB above the subject's absolute threshold, with the constraint that the level could not exceed the maximum output of the system, approximately 100 dB. Consequently, 10 of 35 three-month-olds, 12 of 34 six-month-olds, and 4 of 30 twelve-month-olds, distributed over frequency nearly equally, were tested at a level that was somewhat lower than the estimated 80 dB SL in that condition. We will refer to that stimulus as the "high SL" condition. The average presentation levels in dB SPL for the four age groups is shown in Table I.

Testing was conducted inside a single-walled, sound attenuating chamber. The booth was arranged as is typical for conditioned head-turn studies with infants. A chair for the parent and infant faced the window to the control booth and a video camera. A table was placed in front of the parent and infant. A chair for an assistant was also at the table, to the infant's left. The "visual reinforcer," a mechanical toy enclosed with lights in a smoke-colored Plexiglas box was positioned to the infant's right, at baby eye level. The mechanical toy could not be seen until the lights inside the box were turned on.

C. Procedure

1. General procedure

Infants were tested using an observer-based procedure developed in our laboratory. The details of the procedure and its validation are discussed by Olsho *et al.* (in press). The procedure combines features of the conditioned head-turn technique (Moore *et al.*, 1975; Moore and Wilson, 1978) and the forced-choice preferential looking procedure developed by Teller (1979).

The infant is placed on the parent's lap in the booth, with the earphone taped in place. An assistant manipulates toys on the table before the infant to maintain the infant's attention at midline. The parent and the assistant wear headsets to prevent them from hearing the sounds presented to the infant. Neither of the adults in the booth knows when a trial is in progress.

The observer watches the infant through the window and on the video monitor. When the infant is quiet and attending to the toys, the observer begins a trial. A flashing LED indicates that a trial is in progress. A "signal," defined according to the experiment, occurs on a given trial with a probability of 0.65. The observer does not know whether a signal is being presented on that trial. However, he or she must decide on each trial whether or not a signal has occurred, based on the infant's behavior. At the conclusion of each trial, the observer receives feedback for that trial. In order to increase the probability that the infant will respond to a signal in such a way that the observer will be able to identify signal trials, the mechanical toy described above is activated when the observer decides that a signal has occurred on a signal trial. Clearly, if the observer can identify signal trials at a rate greater than expected by chance, the infant must be doing something to indicate that he or she heard a signal. Of course, if the observer does not achieve greater than chance performance, then it is not clear whether the baby heard a signal or not. We can only conclude, then, that the infant can hear at least as well as the observer can identify signal trials.

The behaviors that observers use to make judgments vary from infant to infant. Head turns toward the visual reinforcer are quite common, although head turns in other directions also occur, particularly with younger infants. This difference in the tendency to turn and in the direction of turning is the only consistent difference we have noticed between 3-month-olds and older infants. Other behaviors, observed in infants at all ages, include facial expression, especially eye widening, increases and decreases in activity, or breaking eye contact with the toys being manipulated on the table.

The definition of "signal" and "no signal" depends on the experiment. In the absolute detection task, a signal was the presentation of a sound; no signal meant no sound. In the frequency discrimination task, a signal trial was one on which the frequency of a tone burst changed on alternate bursts from the standard to a comparison frequency. On a no-signal trial, the frequency of the tone burst stayed at the standard frequency. However, in either case, the observer's job was to distinguish between signal and no-signal trials, solely on the basis of the infant's behavior.

At the beginning of each session, the observer was required to achieve a hit rate of 80% with a false alarm rate of no greater than 20%. During this training phase, the mechanical toy was activated at the end of each signal trial regardless of the observer's decision on that trial. Data collection, the "testing" phase, proceeded only after the criterion had been met.

During the testing phase, the observer was still required to maintain a false alarm rate below 25%. False alarm rate was calculated on the last four no-signal trials. If false alarm rate rose above 25%, testing was interrupted, and the observer received a warning message. When this occurred, the observer had the option of returning to the training phase until the original criterion was re-established. If the observer had received three warnings since the last time the training criterion was met, testing was discontinued. If the false alarm rate for all testing trials was above 25%, the session was discarded.

Each session lasted about 20 min. Estimation of a pure-tone threshold and two FDLs typically required a total of four sessions on different days.

2. Pure-tone detection thresholds

Each subject in the study listened at one frequency for all measures. The first measure taken was the absolute pure-tone threshold. During the training phase, the level of the tone bursts occurring on signal trials was about 60 dB SPL. Once the observer had met the 80% correct criterion (i.e., at least 80% hits and, at most, 20% false alarms) at that level, sound-pressure level was varied according to an adaptive rule to estimate threshold. The adaptive technique used was the hybrid method described by Hall (1981): PEST rules (Taylor and Creelman, 1967) determine signal level on each trial, but threshold is estimated at the end of the session by the maximum likelihood method (Hall, 1968). The PEST rules are essentially a binary search technique in which step size and direction of change in stimulus level are varied according to performance at the current level as well as some aspects of performance prior to the current level. The maximum likelihood method determines by iteration the ogival function that best fits the data obtained, using the likelihood of the obtained data given each underlying function as the criterion for choosing the best fit. Threshold is then calculated as the 50% "yes" point on the best-fitting function. This has turned out to be a good method for infant listeners. Because all of the data points are used to estimate the psychometric function, it is relatively resistant to lapses of attention. Estimates of threshold made by interpolating between data points would be more variable as a result of variability of the points spanning the 50% point, while other adaptive techniques (e.g., a 1-up, 1-down rule) will overestimate threshold if the infant's attention wanders.

Testing continued until either the infant became fussy or sleepy, the false alarm rate exceeded the cutoff, or a total of 50 signal trials, excluding training trials, had been presented. If fewer than 50 signal trials were completed, a threshold was estimated if at least 4 reversals occurred. Otherwise, another absolute threshold run was attempted in the next session.

3. Frequency difference limens

Once an absolute threshold had been obtained, the infant was tested in frequency discrimination under two conditions, at 40-dB sensation level (SL) and at the high SL (see stimulus constraints above). Testing order was counterbalanced across subjects.

Recall that a signal trial in this experiment is one during which the frequency of the repeating tone burst alternates between standard and comparison frequencies. The difference between these frequencies ΔF was fixed at about 10% of the standard frequency during training. Once the training criterion had been met, the FDL was estimated by the method of constant stimuli. By using the method of constant stimuli, we could ensure that we would have a reasonable number of trials from each infant at the same values of ΔF. Six values of ΔF were presented in random order, approximately 10% (the training stimulus), 5%, 2.5%, 1%, 0.5%, and 0.25% of the standard frequency. Threshold was estimated by taking the 70% "yes" point on the best-fitting psychometric function, by the maximum likelihood technique. Data for which the best-fitting psychometric function was flat or raw data that were nonmonotonic near threshold were discarded. The infant was retested in that condition, if possible.

Testing was continued until the infant became fussy or sleepy, until the false alarm rate exceeded the 25% cutoff, or until ten signal trials at each value of ΔF had been presented. If ten signal trials at each ΔF at a given SL were not obtained in one session, then additional data at that SL were collected in the next session, until a total of ten trials at each ΔF were obtained. In such continuation sessions, an abbreviated training procedure was used in which the observer was required to get three consecutive hits with no more than one false alarm on three no-signal trials. Even with repeated sessions, however, it was often impossible to acquire all 60 signal trials in both frequency discrimination conditions for an infant. Of the 145 FDLs obtained, 72 are based on 51–60 trials, 47 are based on 41–50 trials, and 24 are based on 31–40 trials.

The adult listeners were tested in the same laboratory using the same stimuli. The procedure was similar: An observer in the adjacent booth started a trial when the adult indicated that he or she was ready. The listener was instructed to raise his or her hand if the frequency of the tone burst was changing on that trial. The observer recorded these responses, and the visual reinforcer was activated if a positive response was recorded on a signal trial. Otherwise, the training criteria and staircase rules were identical to those used for the infants. All adult FDLs are based on 60 signal trials.

D. Results

1. Psychometric functions

We examined the psychometric functions (percent yes responses as a function of ΔF) of each subject. Although the infant functions were similar in shape to those of the adults, there appeared to be stimulus-related differences between infants and adults in the slope and asymptote of the psychometric function. Representative examples of individual infant functions are shown in Fig. 1. Variability is evident in the shapes of these functions. Some infants or, more properly, some infant–observer pairs, produce quite adultlike functions. The function of a 12-month-old at 4000 Hz, shown in Fig. 1(c), for example, ranges from 0% to 100% and rises monotonically in between. Other infants produce functions that do not reach 100% yes [Fig. 1(b) and (f)] or that are nonmonotonic or flat over some ranges [Fig. 1(a), (d), and (e)]. About half of the infant functions did not reach 100% yes. For many of these, the slope of the empirical function was such that it appeared that performance might have reached 100% if higher values of ΔF had been presented. For others, it was clear that the function was leveling off within the range of ΔF's presented. Examination of the individual functions did not reveal any systematic differences among

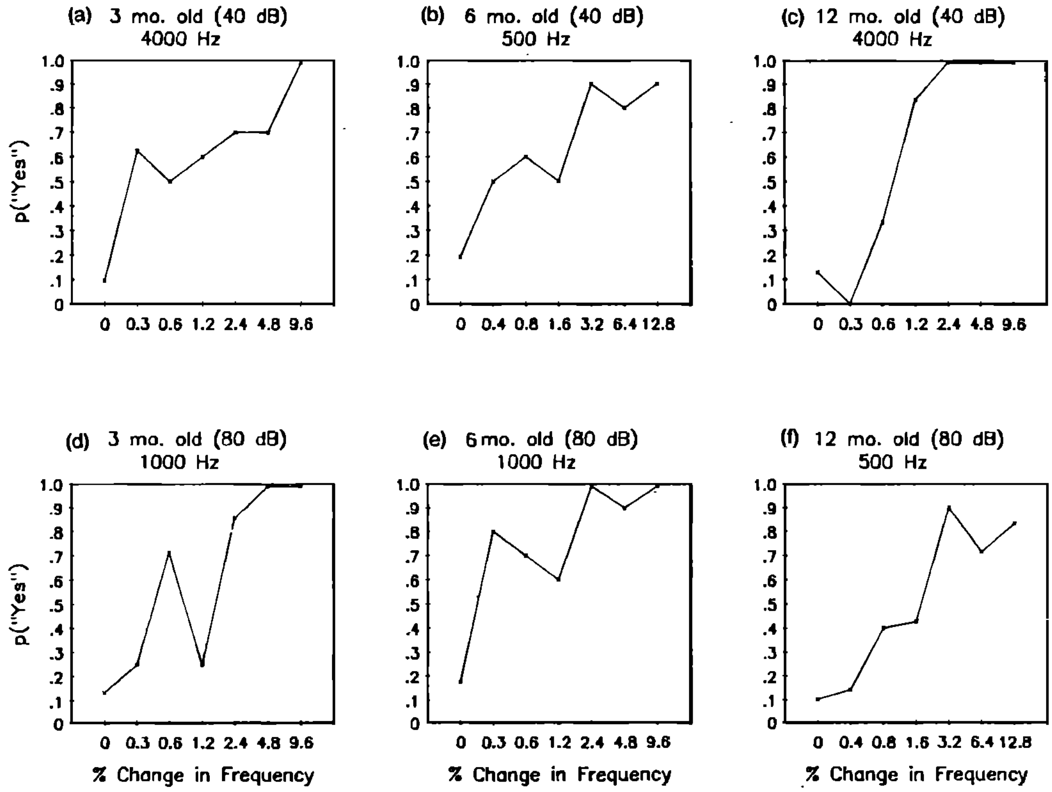

FIG. 1. Examples of individual infant psychometric functions in frequency discrimination at three frequencies.

3-, 6-, and 12-month-olds, although the infant functions seemed to be generally shallower than those of the adults.

For each function, we analyzed three measures: the correlation coefficient *r*, describing the degree of fit of the data points to a cumulative normal curve; the slope of the curve; and the asymptote of the curve, taken as the highest percent yes. There did not appear to be any differences in *r* as a function of age, sensation level, or frequency. The average correlation was above 0.60 in each condition.

There were differences between infants and adults in the slopes of the functions, however. At both 40 dB and the high SL, the infants exhibited shallower slopes than the adults (Table II). There did not appear to be consistent differences between the infant age groups. An age × frequency, analysis of variance of the individual slopes at each sensation level confirmed these impressions: The effect of age was significant in both cases [40 dB: $F(3,66) = 14.65, p < 0.001$; high SL: $F(3,65) = 3.74, p < 0.02$]. *Post hoc* pairwise comparisons showed that each of the three infant groups had significantly shallower slopes than the adults ($p < 0.05$ in each case), but none of the differences between infant groups was significant ($p > 0.20$, in each case).

There also seemed to be a tendency for psychometric functions to be steeper at 1000 Hz than at either 500 or 4000 Hz in each of the four age groups. The effect of frequency was significant in the above analysis at the high SL [$F(3,65) = 7.02, p < 0.002$], but only marginally significant at 40 dB [$F(3,66) = 2.40$, $p < 0.10$]. However, the age×frequency interaction was not significant in either case, both F's < 1.

TABLE II. Average slopes (*z* units/oct) of psychometric functions in frequency discrimination for infants and adults.

	40 dB SL Frequency (Hz)			80 dB SL Frequency (Hz)		
Age	500	1000	4000	500	1000	4000
	Original functions					
3 months	15.08	19.79	17.13	21.31	29.30	15.73
6 months	9.31	18.01	12.34	17.97	21.96	15.46
12 months	5.13	17.94	18.80	15.78	42.19	25.16
Adult	35.86	40.55	37.96	30.96	41.82	27.39
	Rescaled functions[a]					
3 months	20.32	23.68	19.74	26.66	34.79	24.23
6 months	19.78	26.54	25.80	26.55	22.92	25.08
12 months	14.60	21.53	23.92	23.53	44.00	36.49
Adult	35.86	40.55	37.96	30.96	41.82	27.39

[a] Each percent yes on the function was recalculated by the formula, $p'(\text{yes}) \doteq (1-x)\,p(\text{yes}) + x p(\text{yes}|F=0)$, where $x = [p_{max}(\text{yes}) - 1]/[p(\text{yes}|F=0) - 1]$. See text.

It was quite evident from examination of the individual functions, such as those shown in Fig. 1, that the average asymptotic level of performance was below 100%. Since the slope of the psychometric function did not vary reliably with age among the infants, the infant functions were averaged across age groups and compared to the average functions of the adults at each frequency and sensation level. These averaged functions are shown in Fig. 2. Comparison of the infant and adult averages leads to three conclusions. First, infant asymptotes are lower than those of adults. Second, the infant

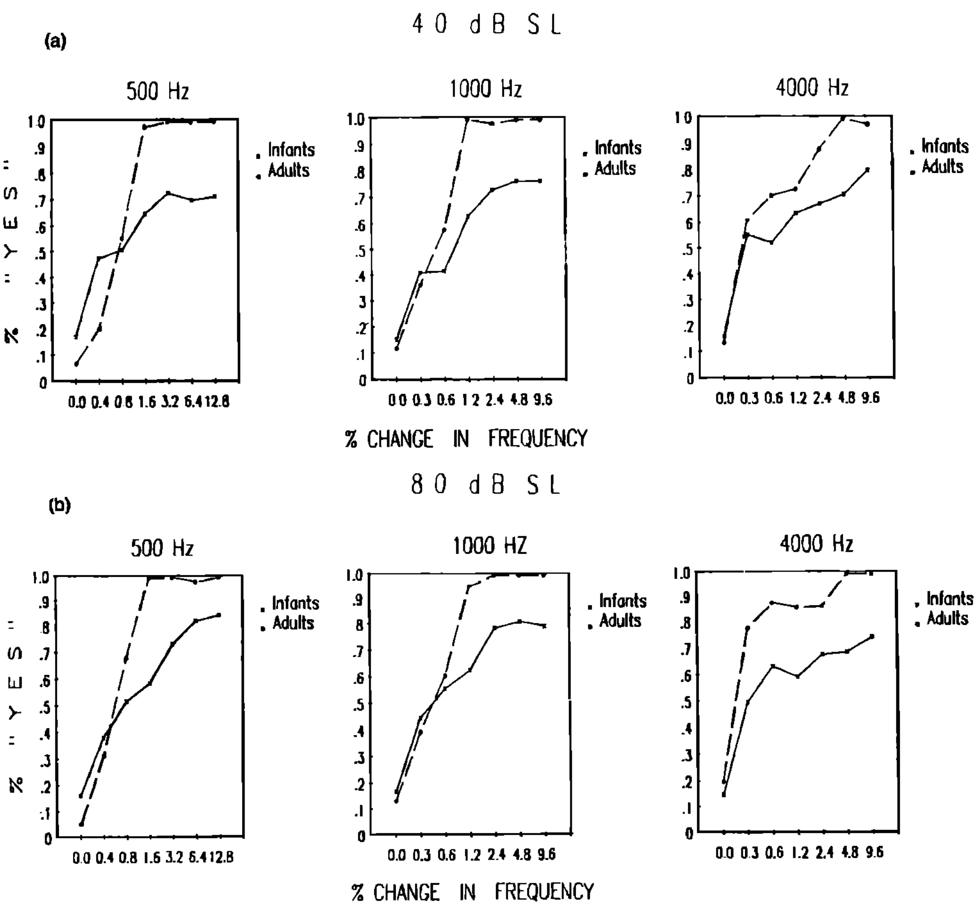

FIG. 2. Average infant and adult psychometric functions for frequency discrimination at 500, 1000, and 4000 Hz, at (a) 40 and (b) 80 dB SL.

asymptote is lower at the lower sensation level of 500 and 1000 Hz. Third, there does not seem to be any systematic effect of frequency on asymptote. An age × frequency analysis of variance on the individual asymptotes at each sensation level confirmed the age difference [40 dB: $F(3,73) = 5.54$, $p < 0.002$; high SL: $F(3,74) = 3.58$, $p < 0.02$], and *post hoc* pairwise comparisons showed that, while the infants had lower asymptotes than the adults ($p < 0.05$, in each case), there were no differences between infant groups ($p > 0.10$, in each case). The effect of frequency was not significant at 40 dB [$F(2,73) = 1.75$, $p > 0.15$] and only marginally significant at the high SL, however [$F(2,74) = 2.52$, $p < 0.10$]. In any case, the age × frequency interaction was not significant, both F's$\leqslant 1$.

To summarize, then, the infant functions have shallower slopes and lower asymptotes than the adult functions, but the infant functions behave in the same way as the adult functions with respect to frequency. This suggests that the age differences in shape may be related to differences in attention: If the infant or observer suffers lapses of attention or, if the observer is simply guessing on some proportion of trials, then % yes at each point on the psychometric function will be reduced. This further suggests that, if the infant functions were rescaled to take into account these hypothetical differences in attention, then, if infant differential sensitivity to frequency is not different from that of the adult, the slope of the infant functions should approach that of the adult functions.

Consequently, we rescaled each infant's entire function so that the highest point on the curve would fall at 100% yes, and each point on the function would be proportionately increased. Obviously, if the infant's function already had an asymptote at 100%, this manipulation would leave the function unchanged. Rescaling did have the effect of increasing the slope of the infant functions (Table II), as would be predicted if the slope difference was the result of lapses of attention. However, even after rescaling, the slopes of the infant psychometric functions were still shallower than those of the adults. Again, this age difference is supported by the results of an age × frequency analysis of variance of the rescaled slopes at each sensation level, showing a significant effect of age [40 dB: $F(3,73) = 5.55$, $p < 0.002$; high SL: $F(3,69) = 3.44$, $p < 0.02$], no effect of frequency [both F's < 1], and no age × frequency interaction [both F's < 1].

It is undoubtedly the case that an infant's tendency to be somewhat inattentive during testing has some effect on the psychometric function obtained in frequency discrimination. However, the results of this analysis imply that differences between infants and adults would still remain, even if infants could be made to be as dedicated to the task as adults are. Our examination of infant psychometric functions also suggests that infant functions are, in many respects, like adult functions. They are well fit by a cumulative normal curve, and their slopes vary with frequency as adults' functions do.

2. The frequency difference limen

The mean FDL, expressed as a proportion of standard frequency in each condition and age group, is plotted in Fig.

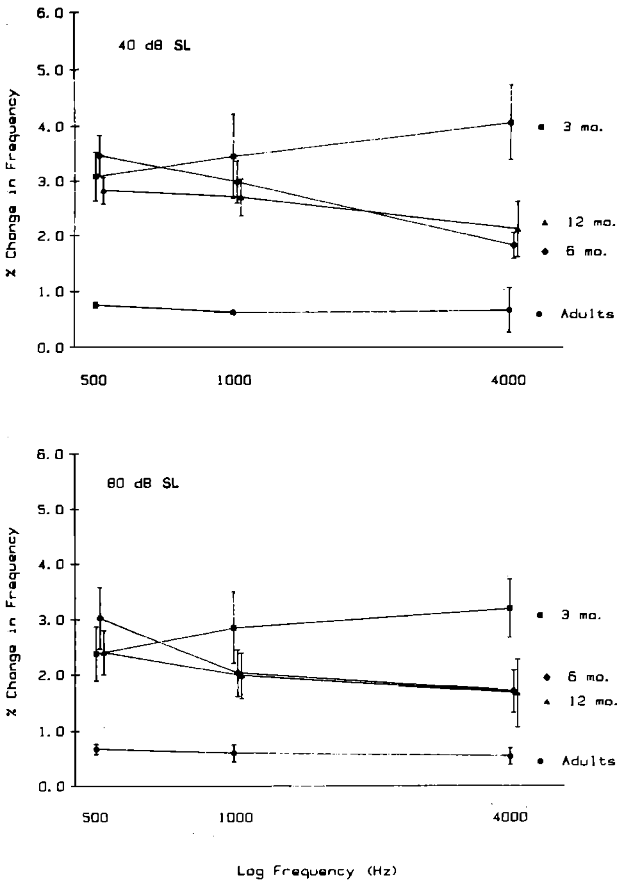

FIG. 3. Average relative frequency difference limen (FDL/frequency) as a function of frequency for infants and adults at 40 dB SL and at 80 dB SL. Error bars represent ± 1 standard error.

3. The infant means include data from all subjects who provided FDLs, both those who were tested at 3, 6, and 12 months and those who were tested at only one or two ages. These means were examined to answer two questions. First, are age differences in FDL frequency dependent? Second, do the age differences observed or their dependence on frequency vary with sensation level?

a. Age-related differences in FDL. Examination of Fig. 3 indicates that, in general, 3-month-olds obtain larger FDLs than 6- or 12-month-olds, who obtain larger FDLs than adults. However, it is also clear that these differences are highly dependent on frequency. At 500 Hz, there is very little difference among the three infant groups. The 6- and 12-month-olds begin to diverge from the younger infants at 1000 Hz and, at 4000 Hz, the two older infant groups are approaching adult levels of performance. In fact, the 3-month-olds' performance deteriorates with increasing frequency, while that of the older infants improves.

These effects were analyzed statistically using analysis of variance. Only the infants who were tested at all three ages were used in this analysis; since the adults were tested at only one age, error terms for the ANOVA were calculated separately for infants and adults and then pooled (Winer, 1971). The age × frequency interaction was significant, $F(6,57) = 7.92$, $p < 0.001$, and *post hoc* comparisons between means (Newman–Keuls) showed that, at 500 and 1000 Hz, all three infant groups had significantly larger

FDLs than the adults ($p<0.05$). There were no significant differences between 3-, 6-, and 12-month-olds at those frequencies. However, at 4000 Hz, the 6- and 12-month-olds did not differ statistically from the adults, while the 3-month-olds had larger FDLs than each of the other age groups ($p<0.05$). While it is apparent in Fig. 3 that the average performance of all the 6- and 12-month-olds (i.e., including those who did not participate at all 3 ages) did not reach the adult level, the difference between the older infants and the adults is still smaller at 4000 Hz than it is at lower frequencies.

The main effect of age was also significant, $F(3,57) = 12.46$, $p<0.001$. There was no significant effect of frequency $F(2,33) = 0.18$, $p>0.25$. Given the nature of the significant age $\times$ frequency interaction, however, these effects have little meaning.

These findings replicate those of the earlier FDL study (Olsho, 1984b) in that 6-month-olds achieve near-adult levels of performance at 4000 Hz, but perform significantly more poorly at lower frequencies. The same pattern holds for 12-month-olds; there appears to be little change in frequency discrimination between 6 and 12 months of age. On the other hand, 3-month-olds look quite different from older infants and adults. Their FDLs at 4000 Hz are actually larger than those at lower frequencies.

b. Effects of level on age differences in frequency discrimination. If the age differences just described and previously reported by Olsho (1984b) result from differences in SL, then we would expect that low-frequency age differences would be reduced or eliminated when SL is held constant. In fact, as just reported, there is still a rather large infant–adult difference at 500 and 1000 Hz at equal SLs. Moreover, this pattern seems to hold at both 40 dB and the high SL (Fig. 3).

A related question is the relative effect of changes in SL for infants and adults. Wier *et al.* (1977) reported increases in FDL ranging from 10% to 46% in this frequency range with a change in SL from 80 to 40 dB. Although Wier *et al.* also found that SL effects were generally greater at lower frequencies, if FDLs at 80 and 40 dB SL are compared in that study, there was little effect for frequencies below 1000 Hz, and the effect was about the same at 1000, 2000, and 4000 Hz. The percentage increase in FDL between high and 40 dB SL in the current data was in the same range, from about 3% to 46%, although it averaged about 22%. That the effect was generally smaller here is probably not surprising, given the fact that these listeners were relatively untrained. At the same time, there was a tendency for the infants to show a greater effect of level than the adults: The infants as a group averaged around 25% increase in FDL, while the adults averaged about 12%. It is difficult to take this difference seriously, however. First, the adult proportional increases in FDL fall entirely within the infant range. Second, the effect does not vary systematically with frequency. Third, if the effect of level depends on some interaction between age and frequency, it is not readily apparent in the data.

The results of the ANOVA supported these conclusions. The effect of level was significant, $F(1,33) = 15.63$, $p<0.001$. At the same time, the age $\times$ level interaction did not approach significance, $F(3,57) = 1.40$, $p>0.20$, and there was no level $\times$ frequency interaction, $F(2,33) = 0.39$, $p>0.25$. Finally, the age $\times$ frequency $\times$ level interaction was not significant, $F(6,57) = 0.52$, $p>0.25$, supporting the claim that the age $\times$ frequency interaction holds at both levels.

c. Relative stability of FDL over infancy. One difficulty in trying to assess the contribution of basic auditory processing to more complex perception has been the absence of meaningful variation in psychoacoustic performance among normal-hearing listeners (McFadden and Wightman, 1983). Correlations between psychoacoustic measures and of psychoacoustic measures with measures of complex processing cannot be demonstrated if individuals differ little on one or more of the measures of interest. One solution to this problem has been to increase variation in performance by including listeners with various degrees of hearing impairment in the sample. Development may provide an alternative solution: Since individuals develop at somewhat different rates, greater variation in performance would be expected during development than at maturity.

However, such an approach can only be successfully applied if measurement error is not so great as to "swamp" the relationships of interest. The infant longitudinal data collected here provided an opportunity to investigate this question. Assuming that individual differences in rate of development are relatively stable during infancy, if a psychoacoustic measure is telling us something meaningful about the individual infant's auditory capacity, then we would expect that infants would tend to maintain their ranks in performance over time. That is not to say that the measures are meaningless in the absence of such stability. Certainly, age group means would still reflect the average state of the auditory system at that age, even though it would not be reasonable to ask questions about interrelationships between measures in that case.

We calculated the correlations of each of the measures and every other measure we obtained (pure-tone threshold, FDL at the high SL, and FDL at 40 dB SL at 3, 6, and 12 months). All of the infants for whom we had the two measures under consideration were included in a correlation. The results of this analysis are considered in two parts: the correlations between measures obtained from the same infant at a single age, and the correlations between measures obtained from the same infant at different ages.

At single ages, the two FDL measures were fairly consistently correlated (Table III). The correlations were significant at 3 months, 6 months, and 12 months. The pure-tone threshold was not as consistently related to either of the FDLs at the same age. At 3 months it was correlated with the FDL at 40 dB, but not at the high SL. At 6 months, both of the correlations were marginally significant, but, at 12 months, neither correlation was significant.

One problem in trying to interpret these correlations as resulting from some stable characteristic of the infant is that each infant listened at the same frequency at each age. Thus the apparent stability may stem from differences between infants associated with different frequencies. In order to determine whether that was the case, a stepwise multiple regression was performed for each age and each pair of vari-

TABLE III. Intercorrelations between infant pure-tone thresholds and FDLs at a given age.

Measure	FDL, 80 dB SL	FDL, 40 dB SL
	3-month-olds	
Pure-tone threshold		
r	0.18	0.40[a]
Increase in R^2	0.0056	0.1186[b]
n	35	35
FDL, 80 dB SL		
r		0.50[a]
Increase in R^2		0.1949[a]
n		30
	6-month-olds	
Pure-tone threshold		
r	0.29[b]	0.27[b]
Increase in R^2	0.0508	0.0648
n	33	35
FDL, 80 dB SL		
r		0.75[c]
Increase in R^2		0.4906[d]
n		28
	12-month-olds	
Pure-tone threshold		
r	0.09	0.31
Increase in R^2	0.0197	0.0868
n	22	23
FDL, 80 dB SL		
r		0.50[a]
Increase in R^2		0.2039[a]
n		21

[a] $p < 0.05$.
[b] $p < 0.10$.
[c] $p < 0.01$.
[d] $p < 0.001$.

ables, in which frequency was always entered into the regression equation before the other predictor variable. We could then test whether the addition of the other predictor variable to the regression equation led to a significant increase in the proportion of variance in the predicted variable accounted for R^2. For example, frequency and FDL at the high SL at 3 months were used to predict the FDL at 40 dB at 3 months. Frequency entered the equation first, then the FDL at the high SL was added to the equation, and the resulting increase in R^2 (the proportion of variance in the FDL at 40 dB accounted for) was tested for significance. This amounts to testing the relationship between the two FDLs with frequency held constant, but allows us to use all of the infants for whom we had both FDLs in the analysis.

The increase in R^2 in each case and the associated significance level are also listed in Table III. Note that, in every case where two FDLs are significantly correlated, the addition of one FDL to the regression equation made a significant contribution to the prediction of the other FDL, over and above that made by frequency alone. The weaker relationship between pure-tone threshold and FDL found in the correlation analysis, however, was not at all evident in the regression analysis: Even in those instances where the pure-tone threshold had been correlated with the FDL, the equation with both frequency and pure-tone threshold entered did not account for a significant proportion of the variance in FDL.

The same analytic strategy was applied to the relationship between the measures taken at one age and those obtained at a later age. The correlations obtained between measures are given in Table IV. The FDLs at high SL at 3

TABLE IV. Intercorrelations between psychoacoustic measures at a given age with those at a later age.

Pure-tone measure	Threshold	FDL, 80 dB SL	FDL, 40 dB SL
3-month prediction of 6-month measures			
Pure-tone threshold			
r	0.07	0.22	0.07
Increase in R^2	0.0077	0.0363	0.0091
n	31	31	31
FDL, 80 dB SL			
r	0.09	0.47[c]	0.79[a]
Increase in R^2	0.0016	0.1728[d]	0.5405[a]
n	31	31	30
FDL, 40 dB SL			
r	0.09	−0.16	0.22
Increase in R^2	0.0026	0.0506	0.0787
n	31	30	28
3-month prediction of 12-month measures			
Pure-tone threshold			
r	0.07	0.30	0.36
increase in R^2	0.0091	0.1225	0.1649
n	29	27	27
FDL, 80 dB SL			
r	−0.30	0.70[a]	0.58[a]
increase in R^2	0.0012	0.1149	0.2077
n	22	22	22
FDL, 40 dB SL			
r	−0.26	0.94[a]	0.71[a]
Increase in R^2	0.0971	0.7400[b]	0.5303[c]
n	23	22	21
6-month prediction of 12-month measures			
Pure-tone threshold			
r	−0.35	0.18	0.40
Increase in R^2	0.0576	0.0147	0.1415
n	27	25	25
FDL, 80 dB SL			
r	0.35	0.91[a]	0.15
Increase in R^2	0.0059	0.4278[a]	0.0008
n	23	22	21
FDL, 40 dB SL			
r	0.67[c]	0.83[c]	0.48[c]
Increase in R^2	0.2810[c]	0.4673[c]	0.3756[d]
n	23	22	22

[a] $p < 0.01$.
[b] $p < 0.001$.
[c] $p < 0.05$.
[d] $p < 0.10$.

months predict both FDLs at 6 months, but the 3-month, 40-dB FDL does not. Both 3-month FDLs are highly correlated with both 12-month FDLs. The 6-month FDLs are correlated with the 12-month FDLs, although the correlation between the 6-month FDL at high SL and the 12-month FDL at 40 dB is not significant. On the other hand, only two of the correlations involving pure-tone thresholds are significant. Moreover, the two significant correlations are between pure-tone thresholds and the FDL at 40 dB, not later pure-tone thresholds. This result is similar to that just described at single ages: FDLs at one age tend to be correlated with FDLs at later ages, but pure-tone thresholds predict neither later pure-tone thresholds nor later FDLs.

The regression analysis indicated that listening at a common frequency at different ages may be responsible for some, but not all, of the relationship between FDLs at different ages. The 3-month, high-SL FDL was significantly correlated with both 6-month FDLs and still contributes significantly to prediction of the 6-month 40-dB FDL when frequency is controlled. However, the 3-month FDL contributes only marginally to the prediction of 6-month, high-SL FDL. Of the 4 significant correlations between 3-month and 12-month FDLs, 2 remain significant, 1 is marginal, and 1 is not significant. However, all of the significant 6-month/12-month relationships hold up. The 6-month, 40-dB FDL is still predictive of the 12-month pure-tone threshold, but the 6-month pure-tone threshold is no longer related to the 12-month, 40-dB FDL.

In summary, there appears to be substantial stability in an infant's performance over the short term, at least with regard to the FDL. Moreover, there is some evidence here that infants maintain their relative positions on FDLs for as long as 9 months.

E. Discussion

We began this study with three goals: (1) to try to get a better estimate of the FDL for 6-month-olds; (2) to examine the effects of level on the infant FDL; and (3) to examine for the first time age-related changes in the FDL between 3 and 12 months of age. The FDL for 6-month-olds at 1000 Hz reported here is about 20 Hz at an average level of 99 dB SPL and about 30 Hz at an average level of 59 dB. These figures are not inconsistent with the estimate of Olsho *et al.* (1982a,b) of 21.6 Hz at a level of 75 dB, also presented through headphones, and with that of Sinnott and Aslin (1985) of 20.3 at 60 dB SPL free-field. We feel confident in concluding that, at moderate to high sound-pressure levels, 6-month-old infants require a 2%–3% change in the frequency of a pure tone at 1000 Hz to be able to detect the frequency change.

This study also replicates the finding of Olsho (1984b) insofar as 6-month-old infants are found to perform relatively better at 4000 Hz than they do at 500 or 1000 Hz, even though infants in this study did not achieve FDLs as low as those in the earlier study. This pattern holds despite the fact that tones were presented at equal SLs for infants and adults at all three frequencies. It holds at both 40 dB and the high SL. Thus we find absolutely no evidence that the low-frequency "deficit" at 6 months is related in any simple way to the development of absolute sensitivity. In fact, changing the SL of the stimulus has an effect on infants very similar to that on adults.

As for changes in frequency discrimination during infancy, there appears to be little change between 6 and 12 months. Not only are the FDLs of infants at these two ages about the same, but the FDL is affected by frequency and level in the same way at both ages. However, there are clear differences between 3-month-olds and older infants. Performance actually declines with increasing frequency at 3 months. While there is little change in frequency discrimination at 500 Hz between 3 and 12 months, there is a pronounced change at 4000 Hz. Again, this seems to be true at both 40 dB and the high SL, but the effects of changes in SL are no different for 3-month-olds than for other ages.

The stability of infant FDLs, over a period as long as 9 months, is extremely encouraging. The mere fact that variation among subjects is not entirely due to transitory effects, such as state of arousal or random measurement error, is important. The source of this stability, on the other hand, is not known. We would like to believe that this measure reflects individual differences in the rate of auditory development. However, it is also possible that the individual differences involved are in nonauditory mechanisms, such as attention, motivation, or cognitive ability, that also influence performance in psychoacoustic tasks.

Given such stability in the FDL during infancy, it is not clear why there is so little apparent stability in the measure of infant absolute sensitivity. It may well be the case that absolute thresholds are more vulnerable to transitory effects such as those mentioned above. Perhaps absolute sensitivity is simply not predictive of later auditory function. Studies of the stability of comparable measures of absolute threshold over short periods of time are needed to help clarify this issue.

We conclude, then, that there are age-related changes in frequency discrimination during infancy and childhood and that the timing and nature of improvement in frequency discrimination with age are dependent on frequency. The question of how to account for these changes remains to be addressed.

Certainly, it is possible that performance in frequency discrimination improves with age as a consequence of maturation in attention, motivation, or some other nonsensory mechanism. Two findings of the current study argue against such interpretations. First, 6- and 12-month-olds obtain FDLs at 4000 Hz that are not statistically different from those of adults tested in a similar procedure. If it were the case that a failure of attention, for example, produces elevated FDLs among infants at 500 and 1000 Hz, how is it that the FDL at 4000 Hz is not similarly affected? Moreover, while increasing stimulus level to the high SL might be expected to draw greater attentiveness from an infant, the low-frequency deficit in frequency discrimination remains in that condition, and the difference between high- and low-frequency discrimination is not reduced.

Second, rescaling the infant functions in an attempt to correct for lapses of attention did not eliminate the age difference in psychometric function slope. While the idea of increasing each data point by the same proportion may be somewhat simplistic, it is hard to imagine a realistic scheme that would serve to steepen the functions further. To achieve such an outcome, the number of positive responses at large values of ΔF would have to be increased more than those at small values of ΔF. It is difficult to believe that infants would actually be less attentive to large frequency changes than to small ones.

Of course, there are several other nonsensory mechanisms that influence performance in frequency discrimination besides attention. Adult psychoacoustic studies suggest that memory for the standard tone may be particularly important (e.g., Jesteadt and Sims, 1975). To the extent that such nonsensory factors are frequency dependent, they cannot be completely eliminated as explanations for the age differences observed here.

At the same time, the finding that frequency discrimination at high frequencies follows a different developmental course than frequency discrimination at low frequencies is consistent with adult studies demonstrating differences in mature processing in the two frequency ranges. For example, Wier *et al.* (1977) found that change in intensity had a greater effect on low-frequency FDLs than on high. Similarly, Dye and Hafter (1980) reported that discrimination of tones in broadband noise, at constant signal-to-noise ratio, improved with increasing signal level at 500 and 1000 Hz, but deteriorated with increasing level at 3000 and 4000 Hz. Models of frequency discrimination based on temporal coding, such as Wakefield and Nelson's (1985) recent extension of Goldstein and Srulovicz' (1977) model, can account for the effects of duration and intensity on frequency discrimination below 4000 Hz, but require a different set of parameters to account for higher frequency data. Finally, Demany (1985) has recently demonstrated that frequency discrimination training at 200, 360, or 2500 Hz all led to improvement in performance at 200 Hz, while training at 6000 Hz produced little improvement in performance at 200 Hz. Not only do our findings with infants parallel those of the adult studies, in that high- and low-frequency discrimination follow different developmental courses, but the cutoff between low and high frequencies in the infant studies falls between 2000 and 4000 Hz, just as it does in the adult studies.

The present results also parallel those of developmental studies of the auditory system. The fact that 3-month-olds have larger FDLs at high frequencies is consistent with a general and early insensitivity to high frequencies associated with a developmental shift in the frequency map of the cochlea and auditory nervous system (e.g., Rubel and Ryals, 1983; Harris and Dallos, 1984; Lippe and Rubel, 1983). Folsom and Wynne (1987) have also observed broadened brain-stem response tuning curves at high frequencies among infants at this age. On the other hand, a developmental gradient in frequency specificity from high to low frequencies in neural tuning curves has also been reported (e.g., Woolf and Ryan, 1985; Romand, 1983). Again, performance in high-frequency discrimination reaches adult levels first among human infants, even though it is initially poorer than low-frequency discrimination.

That the infant data are consistent with the adult psychoacoustic literature, as well as with developmental neurophysiological studies of the auditory system, encourages us in the view that these data reflect characteristics of the infant auditory system, even though they may also be influenced by nonsensory maturation. Any hypotheses about the specific elements or processes that are maturing to produce these changes, however, would be pure speculation at this point. Examination of the effects of signal duration and of different masking conditions in infant frequency discrimination may clarify the issue. In addition, measures of frequency selectivity and temporal resolution during infancy should prove interesting. The value of the current methodology is that a wide variety of questions about human auditory development can now be approached.

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[1] The comparison in question is between infants and adults tested using similar procedures. The adults in the Olsho (1984b) study achieved FDLs of 5–6 Hz at 1000 Hz, 70 dB above average adult thresholds, while Wier *et al.*'s (1977) listeners averaged 1–2 Hz at 1000 Hz, 80 dB SL. The performance of the adults in the Olsho (1984) study, however, is not unreasonable, given the uncertainty inherent in the infant task, and is, in fact, consistent with adult frequency discrimination performance in vigilance tasks (e.g., Moray, 1970).

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