Developmental changes in masked thresholds

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Masked thresholds for octave-band noises with center frequencies of 0.4, 1, 2, 4, and 10 kHz and for a 1-octave-band noise centered at 10 kHz were obtained from listeners 6.5 months to 20.5 years of age at two levels of a broadband masker (0 and 10 dB/cycle). Thresholds declined exponentially as a function of age for all stimuli tested. The rate and extent of this decline, but not its asymptote, were independent of the frequency or bandwidth employed. The time course for this change parallels that found for electrophysiological maturation of more central auditory processes.

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INTRODUCTION

The ability of children to extract signals from noisy backgrounds may well affect the acquisition of speech, language, and listening skills (for a review, see Mills, 1975), yet little is known about its development. In two investigations with infants 6 months to 2 years of age, we found substantial adult–infant differences in masked thresholds for a 4-kHz, octave-band noise (Bull et al., 1981) and for a speech stimulus (Trehub et al., 1981). Nozza and Wilson (1984) also found substantial adult–infant differences in masked thresholds for 1- and 4-kHz pure tones in a broadband masking noise. These studies establish that there are adult–infant differences, but they reveal little about the overall course of development, limited as they are in the range of ages and stimuli used. Other investigators have used masking paradigms with infants and children to determine, for example, the size or shape of the auditory filter (see Irwin et al., 1985, Olsho, 1985), but we know of no attempts to chart the overall developmental course of the detection of signals in noise.

In the present experiment, thresholds for narrow-band noises with center frequencies between 0.4 and 10 kHz were determined at two levels (0 and 10 dB/cycle) of a broadband masker (0.1–20 kHz) for listeners 6.5 months, 13 months, 1.5, 4, 8, and 10 years of age, and a comparison group of young adults. We employed a masked-threshold procedure (Bull et al., 1981; Trehub et al., 1981) that is a modification of an absolute threshold procedure developed for infants (Trehub et al., 1980) but also used with adults, preschoolers (Schneider et al., 1986), and school-age children (Trehub et al., 1988). In this procedure, the infant or child sits in one corner of the test chamber with a masking noise presented continuously over loudspeakers to the child's left and right. During a trial, the test signal, a narrow-band noise, is presented over one of the two loudspeakers, the signal remaining on until the child responds, either by turning 45° to either side (younger children) or by pressing one of two buttons on either side (older children). For all listeners, correct responses are reinforced visually with a toy located near the loudspeaker.

I. METHOD

A. Subjects

Infant and child participants were recruited from letters sent to nearby families, as well as from local preschools, parent groups, grade schools, and high schools. Adult participants were university students who responded to posted notices. There were 799 participants, 185 at 6.5 months of age (±1 month), 142 at 13 months (±1 month), 117 at 1.5 years (±1 month), 111 at 4 years (±1 month), 100 at 8 years (±6 months), 103 at 10 years (±6 months), and 41 young adults (17–25 years of age) with a mean age of 20.5 years. All of the infants and children were healthy, born at term, had no history of ear infections, and were free of colds at the time of testing. Of the infants and children who were tested, 57 were excluded from the final sample for failure to meet a training criterion (36, 15, and 6 at 6.5 months, 13 months, and 1.5 years, respectively), 15 because of side biases (all at 6.5 months), 22 for failure to complete a session because they fussed or fell asleep (13, 7, and 2 at 6.5 months, 13 months, and 1.5 years of age, respectively) and 3 at 6.5 months because of experimenter error.

B. Apparatus and stimuli

Octave-band signals were generated by filtering the output of a white-noise generator (General Radio, model 1381) with a programmable Bruel and Kjaer bandpass filter (model 1617) set for octave bandwidths centered at 0.4, 1, 2, 4, and 10 kHz and for a 1–octave bandwidth centered at 10 kHz. Octave bands were chosen principally because comparison data were available for absolute thresholds with infants (Trehub et al., 1980) and children (Schneider et al., 1986; Trehub et al., 1988). The rate of decrease in energy on either side of the band was 30 dB per octave for the octave bands, and greater than 60 dB per octave for the 1–octave band.

An independent white-noise generator (General Radio, model 1381), filtered by a programmable Wavetek (System 716) bandpass filter with cutoff frequencies set to 0.1 and 20

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kHz, was used to produce a continuous background noise over both of the loudspeakers throughout the session. An equalizer was used to compensate for the acoustic properties of the sound-attenuating chamber to produce a relatively flat spectrum for this broadband masker. Octave-band signals were presented over either the left or right speaker, with a 40-ms rise and decay time. A Commodore microcomputer (model 2001) controlled the delivery of stimuli.

C. Calibration

Sound-pressure levels were calibrated with a Brulé and Kjaer impulse precision sound-level meter (model 2204) without the listener present but at the approximate location of the listener's head. Readings on the linear scale were taken with a 0.5-in. microphone directed at the loudspeaker producing the signal. Sound-pressure variation within a 6-in. radius from the calibration locations never varied by more than ±2 dB at any frequency and typically was less than 1 dB. The test levels of the signal for each age group and stimulus are shown in Table I. Signal levels were determined on the basis of pilot testing.

The settings on the equalizer were adjusted to be as close as possible to a bandlimited white noise for the frequency range from 0.18–14 kHz. To accomplish this, we measured the sound pressure in adjacent 1/2-octave bands starting at a center frequency of 0.2 kHz and ending with a center frequency of 12.5 kHz. We adjusted the equalizer to obtain as close a fit as possible to the energy distribution expected in adjacent 1/2-octave bands for a bandlimited white noise (energy increases of 1 dB for each 1/2-octave step). The results are shown in Fig. 1. For all 1/2-octave bands, the actual level is within 1.5 dB of the expected level. Hence, the actual masking noise presented at the location of the subject's ear is a reasonable approximation to a white noise over this frequency range. Two levels of masking noise were employed, one with an average spectrum level of 0 dB SPL and the other with an average spectrum level of 10 dB. The overall dB SPL for these two maskers was 41 and 51 dB, respectively.

The loudspeakers were placed in an Industrial Acoustics sound-attenuating chamber (double-wall, measuring 3 × 2.8 × 2 m), 1.8 m from the center of the listener's chair, which occupied one corner of the room. A chair for the experimenter was located in the corner opposite the listener's chair. Each loudspeaker was at a 45° angle to the listener's left and right. Below each loudspeaker was a four-chamber, smoked Plexiglas box with four different mechanical toys that served to reinforce correct responses. Adjacent to each loudspeaker was a portable color television set (Sony Trinitron, model KV-1911), which was used for reinforcement during the second session for children older than 1.5 years; the viewing screen was blacked out during periods of non-reinforcement.

D. Procedure

During the test session, 4-, 8-, and 10-year-old children and adults were seated in a test chair equipped with a push button on each arm. They were instructed to indicate their judgment of the location of the signal by pressing the button on the corresponding side; these responses were recorded automatically. For children 1.5 years of age and younger, the parent sat in the test chair with the child on his or her lap facing the experimenter. The required response was a head turn of 45° or greater, which the experimenter recorded by means of a hand-held push button. During the test session, the parent, if present, and the experimenter wore headphones with continuous broadband noise to prevent them from detecting the locus of the test signal.

The task was a two-alternative forced-choice procedure. The experimenter pressed a button to initiate a trial only when the listener was judged to be attentive and looking directly ahead. The signal remained on until the listener responded, either by a head turn in the case of younger children, or by a button press in the case of older children and adults. Older listeners sometimes failed to respond within 4
or 5 s because of their reported inability to hear the sound. At such times they were told that the sound was on and were encouraged to listen carefully and guess the sound location. Correct responses resulted in reinforcement, either the presentation of an animated toy or TV cartoon segment for 4 s. Incorrect responses resulted in a 4-s time-out period during which trials were not presented. The mechanical toys were used during the first session with each subject, and the TV cartoons during the second session. Listeners who participated in a third test session could select either type of reinforcement.

Before the subject was brought into the chamber, the masker was presented over both loudspeakers at one of the two levels (0 and 10 dB/cycle) and remained on for the entire time the subject was in the chamber. Between the first and second sessions, the subject left the chamber, at which time the masker intensity was changed to the level required for the second session.

To ensure that all of the infants and children tested could perform the task of identifying the sound location, a training criterion was employed with sound intensity well above threshold. Initially, the 4-kHz, octave-band signals used for training were presented at an intensity of 70 dB. During the training period, the location of the signal was alternated on successive trials between left and right loudspeakers until the child had made four successive correct responses. We have found this alternation procedure to be effective in minimizing side biases resulting from random selection of the sound location during the early training trials. (In no instance has this procedure generated a continuing strategy of response alternation in infants.) The intensity was then reduced 10 dB and the alternation continued until the infant again made four successive correct responses. When this criterion was reached, the actual test series began. The training criterion for adults required only two successive correct responses at each training intensity. In subsequent sessions, children older than 6.5 months received this abbreviated training procedure and adults received no further training.

The test phase, which consisted of 30 trials, immediately followed the training phase. Each trial consisted of a single instance of one of the five intensity levels for each of the six bandpass noises. To preclude the occurrence of several successive instances of the lowest intensity, the stimuli were randomized as follows. Six random permutations of the five intensity levels were generated (for each subject) so that all five intensity levels were represented in a block of five trials. The bandpass signal associated with each of these intensity levels was randomly assigned (again for each subject), with the constraint that each bandpass signal appeared only once at a given intensity level. Thus each block of five trials had one of the six stimuli at its highest intensity level. Assignment of signal to loudspeaker location was randomized with the constraints that an equal number of signals appeared on the left and right loudspeakers and that no more than three successive trials had signal presentation from the same side. With the exception of adults, who were tested in three sessions at each masking level, the subjects were tested only once at each masking level.

Listeners who showed a persistent side bias were eliminated from the final sample. The criterion for exclusion involved 11 or more errors during a session, with 75% or more of these errors occurring on a single side. Only 15 subjects, all 6.5-month-olds, were eliminated for this reason.

It should be noted that subjects listened to each stimulus only once during a session, making this a within-subjects design with a single presentation of each stimulus–masker combination. We selected a within-subjects design to minimize the effects of intersubject differences, which can be substantial at the younger ages (e.g., Trehub et al., 1986). Because parents are generally unwilling to bring their infants and children for repeated testing, it was not possible to test each subject extensively at each frequency. On the basis of our previous work (Trehub et al., 1980), which showed that infants can be tested in two consecutive sessions without any observable decrements in performance, we conducted two sessions, one for each of the two masker levels. Furthermore, in those studies in which we have used periodic probe stimuli (e.g., Trehub et al., 1989), we have not found any decrements in performance over a session. The advantage of the present design is that it permits within-subject comparisons across frequencies and masker levels; its disadvantage is that it precludes the determination of individual thresholds.

II. RESULTS

In Fig. 2, the percentage of correct localization responses is shown as a function of sound-pressure level for each of the six narrow-band signals with the masker set to 10 dB/cycle. The psychometric functions for each age group are plotted separately for each signal. Each point on the functions is based on a minimum of 100 trials. Note that, for all signals, the psychometric functions shift to the left as a function of age, indicating increasing sensitivity with age. Furthermore, the extent of the shift appears to be independent of frequency. The psychometric functions for the 0-dB/cycle masker exhibit the same pattern as a function of age.

![Figure 2](image-url)
The psychometric functions for both the 0- and 10-dB/cycle noise maskers were used to determine threshold values for each of the stimuli for each age group at both masking levels (see Table II). Threshold was defined as the intensity corresponding to 65% correct and was determined by linear interpolation between the two intensities on either side of this point. The 65% criterion permits comparisons between the present study and similar developmental studies of absolute thresholds (Trehub et al., 1980; Schneider et al., 1986; Trehub et al., 1988). Figure 3 plots the thresholds as a function of age for the five frequencies of octave-band noise and for the 10-kHz, 1-octave-band noise. Exponential decay functions \( y = a + 10 \log(1 + be^{-ct}) \) were fit to the data points for each frequency and masker combination, where \( y \) is threshold in dB, \( t \) is age in years, \( a \) is the asymptotic threshold value, \( b \) specifies the extent of the decline, and \( c \) is the time constant for the rate of decline. Individual exponential functions accounted for 97.8% of the total variance in Fig. 3. However, a single exponential decay function with the same rate and extent of decline \((c = 3.2 \text{ and } b = 20.7)\), but differing in asymptotic level at each frequency and masker level, accounted for 96.3% of the variance. It is these functions that fit to the data points in Fig. 3. The close fit of the functions to the data of Fig. 3 indicates that the decline in thresholds is independent of frequency for octave-band noises and is also independent of bandwidth for 10-kHz noises.

A comparison of these data with absolute thresholds obtained with the same method and stimuli (Trehub et al., 1988) indicates that these masker levels were effective at raising threshold at each of the frequencies tested for each age group with the exception of the youngest ages at 0.4 kHz. The average threshold elevation produced by the 0-dB masker (averaged across age and frequency) was 20.9 dB; for the 10-dB masker, it was 30.1 dB.

It is also interesting to note that the average separation between the 0- and 10-dB/cycle contours in Fig. 3 is 9.3 dB, which is to be expected for maskers at these levels. For moderate to high levels of masking noise, adult data show that an x-dB increase in masker is accompanied by an x-dB increase in signal threshold (Hawkins and Stevens, 1950). For masking levels of 0 and 10 dB/cycle, the average separation between contours for frequencies between 0.4 and 1 kHz is slightly less than 10 dB (see Hawkins and Stevens, Fig. 5).

Figure 4 plots the signal-to-noise ratio (total power in the signal \( S \) divided by the spectrum level of the noise \( N_0 \)) required for threshold as a function of the frequency of the signal from three different studies. In all three studies, the masker was a broadband noise. The signal-to-noise ratios for the octave-band noises from the present experiment (adult subjects only) were averaged over the two masker levels. The data from Hawkins and Stevens (1950) represent the average signal-to-noise ratio found for the masking of pure tones by broadband noise and are taken from Fig. 6 of that article. Finally, Green’s (1960) data for the masking of narrow-band noises (bandwidth = 655 Hz at all frequencies) are also shown. Figure 4 reveals that thresholds obtained in

### Table II. Masked thresholds. Upper and lower entries are the thresholds (dB SPL) for the 0- and 10-dB/cycle maskers.

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>0.4</th>
<th>1.0</th>
<th>2.0</th>
<th>4.0</th>
<th>10.0</th>
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<td>44</td>
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<td>47</td>
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<td>35</td>
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<td>42</td>
</tr>
<tr>
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<td>44</td>
<td>45</td>
<td>48</td>
<td>51</td>
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<td>32</td>
<td>35</td>
<td>41</td>
<td>41</td>
<td>40</td>
</tr>
<tr>
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<td>34</td>
<td>41</td>
<td>42</td>
<td>38</td>
</tr>
<tr>
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<td>40</td>
<td>42</td>
<td>44</td>
<td>43</td>
<td>52</td>
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</tbody>
</table>

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FIG. 3. Masked thresholds as a function of age for five octave-band noises centered at 0.4, 1, 4, and 10 kHz, and a 10-kHz, 1-octave-band noise. Thresholds for two masker levels (0 and 10 dB/cycle) are shown. Exponential decay functions identical in their extent and rate of decline but differing in asymptote are fit to the data.
the present study are about 2 dB higher than those obtained by Green from two experienced psychophysical observers under optimal test conditions. Note, however, that in the present study and in Green's, the signal-to-noise ratios required for threshold are essentially constant for frequencies less than 5–6 kHz and increase thereafter. Thus the overall pattern for the masking of narrow-band noises appears to differ from that of pure tones. Figure 4 indicates that our adult findings are consistent with those from other studies despite substantial procedural differences, including the present use of sound field rather than earphone testing, and the employment of different signal durations and masker bandwidths.

III. DISCUSSION

In the present experiment, masked thresholds for five octave-band noises (center frequencies of 0.4, 1, 2, 4, and 10 kHz) and a 1-octave-band noise at 10 kHz were determined for listeners 6.5 months to 20.5 years of age. Masked thresholds declined exponentially at the same rate and by the same amount as a function of age ($b = 20.7, c = 3.2$), differing only in their asymptotic levels.

A. Localization versus detection

Our procedure requires listeners to identify the loudspeaker over which a signal is presented, which is a judgment of localization as opposed to detection. It is possible, then, that thresholds for detection and localization might differ. Furthermore, the extent of such differences might depend on the age of the listener and the frequency of the signal. Trehub and Schneider (1987) have demonstrated, however, that, in a quiet background, children 1, 3, and 5 years of age as well as adults localized, in a two-loudspeaker localization task, all stimuli that they could detect in a single-loudspeaker detection task. Moreover, there were no interactions between frequency (0.4 and 10 kHz) and type of task (detection or localization). Thus the available data suggest that, for band-limited noise in a quiet sound field, detection and localization thresholds are comparable and are independent of the frequency of the stimulus.

To check whether the presence of a broadband masker differentially affects the two tasks, we compared detection and localization performance in a noisy background (0 dB/cycle) with 1-, 3-, 5-year-old, and adult listeners. In both the detection and localization conditions, broadband noise was presented over both loudspeakers. Only one stimulus intensity was presented during a test session, with each individual tested under both detection and localization conditions. In the detection condition, the signal was presented on the left speaker on 50% of the trials and listeners were required to indicate whether or not a signal was presented. The addition of a noise masker did not significantly affect the relationship between detection and localization thresholds. Overall, sensitivity was roughly comparable for 0.4- and 10-kHz signals in both localization and detection conditions. Taken together, these results suggest that, in quiet or in low levels of masking noise, detection and localization thresholds are similar for both low and high frequencies. Thus it is reasonable to interpret the developmental changes shown in Fig. 3 as reflecting changes in detection thresholds. Details of these experiments will be published in a forthcoming paper (Schneider et al., under review).

Because the signals in the present experiment occurred in the context of identical broadband maskers presented over loudspeakers on each side of the listener, it is possible that some degree of binaural unmasking was present. Two factors suggest, however, that any contribution of unmasking to the observed developmental changes would be negligible. First, a number of studies have shown that very little unmasking occurs when the spectrum level of the masker is as low as in the present experiment (for a review, see Durlach and Colburn, 1978, p. 437). Second, Nozza (1987) and Schneider et al. (1988) have shown that binaural unmasking also occurs in infants, although to a lesser extent than in adults. Thus, even with some unmasking, the adult–infant difference attributable to this factor would be of little consequence.

B. Group psychometric functions

In contrast to most psychophysical investigations, the present design did not incorporate numerous observations from each listener at each frequency. Instead, subjects were presented with each frequency × intensity combination only once during a session, precluding the determination of individual thresholds. Because the children were tested only once at each masker level, the ordinate of their psychometric functions is essentially the percentage of subjects correct at that intensity level. There is some question, then, as to whether thresholds obtained in this manner (i.e., from group-based psychometric functions) are equivalent to individual thresholds averaged over a comparable group. Schneider et al. (1986) report on such a comparison for 4-kHz, octave-band noises presented in quiet to listeners 3, 4, 5, and 20 years of age. Individual thresholds were obtained with the PEST procedure (Taylor and Creelman, 1967) adapted for use with infants and children (Trehub et al., 1986), and group psychometric functions were obtained with the present procedure. Averaged PEST thresholds were equivalent to the group psychometric thresholds at all age levels (see Schneider et al., 1986, Fig. 4). Trehub et al. (1986) have also shown that average PEST thresholds for 6-month-old infants are equivalent to those obtained from group psychometric functions. Although we have no direct comparisons of the two procedures for masked thresholds, there is no reason to expect divergent results for masked but not for absolute thresholds.

It should also be noted that employing a 65% instead of a 75% criterion does not significantly affect the pattern of results. Use of a 75% criterion elevates the threshold estimate (averaged over the five octave-band signals) by 3.14, 2.49, 2.60, 3.02, 2.54, and 2.79 dB at 0.54, 1.08, 1.5, 4, 8, 10, and 20.5 years of age, respectively, for the 10-dB/cycle masker.

C. Factors contributing to changes in masked sensitivity

In signal detection theory, noise and signal-plus-noise trials give rise to different distributions of effects along a decision axis. The subject's task, given an observation along
this decision axis, is to identify the distribution that produced the observation. The ability of the subject to correctly identify the distribution will depend not only on the separation between the means of these two distributions, but also on their variances. Thus developmental changes which, for a fixed signal-to-noise ratio, result in greater separation between the means of these distributions and/or reduction in the variances of these distributions would increase detectability and lower thresholds. On the other hand, developmental changes that shift these two distributions uniformly would not increase detectability in noise but would lower thresholds in quiet.

1. Mechanical efficiency

It is worth noting that changes in masked threshold cannot be attributed to changes in the mechanical efficiency of the outer and middle ear. Suppose, for example, that between 6 months and 8 years, efficiency improves by 10 dB for a given frequency. This improvement in mechanical efficiency would not change the signal-to-noise ratio in a masking experiment because the improved efficiency would enhance both the signal and the noise by the same amount. Because masked thresholds have been shown to depend only on the signal-to-noise ratio for moderate to high levels of the masker, we can conclude that changes in masked thresholds do not reflect maturational changes in mechanical efficiency.

2. Critical band size

Decreasing the size of the critical band would decrease the effective energy in the masker, thereby increasing the separation between noise and signal-plus-noise distributions. Therefore, age-related improvement in masked thresholds could result from developmental changes in the size of the critical band. Measures of the monaural tuning curve or auditory filter in infants and children (Olsho, 1985; Irwin et al., 1986) do not reveal adult-child differences that are large enough to account for the adult–infant differences in masked thresholds. Furthermore, it is unlikely that age-related changes in the size of the binaural filter or critical band are large enough to account for the adult–infant differences in masked thresholds. Several studies (Sondhi and Guttmann, 1966; Sever and Small, 1979; Yama and Robinson, 1982) have shown that the size of the critical band measured in certain binaural situations is somewhat larger than its monaural counterpart, suggesting that the filtering process is different when binaural processing is involved (McFadden, 1975). Thus, it is possible that there are large developmental changes in the size of the binaural filter but not the monaural filter. Because our procedure involves binaural processing, this possibility cannot be discounted. However, direct measures of the size of the critical band in infants and children (Schneider et al., in press) with the present sound-field procedure reveal that its size also undergoes little change with age. Thus the available data suggest that changes in the size of the critical band make a relatively minor contribution to age-related changes in masked thresholds.

3. Motivation and attention

If the critical band changes only a little with age, then how can we explain age-related changes in masked thresholds? One possibility is that infants and young children are simply less motivated to achieve optimal performance. Poorly motivated subjects might be inattentive on some trials, resulting in a performance decrement. It is difficult to rule out such explanations but there are several reasons to suggest that motivational factors contribute minimally to age-related improvements. In the case of adults, masked thresholds: (1) are relatively stable across individuals (Green, 1976); (2) show a negligible practice effect so long as the subject has had some preexposure to the stimulus (Gundy, 1961; Swets and Sewell, 1963); and (3) cannot be shifted by more than 1–2 dB by substantial changes in reward structure (Lukaszewski and Elliott, 1962; Green and Swets, 1966). Our results, obtained from unpracticed adult listeners, are consistent with these observations, since the present masked thresholds are very similar to those obtained from highly trained subjects (see Fig. 4 and associated text). Unless practice effects and motivational factors operate differently in children, we would expect age-related variations in these factors to have little effect on children’s performance in the masking task.

Second, we have observed little inattentiveness at any age, except for 6.5-month-olds. Inattention implies guessing in a forced-choice procedure, and one can demonstrate that guessing on some trials would result in a shallower slope for the psychometric function as well as a lower asymptote. Examination of the psychometric functions (Fig. 2) shows, however, that their slopes are comparable across ages, with the possible exception of 6.5-month-olds. This is shown more clearly in Fig. 5, where the functions have been shifted laterally so that they coincide at the intensity corresponding to the 65% criterion. If infants and children are less attentive than adults, then the slopes of their psychometric functions should be less steep than those of adults, but there is no such evidence in Fig. 5. It should be recalled, however, that the psychometric functions shown in Fig. 5 are group functions. With group functions, it is possible that age-related slope changes are obscured by the averaging process. The argument presented above would be more convincing if we could show that there are no age-related changes in the slopes of individual psychometric functions. Unfortunately, we do not yet have data to demonstrate this.

There are other reasons, however, why we believe that motivation and attentional changes are not solely responsible for age-related changes in masked thresholds. First, 4- and 8-year-olds appeared to be highly motivated, trying hard to detect the location of the stimulus, and occasionally becoming upset when they made errors, despite our warning that some of the signals would be so soft that no one could be expected to hear them. Nevertheless, their thresholds were higher than those of adults. Second, the performance of 4- and 5-year-old children on visual tasks with equivalent psychometric techniques (visual reinforcement of forced-choice looking behavior, see Mayer and Dobson, 1982) revealed individual thresholds and individual psychometric functions that were equivalent to those of adults. By con-
functions is 10 dB/cycle.

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al. were tested under conditions quite similar to those in

PEST subjects in Schneider et al. and the subjects in Irwin et

were considerably less sensitive than adults. Note that the

contrast, the 4-year-olds in the present study, Schneider et al.'s

1986) 4-year-olds and Irwin et al.'s (1986) 6-year-olds

were tested under conditions quite similar to those in

Mayer and Dobson. Therefore, procedural differences such

as greater frequency uncertainty in the present experiment

are unlikely to account for the observed differences. Unless

there are large intermodal differences in motivation and at-
tention, these results also suggest that the observed changes

in masked threshold cannot be attributed solely to age-relat-

ed motivational or attentional changes.

4. Variability in the neural representation of intensity

If the critical band does not change substantially with

age and if inattention is not a contributing factor, then what

else might account for these age-related changes in masked

sensitivity? One possibility is that variability in the neural

representation of intensity decreases with age. Let $E(S + N)$

represent the neural effect resulting from the presentation of

a signal in noise. Suppose that the function relating the mean

value of $E(S + N)$ to signal intensity does not change with

age, but that the variability of $E(S + N)$ decreases with age.

Although a comparison of noise and signal + noise distribu-
tions would show the same mean difference in neural re-

sponse for both infants and adults, the adults would have a

large $d'$ value at every signal intensity because $d'$ measures

the distance between the means of the noise and signal + noise distributions in standard deviation units. Conse-
quently, a decrease in variability would lower thresholds and,
under most circumstances, steepen the slope of the function
relating percentage correct to dB SPL. But we have seen
that, although thresholds decline with age, there is no
evidence that the slope of the psychometric function steep-
ens with age (see Fig. 5). Consequently, there is no evidence
in this study that age-related improvement is attributable to
greater precision (i.e., less variability) in the neural repre-

sentation. However, because there are some circumstances
under which we would not expect a slope change with a
change in variability, we cannot eliminate the possibility that
some of the observed changes in threshold are due to changes
in the variability of the neural representation.

5. Nonlinear changes in the neural representation

Although we cannot readily account for these develop-

mental changes in terms of increasing precision in the neural
code for intensity, we can account for such changes if there

are nonlinear, age-related alterations in this code. Let $f(I_1)$

represent the neural code for the intensity of a narrow-band
signal, $I_1$, and let $f(I_n)$ be the neural representation of
the intensity of the masker, $I_n$, after peripheral critical band
filtering. Suppose, following Zwislocki (1978), that detection
depends on the internal signal-to-noise ratio and that a pow-
er transformation describes the neural code for intensity
within a critical band. According to this model, threshold is
reached when

\[ f(I_1 + I_n) / f(I_n) = (I_1 + I_n)^p / I_n^p = (1 + I_1 / I_n)^p = c, \]

where $c$ is the criterion internal signal-to-noise ratio. Note

that, in this model, an x-dB increase in masker intensity re-

quires an x-dB increase in signal intensity to maintain a con-
stant internal signal-to-noise ratio.

Age-related changes in masked sensitivity can be ex-

plained within this model by assuming that the exponent of

the power function increases with age. Note that, for fixed

signal and masker intensities, $(I_1 + I_n)^p / I_n^p$ increases

with $p$. Therefore, as $p$ increases, a constant external signal-to-

noise ratio produces a progressively larger internal signal-to-

noise ratio. Thus, with increasing age, a progressively
smaller external signal-to-noise ratio is required for detec-
tion.

The Zwislocki model is offered as one example of how

age-related nonlinear changes in the internal representation
of signal and noise could result in a lower signal-to-noise
ratio required for threshold. We have no evidence to support
the notion that there are developmental changes in the expo-

ten governing the growth of loudness, but there are un-
doubtedly other nonlinear transformations that would

generate a similar effect. The important point is that the changes

must be nonlinear to produce the present pattern of results,

for a linear change in $f$ with age would not produce a change

in internal signal-to-noise ratio. Thus the source of the

changes in masked sensitivity cannot be attributed to any

part of the system that remains linear throughout develop-

ment. Because the mechanics of the outer and middle ear are

thought to be essentially linear over a wide intensity range, it

is unlikely that changes in masked thresholds can be attribu-
ted to changes in these systems. (Changes in a linear system

that preserve linearity are linear changes.) Because the co-

chlear microphonic (CM) also appears to be linear over a wide

intensity range (Wever and Lawrence, 1954; Dallos, 1978)

and because the CM is often thought to represent the initial

stages in the cochlear transduction process, it is reasonable
to assume that the chain of events from sound to auditory
perception is essentially linear until the actual transduction into neural impulses. Therefore, developmental changes in these peripheral components should not affect masked thresholds.

At more central stages of neural processing, however, strong nonlinearities occur. Thus the observed developmental changes in masked thresholds most likely result from nonlinear changes in more central neural processes. Although linear changes in the peripheral components of the auditory chain will definitely affect absolute sensitivity in quiet, they are unlikely to have any significant effect on masked thresholds.

If changes in masked thresholds represent nonlinear changes in neural processing that occur over several years, some physiological measures of auditory processing could be expected to change over a comparable time period. Eggermont (1985) has shown that exponential functions characterize the changes that occur in a variety of electrophysiological measures of auditory maturation in many different species. In particular, he describes three different time courses for human auditory maturation in the cochlea, in the brain stem, and in the cortex. His estimate of the time course for cortical development is based on a study by Fabiani et al. (1979), in which they measured differences in latency between wave I and the vertex-negative wave following wave V from 1 to 12 years of age. Eggermont fitted an exponential decay function to their data and arrived at a time constant of 3.15 years, which is almost identical to the one associated with the present decline in behavioral thresholds with age, specifically 3.2 years. Thus the time course for at least one index of the developing auditory nervous system parallels our findings for masking. Obviously, this parallel does not imply that changes in this physiological measure are responsible for the age-related changes in masked thresholds. It illustrates, however, that central components in the auditory nervous system have maturational time constants that match those found for behavioral measures of auditory development. If these age-related changes in central processing of the auditory signal are nonlinear, they could account for the increased detectability of signals in noise.

To recapitulate, the attribution of the source of changes in masked thresholds to nonlinear changes in the neural representation of intensity rests on the following observations and arguments. First, if the initial stages of auditory processing are linear, and remain so over the course of development, then such developmental changes cannot affect masked thresholds. Second, developmental changes in attention are unlikely to be responsible for these changes because attentional changes should be reflected in the slopes of the psychometric functions. However, as Fig. 5 shows, there is no evidence of slope changes with age. Third, it is unlikely that changes in the variability of the internal representation are responsible for the decline in thresholds because such changes should also be reflected in the slopes of the psychometric functions. Because the slopes do not change dramatically with age, it is unlikely that this factor plays an important role. Arguments based on the slopes of group psychometric functions, however, are not as convincing as those based on individual psychometric functions due to the fact that averaged slopes might obscure consistent trends observable in individual functions. Until it can be shown that the slopes of the psychometric functions for individual subjects do not change with age, we must allow for the possibility that some of the variation in masked thresholds might be due to attentional factors or to changes in the variability of the neural representation. Fourth, because there is no compelling evidence that critical band size changes substantially with age, this factor is unlikely to be principally responsible for the decline in the signal-to-noise ratio required for threshold. Fifth, at least one model (Zwislocki, 1978) exists whereby a nonlinear change in the neural representation of intensity would produce a decline in the external signal-to-noise ratio required for detection.

D. Comparisons between absolute and masked thresholds

Signal-detection accounts of absolute threshold typically assume that the signal is detected in the presence of neural noise that is internally generated and is of physiological origin (e.g., Zwislocki, 1978). If this is indeed the case, then both absolute and masked threshold experiments involve the detection of signals in noise; in the absolute threshold case, the noise is internally generated, whereas, in the masked threshold case, the noise is primarily of external origin. Figure 3 showed that the signal-to-noise ratio required for threshold in a masking experiment changes as a function of age. As noted above, this could be because of cognitive factors (motivation, attention, etc.) or because of nonlinear changes in the neural code for intensity. If the same detection process is operative for absolute thresholds, and if the amount of internally generated noise is unchanged throughout development, then we would expect a comparable developmental course for absolute thresholds. The reason for this is that if infants required a higher signal-to-noise ratio than adults in a masking experiment, they would also require a higher signal-to-noise ratio in an absolute threshold experiment. Suppose, for instance, that the masked threshold for infants was 20 dB higher than that of adults. If the same detection process characterizes absolute threshold judgments, then infant absolute thresholds should be 20 dB higher than adult absolute thresholds, and the difference between masked and absolute thresholds for infants should be the same as the comparable difference in adults. Figure 6 plots the difference between masked (10 dB/cycle) and absolute thresholds as a function of age for five frequencies of an octave-band noise. Absolute threshold values were taken from Schneider et al. (1986) and Trehub et al. (1980, 1988), where comparable procedures were employed. Note that the difference between masked and absolute thresholds is constant across the entire age range at 10 kHz but increases with age at the other frequencies. (Exponential functions were fit to frequencies less than 10 kHz.) It should be noted that, for all frequencies, asymptotic levels are reached by about 6–7 years of age, with the greatest changes occurring at 2 and 4 kHz.

Why does the difference between masked and absolute thresholds increase with age at the lower frequencies? One
We thank K. J. Kim for technical assistance and Marilyn Research Council of Canada and the University of Toronto.

FIG. 6. Difference between masked (10 dB/cycle) and unmasked thresholds as a function of age for five frequencies of an octave-band noise.

possibility is that peripheral sensitivity at these frequencies is improving with age. Suppose, for example, that the outer and middle ear become more efficient at delivering energy to the inner ear as the child develops. Such age-related improvements in mechanical efficiency, affecting both signal and noise by the same amount, would not affect masked threshold but would reduce the signal intensity required for absolute threshold, thereby increasing the difference between masked and absolute thresholds. Therefore, the smaller difference between masked and absolute thresholds in younger children could be due to differences in mechanical efficiency between the ears of children and adults. Similarly, the development of a resonant frequency in the outer ear in the 2- to 4-kHz region may make the older child and adult more sensitive at this frequency. Note that an increase in the effective sound pressure in the ear canal, while it would reduce the intensity of the signal required for absolute threshold, would not affect the signal intensity required for masked threshold, providing that the masker was sufficiently intense. Therefore, the difference between masked and absolute thresholds would increase with age. In general, changes in ear resonance, changes in mechanical efficiency, and/or maturational changes in basilar membrane sensitivity could produce an increase in the separation between masked and absolute thresholds. Although it is premature to speculate on the relative contributions of such factors, it should be noted that the constancy in the difference between masked and absolute thresholds at 10 kHz suggests that changes in absolute threshold at high frequencies are due primarily to changes in the signal-to-noise ratio required for threshold. It is only at lower frequencies that additional factors, such as resonance changes, changes in membrane sensitivity, or changes in mechanical efficiency need to be considered.

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"It can be shown that decreasing the variability in the neural representation will result in a change in the slope of the psychometric function \( p(c) vs \text{ SPL} \) unless a power function describes the relation between \( d' \) and stimulus energy \( E \); that is, unless \( d' = kE^p \). (We thank Neal Veiermeister for bringing this to our attention.) Several investigations have shown, however, that the relation between \( d' \) and \( E \) departs significantly from a power function (see, for example, Jeffress, 1967, Fig. 6). The major reason for this departure is that, as the energy in the stimulus is decreased, \( d' \) approaches and reaches zero well before stimulus energy reaches zero. Because the actual relation between \( d' \) and \( E \) is not a power function, a change in neural variability will produce a change in the slope of the psychometric function as well as a change in threshold. To evaluate how much of a change to expect it would require precise determinations of individual psychometric functions at the different ages. Consequently, all that we can conclude on the basis of the group psychometric functions in Fig. 5 is that there is no evidence for a change in neural variability in this study. More precise determinations of individual psychometric functions would allow us to determine the extent to which changes in neural variability should be reflected in slope changes \( p(c) vs \text{ dB} \) and whether or not such changes are indeed occurring.


