Pure-tone sensitivity of human infants[a)]

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Pure-tone thresholds at frequencies ranging from 250 to 8000 Hz were estimated for 3-, 6-, and 12-month-old infants and for adults, using the Observer-based Psychoacoustic Procedure (OPP). Sounds were presented monaurally using an earphone. Psychometric functions of infants were similar to those of adults, although 3-month-olds had shallower functions at higher frequencies. The thresholds of 6- and 12-month-old infants were 10–15 dB higher than those of the adults, with the difference being greater at lower frequencies. This result is in general agreement with results from other laboratories. The thresholds of 3-month-olds were 15–30 dB higher than those of adults. The greatest difference between 3-month-olds and adults was at 8000 Hz. This threshold difference is smaller than that reported in earlier behavioral studies; higher thresholds at high frequencies have been previously reported for newborn and 3-month-old infants. The relative contributions of sensory and nonsensory variables to these age differences are discussed.

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INTRODUCTION

One of the most fundamental characterizations of hearing is the shape of the audibility curve, the function relating absolute sensitivity to acoustic frequency. It follows that any description of auditory development should address age-related changes in the shape of this curve. Several studies have described this curve for human infants older than 6 months of age. The shape of the audibility curve has not been established for younger infants.

For infants older than 6 months, the absolute value of the reported infant threshold varies considerably across studies. The average thresholds reported are summarized in Table I. All but one of these studies (Hoversten and Moncur, 1969) used some variation of Visual Reinforcement Audiometry (VRA) (Moore *et al.*, 1975; Moore and Wilson, 1978), an operant discrimination paradigm, to obtain thresholds. However, studies differ in the stimulus employed, the mode of stimulus presentation (earphone versus loudspeaker), psychophysical paradigm (two-alternative, forced-choice versus go/no-go), and definition of threshold. Some of these differences are also noted in Table I. While these factors undoubtedly contribute to the variability between studies, there is no obvious relationship between methodological variables and the thresholds obtained.

Despite the between-study variability in absolute value of the threshold, several of these studies suggest that, by 6 months of age, thresholds are somewhat close to those of adults at higher frequencies (Trehub *et al.*, 1980; Schneider *et al.*, 1980; Sinnott *et al.*, 1983; Nozza and Wilson, 1984). To make this trend more evident, in Fig. 1, infant thresholds are plotted in decibels *re:* thresholds of adults in the same study. The results of Hoversten and Moncur (1969), the only study not using a conditioning procedure, clearly stand out from the others. At the same time, the range of thresholds expressed *re:* adults is generally smaller than the range of thresholds expressed in dB SPL. The agreement among some of the studies in the shape of the curve for older infants can also be seen.

There are reasons to believe that the audibility curve of younger infants will differ in shape from that of older infants and adults. First, since the shape of the audibility curve in adults is largely determined by the characteristics of the external and middle ears, and since at least some of these characteristics have been shown to change postnatally in humans (McLellan and Webb, 1957; Saunders *et al.*, 1983), one might expect to see postnatal changes in sensitivity on that basis alone. Second, in other mammals, behavioral and physiological thresholds tend to mature first at low to middle frequencies (reviewed by Rubel, 1978). By one estimate (Javel *et al.*, 1986), the auditory system of a 3-month-old human infant would be similar in maturity to the auditory system of a 6-week-old cat. There are no behavioral data for cats between 1 month of age and adulthood, so it is difficult to estimate when kitten thresholds reach adult levels. How-

[a)] A preliminary report of these data was made at the Fall 1986 Meeting of the Acoustical Society of America in Anaheim, CA [J. Acoust. Soc. Am. Suppl. 1 **80**, S123 (1986)].

TABLE I. Summary of studies of infant absolute sensitivity, 6 to 24 months postnatal age. (VRA = visual reinforcement audiometry, infant reinforced for headturn by presentation of mechanical toy; 2AFC = two-alternative, forced-choice.)

Study	Stimuli	N	Age (mos.)	Procedure	Mean threshold, dB SPL (dB re adults) (standard deviation) Frequency (Hz)							
					250	500	1000	2000	4000	8000	10 000	19 000
Hoversten and Moncur (1969)	30-s tones, sound field	22	8	Behavioral observation two observers, ascending method of limits		45 (33) a			50 (58) a			
Trehub *et al.* (1980)	Continuous octave-band noise, sound field	89[c]	6	VRA 2AFC	38[c] b a	33[c] (24) a	25 (22) a	28 b a	23 (19) a		18 (8) a	
		74[c]	12		27[d] b a	25 (16) a	19 (16) a	16 b a	17 (13) a		10 (0) a	
		76[c]	18		31[d] b a	24 (15) a	18 (15) a	20 b a	14 (10) a		19 (9) a	
Schneider *et al.* (1980)	Continuous octave-band noise, sound field		6	VRA 2AFC							24 (6) a	41 (8) a
			12,18								22 (4) a	38 (5) a
			24								19 a a	31 b a
Moore and Wilson (1978)	2-s, 5% warbled tones Earphone	9	6–7	VRA, go/no-go		38 b	25 b		23 b			
		10	12–13			31 b	27 b		25 b			
	Sound field	9	6–7			18 b	18 b		16 b			
		10	12–13			21 b	16 b		14 b			
Berg and Smith (1983)	250-ms tones Earphone	12	6	VRA, go/no-go		23 (11) (5.8)		20 (10) (4.8)		29 (15) (4.1)		
		6	10			27 (15) (5.6)		17 (7) (4.3)		23 (9) (5.3)		
	Sound field	12	10			20 (7) (3.9)		18 (12) (5.4)		21 (11) (5.0)		
		12	14			19 (6) (4.4)		20 (14) (5.6)		21 (11) (5.8)		
		6	18			19 (6) (6.8)		18 (12) (7.1)		21 (11) (4.5)		
Sinnott, Pisoni, and Aslin (1983)	1-s tones, sound field	11–16/ frequency	7–11	VRA, go/no-go	38 (22) (8.53)	30 (21) (11.8)	31 (23) (10.2)	36 (24) (9.0)	34 (27) (12.3)			
	0.5-s tones, sound field	2–7/ frequency				34 (23) (4.98)	35 (26) (7.51)	37 (23) (10.6)	31 (23) (7.79)	25 (18) (9.97)		

Study	Stimuli	N	Age (mos.)	Procedure	Mean threshold: dB SPL (dB *re*: adults) (standard deviation) Frequency (Hz)							
					250	500	1000	2000	4000	8000	10 000	19 000
Nozza and Wilson (1984)	500-ms tones, earphone	screened[f] 11, 1K 12, 4K	6	VRA, go/no-go			21 (14) (5.72)		16 (7) (4.20)			
		unscreened[f] 17					23 (16) (7.30)		20 (11) (10.00)			
		12 screened[f]	12				18 (11) (3.62)		14 (5) (6.10)			
		17 unscreened[f]					22 (15) (9.40)		15 (6) (6.75)			

[a] No variability estimate available; thresholds calculated from group psychometric functions.
[b] No adults tested.
[c] Each subject contributed (one) trial at each of four levels at each of five frequencies.
[d] Actual frequency 200 Hz.
[e] Actual frequency 400 Hz.
[f] Tympanometric screening, criterion for inclusion when screened = pressure peak greater than − 100 mm H_2O.

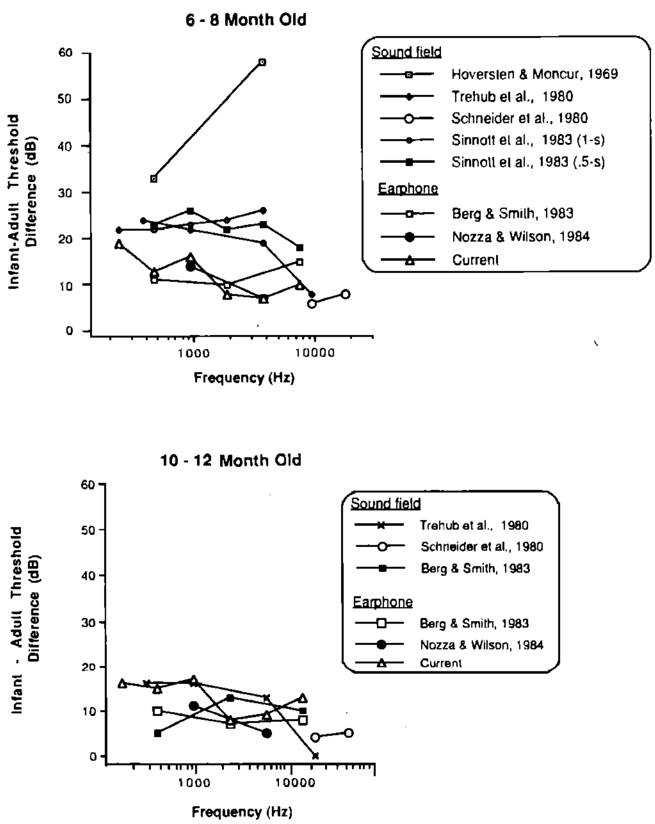

FIG. 1. Average infant–adult threshold difference as a function of frequency for several studies and two infant age groups. Studies are included if the infants tested were older than 6 months of age, and if adult subjects were tested as part of the study. Within a study, only frequencies where both infants and adults were tested are included.

ever, Ehret and Romand (1981) compared detection thresholds of 1-month-old kittens to adult cats and found a difference in sensitivity on the order of 50 dB above 10 000 Hz, but only 40 dB at 1000 Hz and 30 dB at 500 Hz. Thus, over the age range in cats (6–9 weeks) that supposedly corresponds to the period between 3 and 6 months in humans, changes in high-frequency sensitivity are occurring. Third, the results of the few studies of young infants' responsiveness to sound (Hutt *et al.*, 1968; Weir, 1976; Eisele *et al.*, 1975; Hoversten and Moncur, 1969) suggest that, prior to 3 months, infants are relatively insensitive to high-frequency sounds.

Only Hoversten and Moncur (1969) have reported thresholds for 3-month-olds: 55 dB SPL at 500 Hz (43 dB *re*: average threshold of young adults tested in the same study) and 65 dB SPL at 4000 Hz (73 dB *re*: adult threshold). However, for 8-month-olds tested in the same study, thresholds also increased between 500 and 4000 Hz (see Table I and Fig. 1). Because this is the opposite of what is most often reported for 6- to 18-month-olds, Hoversten and Moncur's data do not provide strong evidence for insensitivity to high frequencies at 3 months. Thus neither general sensitivity nor the shape of the audibility curve has been established for infants younger than 6 months of age.

The purpose of the current article is to examine changes in the shape of the audibility curve of human infants between 3 and 12 months of age. Thresholds were estimated over a broader frequency range than in Hoversten and Moncur's (1969) study of 3-month-olds and employed a conditioning procedure. Unlike earlier studies, the same procedure (Olsho *et al.*, 1987b) was used to obtain thresholds for infants at all ages tested.

I. METHOD

A. Subjects

The data described were collected as part of four separate studies: (1) a preliminary study of absolute thresholds and frequency discrimination (Olsho, 1984); (2) a longitudinal study of frequency discrimination (Olsho *et al.*, 1987b); (3) a cross-sectional study of frequency discrimination (Olsho *et al.*, 1987b); and (4) a cross-sectional study of absolute thresholds at certain frequencies undertaken for the purposes of the present article. The numbers of exclusions from each of the first three studies are given in the respective articles. In the fourth group, five other babies were tested who did not provide thresholds, either because the false alarm rate was too high or because the psychometric function was flat. Data from four other infants were lost due to equipment failures. The total number of infants included from each study at each age and frequency is shown in Table II.

Subjects in the preliminary and frequency discrimination studies were selected and recruited as described by Olsho (1984) and Olsho *et al.* (1987b), respectively. In all groups, each infant was tested within 2 weeks of the required age. In addition, all infant subjects met the following criteria for inclusion, as reported by their parents: (1) full-term birth, with no complications of delivery or perinatal course; (2) normal postnatal developmental course; (3) never diagnosed as having hearing loss; (4) free of colds; (5) no occurrence of middle ear infection within 3 weeks prior to testing, and no more than two prior occurrences of ear infections; and (6) no family history of congenital hearing loss.

Six adults were included, aged 18 to 26. Each adult listened at each frequency from 250 to 8000 Hz. None had other experience listening in psychoacoustic experiments. None reported hearing problems, and thresholds were similar to those obtained in our laboratory in other studies using a similar procedure with adults.

TABLE II. Breakdown of subjects by age, frequency, design, and study.

	Frequency (Hz)	Design CS[a]	L[b]	Study '84[c]	'87[d]	Current[e]	Total
3 mos.							
	250	10	0	6	0	4	10
	500	5	10	0	15	0	15
	1000	17	11	6	22	0	28
	2000	17	0	0	0	17	17
	4000	5	10	5	10	0	15
	8000	10	0	0	0	10	10
6 mos.							
	250	10	0	6	0	4	10
	500	5	10	0	15	0	15
	1000	8	9	6	11	0	17
	2000	10	0	0	0	10	10
	4000	6	10	6	16	0	22
	8000	10	0	0	0	10	10
12 mos.							
	250	10	0	6	0	4	10
	500	3	7	0	10	0	10
	1000	3	7	0	10	0	10
	2000	11	0	0	0	11	11
	4000	4	7	0	11	0	11
	8000	11	0	0	0	11	11

[a] CS = cross sectional. Infant participated at one age only.
[b] L = longitudinal. Infant participated at two or more ages.
[c] '84 = Olsho (1984). Infants were also tested in frequency discrimination.
[d] '87 = Olsho *et al.* (1987b). Infants were also tested in frequency discrimination.
[e] "Current" refers to infants tested at a single age for the purposes of this study.

B. Stimuli and apparatus

The stimuli were pure tones generated using a Wavetek (model 171) oscillator. Tone bursts ranging in frequency from 250 to 8000 Hz, 500-ms in duration with 500 ms between bursts, were used. The rise and fall times of each burst were 10 ms. Stimuli were presented in trains of 10 bursts/trial. The tones were switched by a Coulbourn (S84-04) rise–fall gate and attenuated by Coulbourn programmable (S85-08) and manual (S85-02) attenuators. These devices were controlled by an Apple II Plus microcomputer using locally developed software. The computer also controlled stimulus and trial timing and recorded observer judgments.

Two different types of earphones were used to deliver sounds to the right ear. The subjects in the preliminary group listened over TDH-49 headphones in MX-41/AR cushions, which were held in place by two elastic bands with velcro closures (after Moore and Wilson, 1978). The remaining subjects (including the adults) were tested using a Toshiba RM-3 or Sony MDR-E242 "Walkman™"-style earphone held in the infant's ear with micropore tape. The response characteristics of these earphones are described by Olsho *et al.* (1987a, b). Briefly, the response is relatively flat (within 4 dB), from 250 to 4000 Hz, rolling off by about 8 dB at 8000 Hz. For all of the frequencies in this study, the amplitude of the second harmonic was at least 45 dB below that of the fundamental. Both earphones were calibrated using a 6-cm^3 coupler (Bruel & Kjaer 4152) with a 1-in. microphone (type 4144) and a Bruel & Kjaer (2215) sound level meter, using octave-band filters, linear scale. The Walkman™-style phones just fit in the center opening of the MX-41/AR cushion; the MX-41/AR cushion was used to hold the small earphone in place during calibrations. No differences in the infant thresholds obtained with these two types of earphones were noted. However, the number of infants (18 total) listening with the TDH-49 earphone was rather small. Ambient noise levels (octave band) in the test room were measured using a 6-cm^3 coupler (Bruel & Kjaer 4152) with a 1-in. microphone (type 4144) and a Bruel & Kjaer (2215) sound level meter, using octave-band filters, linear scale, with the earphone in place on the coupler at the baby's approximate location in the test booth. The levels were 17 dB SPL at 250 Hz, 11 dB SPL at 500 Hz, 10 dB SPL at 1000 Hz, 13.5 dB SPL at 2000 Hz, 15.5 dB SPL at 4000 Hz, and 15 dB SPL at 8000 Hz.

Testing was conducted inside a single-walled, sound attenuating room (IAC). The infant sat on a parent's lap in the room, facing a window into the control booth and a video camera. There was a table in front of the parent and infant. An assistant sat at the table to the infant's left. The "visual reinforcer," a mechanical toy enclosed with lights in a smoked Plexiglas box, was positioned to the infant's right. The mechanical toy could not be seen until the lights inside the box were turned on under computer control.

C. Procedure

Infants were tested using the Observer-based Psychoacoustic Procedure (OPP). Full details of the procedure are described by Olsho *et al.* (1987a); additional information is given in Olsho *et al.* (1987b).

With the infant seated on the parent's lap, the earphone was placed on the infant's right ear. The parent and an assistant who sat in the test room wore headsets to prevent them from hearing the sounds presented to the infant. The assistant manipulated toys on the table to direct the infant's gaze at midline, but tried not to get the infant so involved with the toys on the table that the infant ignored the auditory stimuli. Neither adult knew when a trial was in progress.

The observer watched the infant through the window and on the video monitor. When the infant was quiet and attending to the toys on the table, the observer began a trial. A flashing LED indicated to the observer that a trial was in progress. A train of tone bursts was presented to the infant on a given trial with a probability of 0.65. The observer did not know whether a stimulus was being presented during the trial. The observer watched the infant during the trial and made a judgment as to whether or not a sound had been presented. The observer received feedback at the conclusion of each trial.

A test run typically lasted 20 min. The session consisted of two phases, training and testing. During training, the stimulus intensity was between 60 and 70 dB, depending on the frequency. If the observer judged that a sound had occurred on a signal trial, the visual reinforcer was activated as soon as the observer made the judgment and continued for 4 s after the end of the stimulus presentation. If the observer missed a signal trial, the reinforcer was activated for 4 s at the conclusion of the stimulus train. If the observer judged that a sound had occurred on a no-signal trial, an error (false alarm) was scored. If the observer judged that no stimulus had occurred on a no-signal trial, this was scored as a correct rejection, but in no case was the reinforcer activated following a no-signal trial. Thus the observer was trained to use the infant's behavior in anticipation of the onset of the visual reinforcer as the basis of the judgment. The infant was reinforced for responding in such a way that the observer could make correct judgments, since the visual reinforcer was activated sooner and for a longer duration when the infant made an observable anticipatory response on a signal trial. Typical behaviors used were head turns; changes in facial expression, especially eye widening; increases or decreases in activity; or breaks in eye contact with the toys being manipulated on the table. Head turns were more frequently observed in 6- and 12-month-olds than in 3-month-olds, but other behaviors were used for some infants in each age group. Once the observer had reached a criterion of four of the last five signal trials correct and four of the last five no-signal trials correct, the training phase ended.

During testing, the visual reinforcer was activated only when the observer judged that a sound had been presented when a signal trial had actually occurred. Stimulus intensity was varied during testing to estimate threshold, following PEST rules (Taylor and Creelman, 1967). The PEST rules essentially generate a binary search, attempting on each reversal to halve the distance between the current level and level of the last reversal. The only exception that we made to these rules was that stimulus intensity stayed at a given level for at least four trials before a decision to change the level was considered. Thus, if the observer was correct on three or four trials at a given level, the level went down on the next trial by an amount specified by the PEST rules. If the observer was correct on fewer than three trials, the level went up on the next trial. This aspect of the procedure makes it more conservative and more resistant to brief lapses of attention on the part of the infant or the observer, since a few missed trials due to inattentiveness would lead to one or two increases in level rather than several increases. The observer was required to maintain a false alarm rate below 0.25 during testing. Testing was continued until either 50 signal trials had been completed, or the observer's false alarm rate exceeded 0.25, or the infant's state precluded further testing. An example of an infant test protocol is shown in Fig. 2.

Thresholds were estimated as the 70.7% "yes" point on the best-fitting psychometric function for each infant, using probit analysis (Finney, 1970) and maximum likelihood criterion (Hall, 1968, 1981). The threshold from a run was used only if (1) at least 30 signal trials had been obtained; (2) the false alarm rate for the run was 0.25 or below; and (3) the slope of the best-fitting psychometric function was greater than zero. For about 25% of the sessions, thresholds were not obtained. Except for the infants noted as exclusions above, thresholds were subsequently obtained at a later visit. The entire procedure (training and testing) was repeated on all visits. Comparison of thresholds obtained in first versus subsequent visits revealed no consistent differences.

Adult thresholds were obtained using the same general procedure except that the adults were instructed to raise their hands when they heard a train of tone bursts. An observer in the control room recorded a "yes" response when-

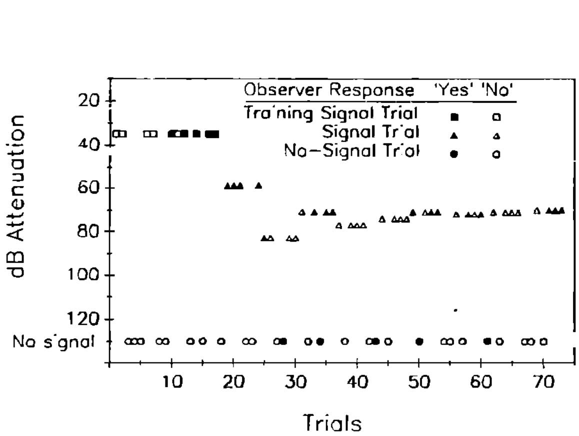

FIG. 2. Example of infant adaptive trial-by-trial protocol. The subject was a 6-month-old tested at 500 Hz. Testing began on trial 18.

ever the adult did so. The reinforcer was activated as feedback, with the same contingencies as described for the infants. Order of testing at the six frequencies was randomized for each subject.

II. RESULTS

A. Psychometric functions

We examined age-group average psychometric functions at each frequency (Fig. 3). The purpose of this analysis was to characterize performance in this procedure; note that thresholds were calculated from individual best-fitting functions, not from the age-group averages. The age-group average functions were obtained by calculating the percent of "yes" responses on all signal trials within a 10-dB range of the given stimulus intensity for all subjects at each frequency and age. The functions exhibit three trends:

(1) Infants' functions, particularly those of 3-month-olds, tend to be somewhat shallower than adults' functions. Where there are differences among infant age groups, namely, at higher frequencies, the 6- and 12-month-olds tend to have similar slopes, which are steeper than those of the 3-month-olds.

(2) Infant functions often do not reach 100% "yes" within the range of intensities employed. In most cases, the slope of the infant age-average psychometric function in the region of 50–60 dB is still relatively steep, implying that the function might reach 100% at still higher intensities. However, it is possible that the infant psychometric functions actually asymptote at a performance level less than 100% "yes."

(3) In most conditions, adult performance is quite similar to infant performance at low stimulus intensities. As the intensity of the stimulus is increased, however, adult performance increases at a faster rate than does infant performance. The meaning of this difference is not clear.

We also examined the average slope of the individual best-fitting psychometric functions for each age and frequency bearing in mind that the slope estimates were based on no more than 50 trials. Psychometric function slopes increased progressively with age: The mean slope and standard error for 3-month-olds was 0.07 ± 0.14 z units/dB, for 6-month-olds, 0.13 ± 0.17 z units/dB, for 12-month-olds, 0.30 ± 0.02 z units/dB, and for adults 0.38 ± 0.01 z units/dB. There did not appear to be any consistent pattern of change with frequency for any of the age groups.

We feel that the psychometric function slopes of infants are, in fact, somewhat shallower than those of older individuals because this pattern emerges in both the age-average group functions and in the individual best-fitting functions. Whether the age difference in slope is frequency specific is not clear at this point. However, in general, the infant psychometric functions are qualitatively similar to those of adults.

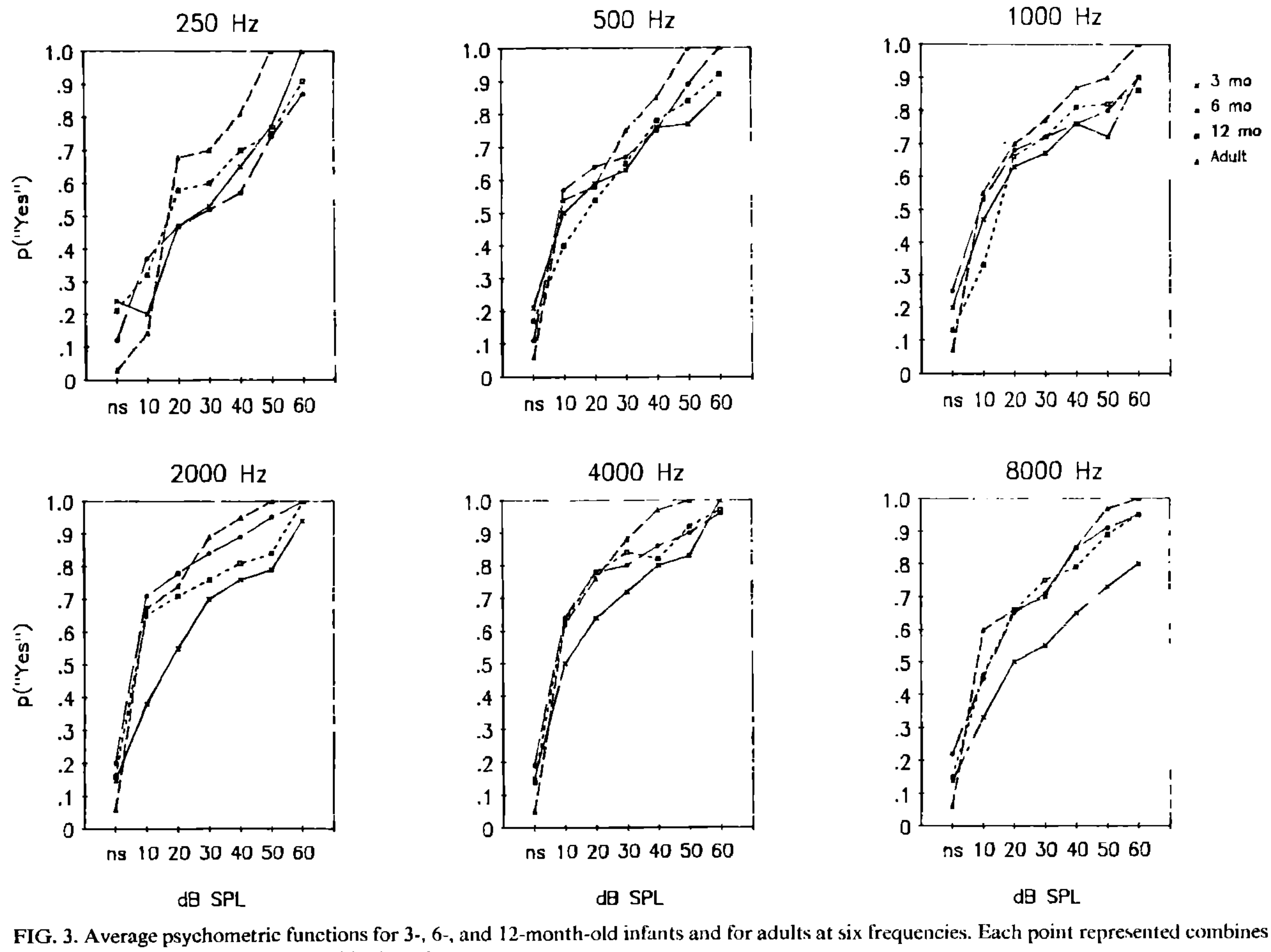

FIG. 3. Average psychometric functions for 3-, 6-, and 12-month-old infants and for adults at six frequencies. Each point represented combines all trials within a 10-dB range around the level indicated.

B. Thresholds

Average thresholds, estimated from the best-fitting psychometric function for each subject, for each age and frequency, are shown in Fig. 4. For frequencies above 250 Hz, there was a decrease in average thresholds between 3 and 6 months, which was more pronounced at higher frequencies. Between 12 months and adulthood, there was a further decrease in threshold, but the change was greater at lower frequencies. The average thresholds of 6- and 12-month-olds were essentially identical at all frequencies.

Comparison of each age group to the adults revealed that the difference between the 6-month-olds and the adults was smaller at higher frequencies, in agreement with other studies of this age group (Trehub *et al.*, 1980; Sinnott *et al.*, 1983). However, this result did not hold for 3-month-olds: The largest difference between 3-month-olds and adults occurred at 8000 Hz.

We tested the significance of these trends using analysis of variance, separately comparing each group of infants to the adults. Because each adult was tested at all frequencies while each infant was tested at only one frequency, the error terms for testing effects involving frequency were calculated separately for the two age groups and then pooled (Winer, 1971, pp. 371–378). For the 3-month-old versus adult comparison, all the effects in the age × frequency analysis were significant: age [$F(1,119) = 459.03, p < 0.0001$], frequency [$F(5,119) = 48.73$, $p < 0.0001$], and age × frequency [$F(5,119) = 2.81, p < 0.05$]. Pairwise comparisons between 3-month-old and adult means indicated significant differences at each frequency, $p < 0.01$ for all comparisons. However, the significant interaction supports the claim that the 3-month-olds' audibility curve does not parallel that of the adults.

For the 6-month-olds, the age [$F(1,109) = 52.62$, $p < 0.0001$] and frequency [$F(5,109) = 29.36$, $p < 0.0001$] effects were significant. However, the age × frequency interaction was not significant [$F(5,109) = 1.07, p > 0.25$]. As Fig. 4 shows, this failure to find a significant interaction between age and frequency in this comparison may well have been due to the great variability between infants in some conditions. In fact, pairwise comparisons did show that the 6-month-olds differed from the adults at 250, 1000, and 2000 Hz ($p < 0.02$ in each case), but not at 500, 4000, or 8000 Hz ($p > 0.2$ in each case).

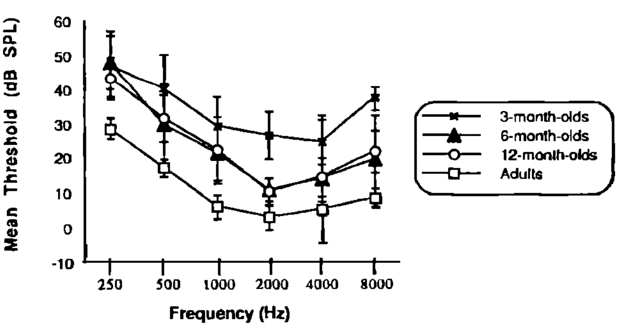

FIG. 4. Mean thresholds ($\pm$ 1 s.d.) as a function of frequency for 3-, 6-, and 12-month-old infants and for adults.

The effects of this variability are apparent when the 12-month-old versus adult comparisons are considered. Not only were the age [$F(1,88) = 207.04, p < 0.0001$] and frequency [$F(5,88) = 99.96$, $p < 0.0001$] effects significant, but the interaction was significant as well [$F(5,88) = 2.65$, $p < 0.05$]. Given that the average thresholds have not changed between 6 and 12 months, this difference must result from the decrease in variability between 6 and 12 months. Pairwise comparisons between the 12-month-olds and adults at each frequency revealed that all differences were significant ($p < 0.05$ in all cases). However, as the significant interaction implies, the age difference was smaller at higher frequencies.

To summarize, the average thresholds of 3-month-olds are higher than those of adults, by 15–20 dB between 250 and 4000 Hz, and by about 30 dB at 8000 Hz. By 6 months, sensitivity at high frequencies improves; at 250 Hz, thresholds are still elevated by about 15 dB, but, at 8000 Hz, the difference between infants and adults is less than 10 dB. Thus the period between 3 and 6 months is marked by a 20-dB improvement in sensitivity at 8000 Hz. Between 3 and 6 months, the amount of threshold improvement increases regularly with increasing frequency across the frequency range. Essentially no change occurs between 3 and 12 months at 250 Hz. The only notable change between 6 and 12 months is a decrease in variability. The low-frequency age difference is resolved between 12 months and adulthood. Studies of absolute thresholds among older children suggest that low-frequency thresholds may not reach adult levels until school age or later (e.g., Schneider *et al.*, 1986; Elliott and Katz, 1980).

III. DISCUSSION

Two major conclusions can be drawn from these results. First, pure-tone thresholds improve between 3 months and adulthood. Second, the timing of this improvement is frequency dependent: Between 3 and 6 months, the improvement is greater at higher frequencies; improvement at low frequencies does not occur until some time after 12 months.

In general, the results for 6- and 12-month-olds are in good agreement with those of previous studies. This is evident in Fig. 1, where the results of this study are plotted in decibels *re:* adult thresholds, along with the results of the earlier studies. The infant–adult differences observed here are of the same magnitude as those previously reported in conditioning studies using earphones and show a similar tendency to decrease at higher frequencies.

A decrease in variability was also noted here between 6 and 12 months of age, especially at 4000 and 8000 Hz. Nozza and Wilson (1984) also reported a decrease in variability at 4000 Hz between 6 and 12 months, but only for infants who were not screened by tympanometry on the test date (see Table I). Thus at least some of the variability in performance we see, particularly at high frequencies at 6 months, may stem from variation in middle ear function.

This study represents the first report of absolute thresholds for 3-month-olds over a broad frequency range. The current results differ from those of Hoversten and Moncur

(1969) in two respects. First, the thresholds reported here are much lower. Three-month-olds achieved thresholds of 15–30 dB relative to those of adults here; Hoversten and Moncur (1969) report infant–adult differences of 40–70 dB. The use of visual reinforcement in OPP undoubtedly accounts for some of this difference. Similar threshold improvements are seen among older infants when reinforcement procedures are compared to nonreinforced behavioral observations (Moore *et al.*, 1975). Second, the difference between 3-month-olds and adults is not particularly pronounced at 4000 Hz: Three-month-olds' thresholds at 500 Hz average about 23 dB higher than those of adults, while at 4000 Hz they average about 19 dB higher. Hoversten and Moncur (1969) report a 43-dB infant–adult difference at 500 Hz and a 73-dB difference at 4000 Hz. The reason for the discrepancy between the studies is not clear, but it should be noted that Hoversten and Moncur also reported a pronounced threshold elevation at 4000 Hz for 8-month-olds and that no other laboratory has reported such a result for older infants.

The greatest difference between 3-month-olds and adults in the current study (almost 30 dB) occurred at 8000 Hz. It could be argued on that basis that human infants are similar to other mammals in demonstrating an early insensitivity to high-frequency sound. However, a simple "low frequencies first" rule does not describe the pattern reported here very well. Despite the early insensitivity at 8000 Hz, by 6 months behavioral thresholds at higher frequencies approach those of adults. Thus it is difficult to describe any general developmental sequence for mammalian auditory behavior. Such a description awaits a better understanding of the sources of infant–adult differences in behavioral thresholds, as well as a more detailed account of the development of auditory behavior in other mammals.

To what extent can the age differences described be attributed to sensory immaturity? Immaturity of the response system and/or of the connections between the sensory and response systems may influence the thresholds we obtain (see discussion by Olsho, 1986). Moreover, adult pure-tone thresholds are influenced by learning and by other variables not inherent in the auditory system. These variables appear to have a greater effect at low frequencies (Watson *et al.*, 1972; Zwislocki *et al.*, 1958). One might also argue that the demands of the detection task in the OPP and VRA experiments are actually greater for the infants than for the adults, since the infant's attention is divided between the assistant's tabletop toys and the auditory stimulus. It is not clear whether the effect of divided attention would be frequency dependent. Thus there are variables such as learning and attention that would be expected to affect adult performance. In the case of learning, at least, the effect may be frequency specific.

It would not be difficult to believe that these variables would have an exaggerated effect on the performance of an individual with limited processing resources, and could contribute to the differences between infants and adults in detection thresholds. Along the same lines, Olsho *et al.* (1988) found that adults show a greater effect of practice in discrimination of low frequencies, and that this effect could account for part of the difference between infants and adults in frequency discrimination.

We would argue on several grounds that there is little difference between 6-month-olds and adults in absolute sensitivity. First, the size of the average difference in thresholds is not large, and some 6- and 12-month-olds have thresholds that fall within the adult range at each frequency. Second, the psychometric functions of infants at these ages are quite similar to those of adults tested under similar conditions, suggesting that the function reflects a similar underlying process at each age. Third, 6- to 12-month-old infants differ most from adults in the frequency range where practice appears to have the greatest effect on adult thresholds (Watson *et al.*, 1972; Zwislocki *et al.*, 1958). Thus age differences at low frequencies are likely to reflect poorer infant performance under apparently more difficult listening conditions.

Such arguments, however, do not account for the differences between 3-month-olds and older listeners. First, the age difference is considerably larger in this case, and we rarely see 3-month-olds with thresholds in the adult range. Second, although individual psychometric function slopes are quite variable, the age-group average psychometric function of 3-month-olds also appears to grow shallower, relative to older listeners, at higher frequencies. This suggests, at least to us, an insensitive system. While nonauditory factors, such as lapses of attention, might also produce a flatter psychometric function, these factors would also be expected to produce a function with a lowered upper asymptote. It is difficult to draw any strong conclusions about an upper asymptote from these data, since it is not clear that asymptotic performance was reached at any frequency except 4000 Hz. However, there is no evidence of a correlation between function slope and upper asymptote among the 3-month-olds, as would be predicted if lapses of attention were responsible for the observed differences. Thus, although incomplete, the psychometric function data are consistent with a sensitivity difference between 3-month-olds and older listeners. Third, even if practice or learning account for the low-frequency threshold difference, such factors cannot explain why the difference between 3-month-olds and adults is greatest at 8000 Hz.

If the differences between 3-month-olds and adults reflect immaturity of the auditory system at 3 months, it is still not clear where the immaturity lies. An obvious potential contributor to the threshold differences between infants and adults is the resonance of the external ear. Unfortunately, the results of the only study to examine infant concha-ear canal resonance directly (Kruger and Ruben, 1987) are at variance with predictions based on ear canal length and compliance (McLellan and Webb, 1957; Saunders *et al.*, 1983). At this point, then, it is difficult to assess possible external ear effects. In addition, threshold differences at 250 or 500 Hz obviously require another explanation. Middle ear effects (Relkin, 1986), including undetected middle ear effusions, must be considered along with immaturity of the cochlea and auditory nervous system (Rubel *et al.*, 1984), in addition to the nonauditory factors discussed above.

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