

Auditory Frequency Discrimination in Infancy

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The ability of 5-8-month-old infants and of young adults to detect changes in the frequency of pure tones was investigated. A head turn for visual reinforcement technique was used to obtain difference thresholds for 14 infants and 5 adults at 1000, 2000, and 3000 Hz. With signals presented at 70 dB above adult detection thresholds, infants reliably detected frequency changes on the order of 2%, whereas adults could detect changes of about 1%. These data not only confirm the findings of previous studies that infants can distinguish different frequencies but indicate that infants can make relatively fine discriminations.

The human auditory system's ability to resolve differences in sound frequency plays an important role in the perception of pitch, loudness, speech, and music (Tobias, 1970). Moreover, infants as young as 1 month of age are able to detect changes in frequency. For example, Wormith, Pankhurst, and Moffitt (1975) reinforced nonnutritive sucking of 1-month-olds with the presentation of a pure tone at either 200 or 500 Hz frequency. Following the habituation of this response, it was found that sucking rate would increase if the frequency of the tone shifted from 200 to 500 Hz or from 500 to 200 Hz, indicating discrimination between 200 and 500 Hz tones. Similarly, Berg (1972) showed that 4-month-olds' cardiac

response to a tone recovered when the frequency of the tone shifted from 1100 to 1900 Hz. Although some studies fail to find evidence for frequency discrimination (e.g., Keen, 1964, with newborns; Leventhal & Lipsitt, 1964, with newborns; Trehub, 1973, with 4-17-week-olds), Kessen, Levine, and Wendrich (1979) reported that 3- and 6-month-old infants could not only discriminate among three sung notes, but would actually vocalize at the pitch presented.

However, the limits of the infant's ability to detect frequency changes have not been tested. On the basis of studies of vowel discrimination with infants, one might predict that infants can actually make discriminations finer than the 300 Hz reported by Wormith et al. (1975). Swoboda, Morse, and Leavitt (1976), for example, found that infants 2 months of age could distinguish between vowel sounds in which the maximum frequency difference between corresponding formants was about 75 Hz at 2300 Hz, a difference of about 3%. However, since adult listeners can detect differences on the order of .2% at the same frequency, the infant's frequency difference threshold, or difference limen (DL), may be considerably lower than 3%.

The purpose of the current experiment was to determine frequency DLs for human infants. The methods previously used to test frequency discrimination in infancy are not suited to threshold determinations. Habituation techniques, such as those employed by

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Wormith et al. (1975) and Berg (1972), would require repeated testing using tone pairs with progressively smaller frequency differences. It is unlikely that an infant would continue to respond to the original tone over several sessions. Therefore, in this study we employed a head turn for visual reinforcement technique, which was originally developed by Wilson, Moore, and Thompson (Note 1) to obtain auditory thresholds and adapted by Eilers, Wilson, and Moore (1977) to study speech-sound discrimination. With modifications developed by Aslin and Pisoni (1980), this technique can be used to determine a DL within a single, 30-minute session. The technique has the additional advantage that adults can be tested within the same paradigm, helping to eliminate confounding procedural effects and allowing direct comparisons between age groups.

Method

Subjects

Twenty-seven full-term infants were recruited from the birth records of a Chicago hospital serving a middle-class area of the city and nearby suburbs. The infants' chronological ages ranged from 4 months 10 days to 8 months 1 day. Although it was anticipated that most 4-month-olds would not complete the procedure, 4 such infants were included in hopes of obtaining data on some younger subjects. Of the 27 infants recruited, usable data were collected on 14 subjects (7 males, 7 females). The remaining 6 males and 7 females were not included, either because they became fussy or sleepy during testing and did not return for subsequent sessions (10 infants) or because they failed to reach criterion performance within 15 minutes during training (3 infants). The mean age of the subjects completing the procedure was 6 months 10 days; of those not completing the procedure, mean age was 6 months 11 days.

Parents were questioned about the infant's birth weight, current weight, and the occurrence of colds, ear infections, or developmental abnormalities. No infant's birth weight percentile deviated more than 25 points from the current weight percentile. Testing sessions were postponed if the parent reported that the child had a cold; no ear infections or developmental abnormalities were reported. The infant subjects were paid at the rate of \$5 per visit.

Two male and three female volunteer graduate and undergraduate students served in the comparison group. One of these subjects had participated in other psychoacoustic experiments.

General Procedure, Apparatus, and Stimuli

Tone bursts were presented to the infant's right ear over an earphone held in place by elastic straps. None of the subjects rejected the earphone. Infants were

trained to make a head turn to the right of midline when they detected a change in frequency of the repeating signal from the background to the comparison level. A correct head turn was reinforced by activation of a mechanical toy bear or dog. The toy animal was enclosed in a dark Plexiglas box so that it could not be seen until a light inside the box was illuminated. The box was located to the infant's right at his or her eye level.

Throughout the procedure the infant was seated on his or her parent's lap in the test room. An assistant, seated to the infant's left, attracted his or her gaze by manipulating toys on a table directly in front of the infant. With the earphone properly in place, neither the parent nor the assistant could hear the signal.

Two experimenters were stationed in an adjoining control room and observed the subject through a one-way window. The control room also housed signal generation, logic, and timing devices. Neither experimenter could hear the acoustic signal. Experimenter 1 set the standard frequency and signal level at the beginning of each session, set the comparison frequency prior to each frequency change, triggered a trial when the infant was in a ready state, monitored the subject's progress throughout the session, and reset the logic device for each phase of the procedure described below. Both experimenters held push buttons for recording head turns. Experimenter 1 "voted" on head turns during frequency changes only. Experimenter 2, on the opposite side of a partition and not in view of Experimenter 1, recorded head turns observed at any time during the session, and was unaware of the standard and comparison frequencies, the phase of the procedure being completed, and the occurrence of frequency changes. The experimenter had to agree that a head turn had occurred during a frequency change in order for the response to be counted. The experimenters were in agreement, on the average, on 96.4% of frequency changes during training and on 96.1% of frequency changes during testing.

Any head turn recorded by Experimenter 2 between frequency change periods was counted as a false alarm. In the 20-minute period typically required to obtain a single DL, during which about 25 frequency changes occurred, the number of infant false alarms ranged from 0 to 22, with a median of 5.3. The range for adult listeners was 0 to 10, median 1.0; adult testing sessions rarely took longer than 10 minutes to complete. Adult false alarms tended to become more frequent as the frequency difference decreased. This was not the case for the infants. Two of the four individuals who served as Experimenter 2 observed, anecdotally, that infant false alarm head turns tended to be accompanied by general motor activity, whereas "hits" did not. We believe, therefore, that the training procedure in conjunction with the manipulation of toys at the infant's midline is effective in controlling false alarm rate during testing.

The logic device contained three timers. One timer controlled the duration and duty cycle of the signal. The trial timer, triggered by push button, controlled the duration of frequency change periods. The reinforcement timer operated the visual reinforcer if both experimenters had recorded a head turn during the frequency change period just completed. Each frequency change period lasted 4 sec. If a head turn was scored, signal frequency stayed at the comparison level and the toy animal was activated for the following 2 sec. The logic device also included an override switch, so the visual

reinforcer would be activated following each frequency change, without other contingencies. In addition, the device could be set so that frequency changes would occur on a randomly chosen 50% of the trials initiated by Experimenter 1. The judgments of the experimenters and the type of trial presented (change or no change) were automatically recorded and printed by the device on a trial-by-trial basis.

Whenever possible, DLs were determined for each subject at standard frequencies of 1000, 2000, and 3000 Hz. The sinusoids were generated by a Wavetek 136 oscillator. The comparison frequency and the amplitude of the comparison signal were controlled by adjusting the voltage to the Wavetek's VCG and VCA inputs, respectively, using two potentiometers. Signal frequency was calibrated using a Hewlett Packard 5381A frequency counter. Signal level was set at 70 dB above the average thresholds of three adult observers tested in the same laboratory.¹ The 1000 Hz signal was presented at 77 dB SPL, the 2000 Hz signal at 78 dB SPL, and the 3000 Hz signal at 77 dB SPL. Signal level was controlled using a Hewlett Packard 350D attenuator and calibrated using a B & K 2203 sound-level meter with octave band filters coupled to a 6 cm³ artificial ear. The ambient noise level in the test room was approximately 29 dB on the sound-level meter's A scale, with the microphone placed in the approximate location of the infant's head.

A Coulbourn S84-04 electronic switch was used to shape the tone bursts. Each burst was 500 msec in duration with a 20-msec rise-fall time. A 500-msec interval occurred between bursts.

Specific Procedures

Training. Two phases of training were completed. During Phase 1, only change trials occurred, the frequency change (Δf) was always 96 Hz, and the visual reinforcer was activated following each frequency change. Initially the level of the comparison signal was 2 dB higher than that of the standard. Because the activation of the reinforcer was a salient visual event, the infant turned away from the assistant to look at it. Eventually, the infant anticipated the activation of the reinforcer when the comparison signal was presented. Following three consecutive anticipatory head turns, the sound-pressure level of the comparison was reduced to equal that of the standard. Three additional consecutive anticipations of frequency changes were required to complete Phase 1.

During Phase 2, both change and no-change trials occurred, randomly interspersed with the restriction that no more than three consecutive trials of one type could occur. Neither experimenter knew whether a change would occur on a given trial. When a frequency change did occur, Δf was 96 Hz. The visual reinforcer was activated only if the infant turned his or her head on a frequency change. If either experimenter judged that a head turn had occurred on a no-change trial, an error was scored. The subject remained in Phase 2 until the performance criterion—four of the last five change trials correct and four of the last five no-change trials correct—was met.

Testing. An adaptive psychophysical procedure (Aslin & Pisoni, 1980; Levitt, 1971) was used to determine DLs. Only change trials were included. At each standard

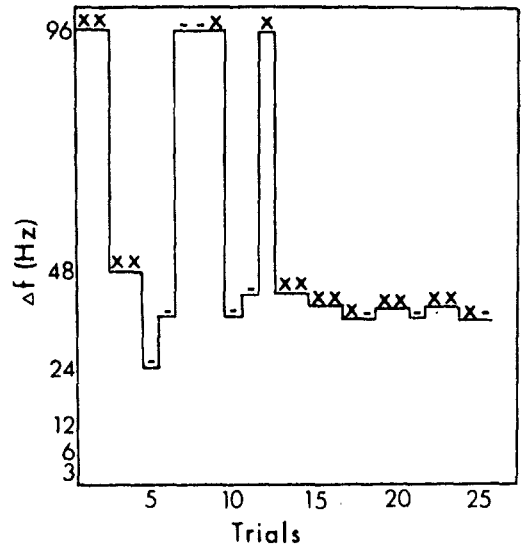


Figure 1. An example of an infant response protocol. (x = head turn; - = no response; Δf = frequency change. The standard frequency was 2000 Hz. Threshold was calculated at 37.5 Hz.)

frequency, testing began with $\Delta f = 96$ Hz. Two consecutive correct responses led to a one-step decrease in Δf ; one incorrect response led to a one-step increase in Δf . If the subjects failed to respond on two consecutive trials, Δf was set at 96 Hz on the following trial. If the subject responded on this "probe" trial, testing was continued with Δf at the level of the last trial before the probe trial. Otherwise Δf remained at 96 Hz until the infant responded. If the infant failed to respond after 10 trials at 96 Hz, testing was discontinued.

Step size, the amount by which Δf was changed, was systematically decreased over trials. The first time Δf changed, step size was 48 Hz. On each succeeding change in Δf , the step size would be halved. So, for example, if the infant gave two correct responses at $\Delta f = 96$ Hz, Δf on the next trial would be reduced by one step (48 Hz), resulting in $\Delta f = 48$ Hz. If the infant missed the $\Delta f = 48$ Hz trial, on the fourth trial Δf would be increased by one step (now 24 Hz) to 72 Hz. Once step size reached 3 Hz, it was maintained at that value for the remainder of testing. The advantage of reducing step size in this way is that, although Δf approaches threshold rapidly, a relatively precise estimate of the DL can still be made (Levitt, 1971). An example of an infant's response protocol is given in Figure 1.

¹ Although we had originally planned to adjust sensation levels for each subject, we found that the additional time required to obtain pure tone thresholds made it impossible to obtain more than one DL for the infants. However, Wilson (Note 2) reported that for infants of this age, pure tone thresholds are only about 5 dB higher than those of adults, when tested using the head-turn technique. Wier, Jesteadt, and Green (1977) reported that a decrease in sensation level from 80 to 40 dB at 1000 Hz results in an increase in DL from 1.3 to 1.9 Hz for adult listeners.

In all cases, we attempted to continue testing for 12 reversals. However, few infants were able to continue for more than nine reversals. Since early reversals would span a broad Δf range, adding variability to the threshold estimates, only reversals after the first two were averaged to obtain a final estimate of the DL. Consequently, some of the infant DLs were based on only two or three reversals and must be viewed with caution. The total number of reversals obtained for each subject at each standard frequency are given in Table 1.

One DL determination usually required 15-30 trials. Each session lasted about 30 minutes, and DLs at three standard frequencies were typically obtained in two sessions (range, 1-5 sessions). Subjects were retrained before testing at each standard frequency. If a session had to be interrupted before a DL could be obtained, the entire series (including training) at the frequency was rerun during the next session.

One unforeseen difficulty emerged during the course of piloting the procedure: Infants rarely achieved stable performance when tested first at 2000 or 3000 Hz. If the infant completed the 1000 Hz series first, this difficulty with the higher frequencies did not appear. As a consequence all subjects were tested in the order 1000, 2000, 3000 Hz. It is possible, therefore, that practice effects may have influenced the size of the DL relative to the standard frequency at 2000 or 3000 Hz.

Adult subjects listened alone in the test room. They

completed the same training and testing sequence, however. The stimulus parameters and response criteria were identical, and the toy animal was activated as feedback that a frequency change had been correctly detected.

Half of the subjects heard frequency increases; half heard frequency decreases. There was no difference in DL between these two groups.

Results

Difference limens were obtained at all three frequencies for seven infants, at 1000 and 3000 Hz for two infants, and at 1000 Hz only for five infants. These data are shown in Table 1, along with the adult DLs at the three frequencies. Threshold increased with standard frequency for both infants and adults. The infants, however, exhibited higher DLs than adults at all frequencies. A repeated measures analysis of variance for unequal group size, using a least squares solution (Winer, 1971) was performed on log DL for the seven infants for whom a complete

Table 1
Age, Sex, Testing Variables, and Difference Thresholds of Infant and Adult Subjects at Three Standard Frequencies

Subject	Age (month-day)	Sex	1000 Hz		2000 Hz		3000 Hz	
			No. of reversals	DL	No. of reversals	DL	No. of reversals	DL
1	8-1	F	9	18.0	9	32.1	10	57.6
2	8-1	F	6	37.7	9	65.0	5	75.0
3	7-22	M	4	33.8	—	—	—	—
4	7-16	M	6	29.5	7	37.5	7	53.0
5	6-6	F	6	18.5	6	30.0	12	58.2
6	6-3	F	7	7.0	—	—	—	—
7	5-27	F	5	57.0	—	—	—	—
8	5-23	M	5	6.8	—	—	9	58.0
9	5-23	F	6	17.0	—	—	6	43.3
10	5-20	M	9	40.2	—	—	—	—
11	5-20	F	6	9.0	—	—	—	—
12	5-18	M	8	14.3	4	31.5	8	40.1
13	4-26	M	5	7.3	7	27.5	7	57.0
14	4-21	M	5	6.8	4	30.8	4	51.6
<i>M</i>	6-10		6.2	21.6	6.6	36.3	7.6	54.9
1'	Adult	M	12	5.0	12	17.5	12	21.5
2'	Adult	M	12	5.0	12	13.5	12	28.9
3'	Adult	F	12	5.8	12	16.5	12	32.3
4'	Adult	F	12	12.3	12	14.5	12	30.9
5'	Adult	F	12	9.0	12	21.5	12	48.0
<i>M</i>			12.0	7.4	12.0	16.7	12.0	32.3

Note. DL = difference limen; F = female; M = male.

set of data was available and for the five adult subjects. This analysis confirmed the existence of the trends noted above: The effects of age and of frequency were both significant, $F(1, 10) = 17.11$, $p < .005$, and $F(2, 20) = 65.53$, $p < .001$, respectively. The Age \times Frequency interaction was not significant ($F < 1$). The average DLs for all infants and adults are plotted in Figure 2.

The DLs obtained from the infants were highly variable across subjects. At 1000 Hz, for example, infant DLs ranged from 6.75 to 57 Hz. No predictors of infant DL were identified, however. Neither the infant's age, birth weight, current weight, nor stability of growth were found to be related to his or her DL (by Pearson product-moment correlation, $p > .05$ for all correlations). The average DL for female infants at 1000 Hz was 23.45 Hz and for males, 19.77 Hz; the difference proved to be nonsignificant, $t(12) = .45$, $p > .10$. Furthermore, DL was not related to the number of trials required for training (1000 Hz: $n = 14$, $r = .11$; 2000 Hz: $n = 7$, $r = .21$; 3000 Hz: $n = 9$, $r = .19$; $p > .05$ for all three correlations).

Other data from our laboratory indicate that for adult listeners, the head-turn procedure yields higher thresholds than does a procedure that reduces uncertainty about when a frequency change might occur. It might be suggested, then, that the head-turn procedure will underestimate the infant's sensitivity to some extent. It is nearly impossible, however, to estimate the size of the procedural effect for infants, since the infant's possible attentional or sensitivity deficits could interact with the procedural effect. Let it suffice at this point to note that psychoacoustic data obtained via the head-turn procedure can only be taken as an estimate of the lower limit of the infant's actual capacities.

Discussion

The major finding of this study is that 4-8-month-old infants are relatively good frequency discriminators. Some of the infants we tested were able to detect frequency changes as well as adults, but all of the infants responded to frequency differences well

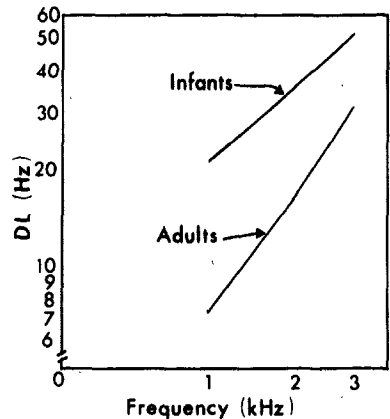


Figure 2. Average difference limen (DL) as a function of standard frequency for infants and adults.

below those detected by infants in previous studies (e.g., Wormith et al., 1975). Thus, it is clear that infants can use frequency information in discriminating sounds.

We did observe some infant-adult differences in performance. Of the 14 infants tested at 1000 Hz, nine had DLs above the adult range. This performance may reflect continuing maturation of the auditory system during the first year of life, and the variability among the infant listeners may stem from sampling infants at various stages of development. However, other factors, such as the infant's short attention span (Kagan, Kearsley, & Zelazo, 1978), cannot be eliminated as contributors to the age difference. We are currently attempting refinements in our procedure that would enable us to make a more definitive statement about the roles of sensitivity and performance factors in determining infant DLs. Until those refinements are made, however, any conclusions about the sources of the observed age difference must be tentative.

The problem in obtaining DLs at 2000 and 3000 Hz in the first session deserves comment. Although we considered the possibility suggested, for example, by Eisenberg (1976) that the infants found these tones unpleasant, we feel that it is more likely that task difficulty was the major factor involved. Because for a given value of Δf the difference in frequency would be closer to the DL at 3000 Hz than it would be at 1000 Hz, it may

have been that infants were reluctant to "work hard" in the early stages of testing. Whereas increasing the number of practice trials or the maximum value of Δf might remedy the situation, either of these solutions would also increase the length of the first testing session beyond what most infants would tolerate. We are currently experimenting with using the first session as a warm-up, postponing actual data collection until the second session.

Whatever the source of the age difference, it is apparent that infants can detect frequency changes and that they can use frequency information to guide their behavior. Further testing over a wider frequency range is needed to elucidate the status of frequency selectivity in infancy, but this experiment clearly supports the position that the ability to discriminate frequencies is present early in life.

Reference Notes

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