Size of Critical Band in Infants, Children, and Adults

Bruce A. Schneider, Barbara A. Morrongiello, and Sandra E. Trehub
University of Toronto, Mississauga, Ontario, Canada

Masked thresholds at two signal frequencies (0.8 and 4 kHz) were obtained from listeners aged 6.5 months, 2 years, 5 years, and 20.5 years in the presence of constant spectrum level, narrow-band maskers of differing bandwidths. Consistent with the classical results of Fletcher (1940), masked threshold for all age groups increased with bandwidth up to a critical width, beyond which further increases in bandwidth were ineffective in increasing threshold. These critical widths (estimates of critical band size) did not change substantially with age (critical widths for infants were no more than 50% larger than those of adults) despite substantial changes in masked thresholds with age. Thus, contrary to previous claims, changes in auditory filter width cannot account for developmental changes in masked or absolute thresholds.

The concept of a critical band or auditory filter has been invoked in virtually every auditory phenomenon (e.g., Moore, 1982; Scharf, 1970) and has been the concern of numerous studies in auditory psychophysics and auditory psychophysiology. Indeed, the perception of many auditory events seems to depend on whether the energy in the stimulus is contained within a limited frequency region (i.e., a critical band) or is spread across two or more such regions. Consider, for example, the classic experiment by Fletcher (1940), in which listeners were required to detect the presence of a pure tone centered in narrow-band noises of different bandwidths, with the spectrum level (dB per cycle) of each noise band held constant. (Because the spectrum level was held constant, the total power in the masker was proportional to the bandwidth of the masker.) Fletcher found that pure-tone thresholds increased with bandwidth (total power) up to a certain point, beyond which no further increases in threshold were observed, in spite of enormous changes in masker bandwidth and power. This basic result has been confirmed a number of times (e.g., Greenwood, 1961; Schafer, Gales, Shewmaker, & Thompson, 1950; Swets, Green, & Tanner, 1962), indicating that only the energy in a narrow frequency region centered on a pure tone is effective in masking that pure tone. As Scharf (1970) has documented, the dependency of masked thresholds on critical bandwidth is but one of many instances in which auditory phenomena function differently within and across critical bands.

Because of the importance of the critical band concept, any theory of auditory development would be incomplete without some understanding of how the critical band or auditory filter changes with age. For example, there are substantial adult-infant differences in masked thresholds (Bull, Schneider, & Trehub, 1981; Nozza & Wilson, 1984; Trehub, Bull, & Schneider, 1981), and these differences decline exponentially over the first decade of life (Schneider, Trehub, Morrongiello, & Thorpe, 1989). Changes in the size of the critical band could easily account for these developmental trends (Schneider & Trehub, 1985). Figure 1 (upper panel) illustrates how this might occur. The solid horizontal line represents the spectrum level \( N_0 \) of a band-limited Gaussian noise (i.e., flat power spectrum), the vertical arrow represents the power in a 0.8-kHz pure tone, and the dashed vertical lines indicate the upper and lower boundaries of the critical band centered at 0.8 kHz. In line with the notion of an auditory filter or critical band, we assume that energy falling outside the critical band cannot affect quantities calculated from energy within the band. Therefore, only the portion of the masker that falls within the critical band is effective in masking the pure tone at its center. Suppose that threshold is reached when the ratio of signal power to noise power in the critical band exceeds some criterion value, that is,

\[
I_s/I_{nob} = C,
\]

where \( I_s \) is the power in the pure tone, \( I_{nob} \) is the noise power within the critical band, and \( C \) is the threshold constant. Because the spectrum of a Gaussian noise is flat, it is clear that \( I_{nob} = N_0 \cdot CB \), where \( CB \) is the width of the critical band. Now suppose that the criterion signal-to-noise ratio, \( C \), remains unchanged throughout development but that the size of the critical band decreases with age. Because the noise power in the critical band is proportional to bandwidth, then as critical bandwidth shrinks with age, the signal power required for threshold decreases proportionally. A number of studies (Bull et al., 1981; Nozza & Wilson, 1984; Schneider et al., 1989; Trehub et al., 1981) have shown that the masked threshold of infants is 8–15 dB higher than that of adults. If changes in masked threshold are to be accounted for by changes in critical band size, then the size of the critical band in infants should be 6 to 30 times as large as it is in adults.

Despite the importance of the concept of an auditory filter to a theory of auditory development, we know of only two attempts to measure its size in nonadult populations. Olsho

This research was supported by grants from the Medical Research Council of Canada and from the University of Toronto. We thank K. J. Kim, Marilyn Barras, Donna Laxdal, and Elizabeth Olsho for assistance in data collection.

Barbara A. Morrongiello is currently affiliated with the Department of Psychology, University of Western Ontario, London, Ontario, Canada N6A 3K7.

Correspondence concerning this article should be addressed to Bruce A. Schneider, Department of Psychology, Erindale Campus, University of Toronto, Mississauga, Ontario, Canada L5L 1C6.
(1985) used a visually reinforced head-turning technique to determine psychophysical tuning curves for infants. The listener's task in this procedure is to detect a low-level probe of fixed frequency and intensity when it is presented simultaneously with a masker tone of the same or different frequency (Chistovich, 1957; Small, 1959; Zwicker, 1974). The level of the masking tone is adjusted to determine the masker intensity at which the listener can no longer detect the probe tone. As the frequency separation between masker and probe increases, so does the masker intensity required to suppress the perception of the probe tone. The width of the resulting tuning curve is considered to be a behavioral measure of auditory filter width. Olsho (1985) found no substantial differences in the widths of the tuning curves for infants and adults, but infants were more susceptible to masking effects.

Irwin, Stillman, and Schade (1986) measured the width of the auditory filter in two 6-year-olds, two 10-year-olds, and two adults by having them detect a pure tone centered in a spectral notch in a band of noise. The signal power necessary for detection was determined as a function of notch width. There were no significant differences in auditory filter widths between 10-year-olds and adults, but the auditory filter widths of 6-year-olds were about 30% larger than those of the two older groups, a difference that is much too small to account for the differences in masked thresholds between these age groups.

In the present experiment, we attempted to determine the size of the critical band with the classic paradigm used by Fletcher, modified, as required, for the limitations of young participants. In the classic measurement procedure, pure-tone thresholds are determined in a background of band-limited Gaussian noise. The bandwidth of the masker, but not its spectrum level, is increased systematically to observe how the bandwidth of the noise affects the threshold of the pure tone. For a constant-spectrum rectangular band of noise, the total power in the masker is proportional to the bandwidth. We would expect, therefore, that the threshold for the signal would continue to increase with increasing bandwidth, until the bandwidth matched or exceeded the critical band. Beyond that point, further increases in bandwidth should not affect tone threshold. The insert in the upper panel of Figure 1 shows how the threshold for a 0.8-kHz pure tone should vary as a function of the bandwidth of a constant spectrum level masker.

In our adaptation of this technique for infant participants, we used a two-alternative, forced-choice procedure (Bull et
al., 1981; Schneider et al., 1989; Trehub et al., 1981) that we have used previously to determine masked thresholds in infants, children, and adults. We used 1/3-octave bands of noise instead of pure tones to permit direct comparisons with these earlier studies and to reduce amplitude variation in the signal measured at different locations in the sound field (Dillon & Walker, 1982) while still retaining adequate frequency specificity. The infant or child sits in one corner of the test chamber with a masking noise presented over loudspeakers to the left and right. During a trial, the test signal, a 1/3-octave band of noise, is presented over one of the two loudspeakers, the signal remaining on until the infant or young child turns 45° to the right or left. Older children press one of two buttons to indicate the location of the sound. For all listeners, correct responses are reinforced visually with a toy located near the loudspeaker; incorrect responses result in a short intertrial delay. In the present experiment, four values of signal intensity were used at each of the eight bandwidths of a constant-spectrum masking noise to determine how threshold for the signal changes as a function of the bandwidth of the masking noise.

In line with the adult research, we expected that thresholds for the 1/3-octave band signal would increase with masker bandwidth until the width of the masker reached a critical value, after which further increases in bandwidth would be ineffective in raising threshold. The theoretical value of the bandwidth at which this transition takes place should not be the same as that found for the masking of pure tones by narrow-band noises. We have illustrated the reasons for this in Figure 1 (lower panel), where we represent the signal as a rectangular, 1/3-octave band centered on 0.8 kHz. The critical band for a 0.8-kHz pure tone is indicated by the dashed vertical lines in the upper panel. Note that some portion of the energy in the signal falls outside the critical band for a 0.8-kHz tone. Clearly, energy in a masker that falls outside the critical band centered on 0.8 kHz will be effective in masking this signal because a portion of the energy in the signal itself falls outside this bandwidth. If, on the other hand, we consider critical bands centered on the lower (f1) and upper (f2) cutoff frequencies for the 1/3-octave band (indicated by the dashed vertical lines in the lower panel of Figure 1), then energy in the masker at frequencies to the left of the leftmost dashed line and to the right of the rightmost dashed line should be ineffective in masking the 1/3-octave band.

The lower cutoff frequency is given by $f_1 - 0.5^*CB(f_1)$ and the upper cutoff frequency by $f_2 + 0.5^*CB(f_2)$. By using tables of critical bandwidth as a function of frequency (Scharf, 1970), the effective upper and lower cutoff frequencies are calculated to be 647 and 973 Hz, respectively, for a 1/3-octave band of noise centered at 0.8 kHz, for an effective critical bandwidth of 326 Hz. Similarly, the effective critical bandwidth for a 4-kHz, 1/3-octave band of noise is calculated to be 1.62 kHz. Therefore, the threshold for a 0.8-kHz, 1/3-octave band noise should no longer increase with masker bandwidth once the bandwidth exceeds 326 Hz. A similar pattern should hold for a 4-kHz, 1/3-octave band signal, but with the transition from a rising to a constant threshold level occurring near 1.62 kHz. These theoretical calculations, which represent an upper limit on expected critical band size, were used to evaluate the effectiveness of our procedure in measuring critical bands in adults and the relative sizes of critical bands in infants and children.1

Method

Infant and child participants were recruited primarily from letters sent to local families. Adult participants were university students who responded to posted notices. There were 733 participants; 270 were 6.5 months old (+/-1 month), 245 were 2 years old (+/-1 month), 109 were 5 years old (+/-3 months), and 109 were approximately 20.5 years old (17-25 years). All 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, 234 were excluded from the final sample because of failure to meet a training criterion (75 and 27 from the 6.5-month and 2-year group, respectively), 111 because of side biases (56 and 55 from the 6.5-month and 2-year group, respectively); and 21 because of fussing during the session (all from the 2-year group).

Apparatus

The apparatus was identical to that used in Schneider et al. (1989). The 1/3-octave signals were produced by filtering the output of a white noise generator (General Radio, model 1381) with a Bruel and Kjaer bandpass filter (model 1617). Third-octave bands were chosen as signals to provide good frequency specificity while still minimizing amplitude variation at different positions in the sound field (Dillon & Walker, 1982) and to keep testing conditions as close as possible to those in Schneider et al. (1989). The rate of decrease in energy on either side of the band was greater than 60 dB/octave. During signal presentation, the 1/3-octave band was added to the background noise over one of the speakers.

The narrow-band background noise was produced by filtering an independent white noise generator (General Radio, model 1381) with a programmable Wavetek (System 716) bandpass filter. The rate of decrease in energy on either side of the band was 115 dB/octave. We set the filter to a wideband (0.1 to 20 kHz) and used an equalizer (Altec-Lansing 729) to compensate for the acoustic properties of the sound-attenuating chamber so as to provide an appropriate noise in the sound field with a relatively flat spectrum. Calibrations of this background noise showed that the sound pressure levels obtained at 1/3-octave intervals for both left and right speakers were within 1.5 dB of the expected levels for white noise (see Figure 1 in Schneider et al., 1989). During a session, the upper and lower cutoff frequencies of the Wavetek filter were set to present the desired narrow-band noise (see Table 1). The spectrum level of the masking noise was set to 0 dB for the 6.5-month-olds and to 10 dB for the 2- and 5-year-olds and for adults. Electronic switches (rise/fall times = 40 ms) were used to turn the signals and maskers on and off.

1 In calculating these theoretical bandwidths, we used Scharf’s (1970) estimates of critical bandwidth and assumed that subjects were attending to critical bands centered on the cutoff frequencies of the noise signal. More effective listening strategies (see Discussion) or the use of smaller estimates of critical band size (see Green, 1988) would result in a smaller estimate of the theoretical bandwidth for these 1/3-octave-noise signals. Thus these values of 326 Hz at 0.8 kHz and 1.62 kHz at 4 kHz should be considered upper boundaries on the effective size of the critical band.
Table 1
Nominal Bandwidths (NB) and Equivalent Rectangular Bandwidths (ERB) in Hz for Maskers Centered at 0.8 and 4 kHz

<table>
<thead>
<tr>
<th></th>
<th>0.8 kHz</th>
<th></th>
<th>4 kHz</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>ERB</td>
<td>NB</td>
<td>ERB</td>
<td>NB</td>
</tr>
<tr>
<td>0</td>
<td>84</td>
<td>0</td>
<td>421</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>185</td>
<td>400</td>
<td>823</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>285</td>
<td>800</td>
<td>1224</td>
<td>0</td>
</tr>
<tr>
<td>300</td>
<td>385</td>
<td>1200</td>
<td>1625</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>486</td>
<td>1600</td>
<td>2027</td>
<td>0</td>
</tr>
<tr>
<td>600</td>
<td>686</td>
<td>2000</td>
<td>2428</td>
<td>0</td>
</tr>
<tr>
<td>800</td>
<td>887</td>
<td>2400</td>
<td>2829</td>
<td>0</td>
</tr>
<tr>
<td>9800</td>
<td>10370</td>
<td>9800</td>
<td>10370</td>
<td>0</td>
</tr>
</tbody>
</table>

Note. Upper and lower cutoff frequencies for all but the largest nominal bandwidth were symmetrically located above and below the signal frequency. The largest band at both frequencies had nominal cutoffs of 0.2 and 10 kHz.

The loudspeakers were placed in an Industrial Acoustics sound-attenuating chamber (double-wall, measuring 3 × 2.8 × 1.8 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 also used for reinforcement during the second session for the 5-year-old children. The viewing screen was blacked out during the periods of nonreinforcement.

Calibration

Sound pressure levels were calibrated with a Brüel 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-inch (1.3-cm) microphone directed at the loudspeaker producing the signal. Sound pressure measurements were taken within a 1-square-foot (approximately 0.1 m²) area centered on the approximate location of a subject's ear for signals and maskers. Signal/masker ratios (in dB) were determined at the center of this 1-square-foot (0.1 m²) area and at eight other points along the perimeter. The standard deviation of these signal/masker ratios for both 0.8- and 4-kHz signals was ≤1 dB for all but the broadband masker, in which the standard deviation was about 1.6 dB. Thus, head movements in the younger subjects were unlikely to have exerted a significant effect on the results.

The signal levels used were determined on the basis of pilot testing and were the same for all bandwidths tested. They were 30, 38, 46, and 54 dB for both the 0.8- and 4-kHz signals for nonadult participants. Signal levels for adults were 16 dB lower than those for children at 0.8 kHz, and 12 dB lower than those for children at 4 kHz.

Table 1 shows both the nominal bandwidths used and their equivalent rectangular widths. Because the rate of attenuation on either side of the nominal cutoff frequencies was not infinite, the actual power in the band was greater than \(N_0 f_2 - f_1\), where \(N_0\) is the average power in a one-cycle wideband noise and \(f_1\) and \(f_2\) are the nominal lower and upper cutoff frequencies of the band. Therefore, equivalent rectangular bandwidths were calculated. The equivalent rectangular bandwidth is the width of a hypothetical rectangular band of noise with the same gain at its center frequency as the actual band of noise, and whose total power is the same as the power in the noise band actually presented to the listeners. The equivalent rectangular bandwidths for the 0.8 and 4 kHz 1/3-octave bands were 185 and 926 Hz, respectively.

Procedure

During the test session, the 5-year-old children and the 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 the 6.5-month-old infants and 2-year-old children, 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.

A within-subjects design was used with four levels of signal intensity crossed with eight bandwidths of noise to yield 32 Signal Intensity × Bandwidth combinations. We tested each of these 32 combinations for a single signal frequency within a single session. Whenever possible, we tested each subject in two sessions with signal frequency changed between sessions. Of the 6.5-month-olds, 70 completed both sessions, 37 completed only one session at 0.8 kHz, and 32 completed only one session at 4 kHz. Data were recorded for all subjects tested at a particular frequency. Of the 2-year-olds, 59 completed both sessions, 41 completed only one session at 0.8 kHz, and 42 completed only one session at 4 kHz. Of the 5-year-olds, 103 completed both sessions, 3 completed only one session at 0.8 kHz, and 3 completed only one session at 4 kHz. Of the adults, 102 completed both sessions and 7 completed only one session at 0.8 kHz. The center frequency of the signal (0.8 or 4 kHz) was changed across sessions.

Because there were only 32 trials per session, each listener experienced each level of Bandwidth × Intensity combination only once in each session. A trial began with the simultaneous presentation of the narrow-band masker over the left and right loudspeakers. The experimenter presented a signal over one of the loudspeakers by pressing a button only when the masker was on and the child was looking directly ahead. Thus, the delay between masker onset and signal onset was variable and was determined by the subject's head orientation. The signal and masker remained on until the listener responded, either by a headturn of at least 45°, in the case of younger children, or by a button press, in the case of older children and adults. Responses terminated the masker and signal, with correct responses resulting in reinforcement (the presentation of an animated toy) and incorrect responses producing a 4-s time-out before the beginning of the next trial.

To ensure that all of the infants and children tested could perform the task of identifying the location of the signal, we used a training criterion with sound intensity well above threshold. Initially, the signal (either a 0.8 or 4-kHz 1/3-octave band noise) was presented at an intensity of 65 dB in the presence of a narrow-band masker (750 to 850 Hz for the 0.8-kHz signal and 3.8 to 4.2 kHz for the 4-kHz signal). The same narrow-band masker was used throughout training. During the training period, we alternated the location of the signal on successive trials between left and right loudspeakers until the child made four successive correct responses. We have found this alternation procedure to reduce 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.) We then reduced the intensity by 10 dB and continued the alternation until the listener 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.

The test phase, which consisted of 32 trials, immediately followed the training phase. Each trial consisted of a single instance of one of the masker bandwidths combined with one of the signal intensities. To preclude the occurrence of several successive instances of the lowest intensity, the stimuli were randomized as follows. Eight random permutations of the four intensity levels were generated (for each listener) so that all four intensity levels were represented in a block of four trials. The narrow-band masker associated with each of these intensity levels was randomly assigned (again for each subject), with the constraint that each masker appeared only once combined with a given 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.

Listeners who showed an extreme 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. All participants eliminated on the basis of side bias were from the 6.5-month- and 2-year-old groups.

Note that, in this procedure, the bandwidth of the masker changed from trial to trial, requiring that the masker be turned on and off for each trial. In our previous masking studies (Bull et al., 1981; Schneider et al., 1989), the masker was on continuously during the entire session. Changing the masker was disruptive for the youngest participants, as indicated by their high failure rates in the training phase. For example, 27% of the 6.5-month-olds failed to meet our standard training criterion as compared with 19% of the 6.5-month-olds in the Schneider et al. (1989) experiment. Furthermore, 28% of the infants who met the training criterion in this study were subsequently eliminated because of side biases in the test phase as compared with 10% in the Schneider et al. (1989) experiment, again indicating that the younger listeners were experiencing some difficulty with the procedure. Nevertheless, 51% of the 6.5-month-olds and 58% of the 2-year-olds successfully completed the requisite test sessions.

Results

In Figure 2, the percentage of correct responses is plotted as a function of the intensity of the 0.8-kHz signal for each of the eight bandwidths of the masker for the 6.5-month-olds and adults. (The bandwidths of the maskers are specified in terms of the equivalent rectangular bandwidths.) For both infants and adults, the psychometric functions were displaced to the right as bandwidth increased until it exceeded about 400 Hz, whereupon further increases in bandwidth produced no further shifts in the psychometric functions. A similar pattern held at the other ages, as well as for all ages tested with the 4-kHz signal.

The psychometric functions were used to determine thresholds for both signal frequencies at each masker bandwidth for the four age groups. Threshold was defined as the intensity corresponding to 68% correct. We chose this value because at some of the larger bandwidths used with the 4-kHz signal, performance never reached 75% correct at the highest intensity values tested. Use of a 68% criterion permitted the threshold value to be determined by linear interpolation between the two intensities on either side of this point in all but two cases (5-year-olds: 4-kHz signal, masker bandwidth 10.4 kHz; adults: 4-kHz signal, masker bandwidth 2.8 kHz). Because the psychometric functions approached but did not reach 68% for these two cases, thresholds were defined as the highest stimulus intensity presented.

Figure 3 (lower right panel) shows how threshold changes as a function of masker bandwidth for adults tested with the 0.8-kHz signal. Figure 4 (lower right panel) plots the equivalent function for the 4-kHz signal. In each figure, the ordinate is the threshold signal-to-noise ratio (total signal power/N0) expressed in dB. For the 0.8-kHz signal, a horizontal straight line was fit to threshold values for masker bandwidths larger than 326 Hz, the predicted upper limit for the critical band in this experiment. For bandwidths less than that value, a second straight line was fit to the data, with the constraint that the line must intersect the horizontal portion of the function at 326 Hz. A similar procedure with a transition bandwidth of 1.62 kHz was used to fit a function to the data in Figure 4. The adult data in Figures 3 and 4 correspond quite closely to the expected pattern.

The data for the three younger age groups are also plotted along with the data from adults in Figures 3 and 4 for the 0.8- and 4-kHz signals, respectively. In both cases, horizontal lines were fit to the threshold values when maskers exceeded the predicted upper limit for the critical band. Straight lines intersecting these horizontal lines at the calculated critical bandwidth were fit to the threshold values for maskers less than the calculated critical widths. Although the data were more variable at the younger ages, these theoretical functions provide a good description of the manner in which thresholds change as a function of bandwidth. For maskers of less than critical width, thresholds increased with bandwidth at all ages and at both signal frequencies, with the exception of 6.5-month-olds at 4 kHz. For the 6.5-month-olds at 4 kHz, thresholds for subcritical bandwidths, although less than those for supracritical widths, did not increase systematically with bandwidth. Thresholds for supracritical widths were roughly constant for all ages at both signal frequencies.

Discussion

Size of the Critical Band for 1/3-Octave Band Signals

Figures 3 and 4 show that signal threshold rises with masker bandwidth until the masker bandwidth exceeds the predicted upper limit for the critical band, after which no further increases in threshold are evident. The absence of further masking after the upper limit is exceeded confirms that energy in the masker that is spectrally remote from the signal is ineffective in masking the signal. It should be noted, however, that for subcritical masker bandwidths, threshold increases much more rapidly with bandwidth than one would expect if detection of the signal were based on a critical band centered on the signal. However, if subjects listen in critical bands.

2 Assume a masker whose bandwidth was identical to the critical band. If we reduce the masker bandwidth by half, we reduce the power in the critical band by 3 dB, which, in turn, should lower the threshold for the signal by 3 dB. If the effective bandwidth is 326 Hz in Figure 3, then signal threshold for a masker bandwidth of 163 Hz should be reduced by 3 dB. Similarly, signal threshold for a masker whose width is 81.5 Hz should be 6 dB lower than for a broadband masker. In Figure 3, however, the threshold for an 81.5-Hz band is considerably more than 6 dB lower than that for a broadband noise.
above or below the center frequency of the signal, quite rapid increases in threshold with masker bandwidth are possible. To see why this would be the case, consider what happens when the bandwidth of the masker is less than the bandwidth of the signal. Figure 5 shows the spectral density functions for a rectangular masker (bandwidth = 84 Hz) and for a 1/3-octave 0.8-kHz signal (bandwidth = 185 Hz). Note that a considerable portion of the energy in the signal falls outside of the masker bandwidth. Imagine a rectangular critical band whose upper frequency is set to the lower edge of the masker. Such a critical band would not be affected by the energy in the masker because all of the energy in the masker is at frequencies above the range of this critical band. Therefore, as long as the energy in the signal falling within this critical band exceeded that required for absolute threshold, detection would occur. Figure 6 (upper panel) plots the signal-to-noise ratio required for detection within this critical band as a function of the bandwidth of the masker for widths up to 185 Hz. Above 185 Hz, it is assumed that the signal-to-noise ratio required for detection is constant, an assumption consistent with a critical band whose width is less than that of 1/3-octave signal. Note that below a masker bandwidth of 185 Hz (the width of the signal), the function rises steeply with bandwidth, much more steeply than the actual data points plotted in this figure.

Figure 6 shows that off-frequency listening should produce a sharp rise in threshold as the bandwidth of the masker approaches the bandwidth of the 1/3-octave signal. One reason why the predicted rise in threshold is much steeper than

3 At 0.8 kHz, the ideal 1/3-octave filter is a rectangular band of energy whose width is 185 Hz (713–898 Hz). Assume an 84-Hz rectangular masker centered at 0.8 kHz. Assume, further, a critical band whose upper boundary occurs at 758 Hz. None of the energy in the masker falls within this critical band, but (758 – 713)/185 = 9/37 of the energy in the 1/3-octave signal falls within this band. Let y dB SPL be the threshold value for a pure tone centered in this band. It follows that the sound pressure for a 1/3-octave band of noise (centered at 0.8 kHz) would have to be y + 10 log(37/9) dB to ensure that the energy from the signal falling into this critical band reached threshold. (We assume here that a narrow-band noise exactly filling the critical band would be at threshold when its power equals the power in a pure tone at threshold.) In general, the intensity required for threshold for the 1/3-octave band noise would be y + 10 log(185/800 – MBW/2 – 713), where y is the threshold for a pure tone centered in a critical band whose upper boundary is 800 – MBW/2 Hz, where MBW is the bandwidth of the masker. Note that this model represents the ideal situation for ideal (i.e., rectangular) signals and noise. Pure-tone thresholds in the sound field were taken from Robinson and Whittle (1964).
the actual rise (see Figures 3 & 4) is due to the fact that our masker and signal bands are not really rectangular. Figure 7 plots the actual spectral density functions for the 0.8 kHz, 1/3-octave band signal and for two bandwidths of masker (nominal bandwidths of 0 and 100 Hz). Note that if the upper edge of the critical band is placed on the nominal lower cutoff frequency in the masker, some of the energy in the masker will fall into that critical band. Therefore the energy in the signal falling within this critical band will be partially masked by the energy in the masker that also falls within this band. The upper edge of the critical band, however, can be progressively lowered until the amount of energy in the critical band due to the masker is decreased to the point at which it is no longer an effective masker. In plotting the predicted function in the lower panel of Figure 6, we located the critical band so that the energy falling within it from the masker is just below threshold for effective masking. We then adjusted the intensity of the 1/3-octave signal so that the amount of energy from the signal falling within that critical band was just at absolute threshold. The signal intensity (in terms of signal-to-noise ratio) that would produce a threshold response in this critical band is shown in the lower panel of Figure 6 along with the actual data points for that experiment. A comparison of upper and lower panels shows that the nonrectangular nature of the actual bandwidths will affect the rate at which the threshold for the signal increases with bandwidth. Moreover, the actual rate of increase with bandwidth will be affected by random noise in the system and may not be as steep as the theoretical calculations in Figure 6 would indicate.

Figure 6 shows that off-frequency listening will produce rapid increases in masked threshold until the bandwidth of 4. It is generally assumed that energy in a critical band is no longer effective in masking a pure tone at its center when the total energy from the masker falling into that critical band is less than or equal to the energy of a threshold pure tone at the center of the band. In deriving the predicted function in the lower panel of Figure 6, for each masker bandwidth, we searched for the critical band such that the energy falling in that critical band from the masker just equaled the threshold energy for a pure tone in the center of that band. A linear interpolation applied to the data of Robinson and Whittle (1964) was used to determine the threshold value for a pure tone at the center of the band. A linear interpolation of the data of Scharf (1970) was used to determine the bandwidth of the critical band in that frequency region. The spectral density functions of Figure 7 were used to determine the amount of energy falling into that critical band from both the signal and the masker. The predicted threshold for the 1/3-octave signal was taken to be $y + 10 \log(x/\zeta)$, where $y$ is the estimated threshold value for the pure tone at the center of the critical band, $x$ is the total energy in the 1/3-octave signal, and $\zeta$ is the energy in the 1/3-octave signal between $f_s$ and $f_r$, where $f_s$ and $f_r$ are the lower
the masker exceeds the bandwidth of the signal. If the size of the critical band is less than the bandwidth of the signal, then no further masking should occur once the bandwidth of the masker exceeds the bandwidth of the signal. The obtained functions for adults indicate, however, that the effective size of the critical band is larger than the bandwidth of the 1/3-octave signal but does not exceed the upper boundary suggested by the arguments presented in the introduction. Therefore, energy within half a critical bandwidth of the upper and lower cutoff frequencies of 1/3-octave signals appears to be effective in masking those signals; energy falling outside of this region is ineffective.

Developmental Changes in Critical Band Size

In Figures 3 and 4, the same values for the effective critical band were used to derive the straight-line functions fit to the data. An examination of Figures 3 and 4 reveals that the fit of the functions to the data is not as good for infants and children as it is for adults. At 4 kHz, the intersecting straight-line functions account for 49%, 82%, 90%, and 98% of the variance in thresholds for the 6.5-month-old, 2-year-old, 5-year-old, and adult participants, respectively. At 0.8 kHz, the same pattern holds in that the function accounts for a greater proportion of the variance in the adult data (73%, 69%, 81%, and 77% of the variance for 6.5-month-old, 2-year-old, 5-year-old, and adult participants, respectively). The better fit for adults might arise because their performance is less variable than that of infants and children or because the effective critical band is larger in children than in adults.

We evaluated the latter possibility in two ways. First, by visual inspection of Figures 3 and 4, we attempted to pinpoint the exact bandwidth at which there is no further increase in thresholds for the younger listeners. An examination of Figure 3 shows no clear evidence of further increases in threshold as bandwidth increases beyond 500 Hz. This impression was confirmed by determining the best-fitting two-part functions to the data in Figure 3. The two-part function consisted of a

---

4 Given off-frequency listening, we would not expect our measure of the critical band to be smaller than the width of the 1/3-octave signal. Thus, even though other investigators (see Green, 1988, for a summary) have arrived at critical bands less than half those suggested by Schair (1970) in situations that are similar to ours, our data cannot address this issue.
linear ramp that ended at the effective critical bandwidth and a horizontal section that continued beyond that bandwidth. The value of the effective critical bandwidth was varied systematically until a value was found for which the sum of squared deviations of the data points from the function was at a minimum. The largest best-fitting effective critical band was 485 Hz for 5-year-olds. Thus, a least-squares analysis supports the visual impression that thresholds are independent of bandwidth for masker bandwidths greater than 500 Hz. If we assume that 500 Hz is an upper boundary on the effective critical band for the younger age groups, then the effective critical band for the younger ages is no more than 54% larger than the effective critical band of adults.

Visual inspection of Figure 4 indicates that there are no further increases in threshold beyond 2 kHz at any age. The transition points for the best-fitting functions for all but the 6.5-month-olds are less than 2 kHz. (The best-fitting function for the 6.5-month-olds has a maximum of 2.4 kHz, which can be attributed to the fact that the thresholds for the first three bandwidths do not increase with bandwidth.) Thus, results at this frequency indicate that, for children 2 years and older, the size of the effective critical band is, at most, 50% larger than it is for adults.

Perhaps developmental changes in the size of the critical band depend, in part, on certain features of our measurement procedure, which requires judgments of localization as opposed to detection. It is possible, in principle, for detection and localization thresholds to differ and for the extent of such differences to depend on the age of the listener and the frequency of the signal. Trehub and Schneider (1987) demonstrated, however, that in a quiet background, listeners 1, 3, 5, and 20 years of age 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). Schneider et al. (1989) have reported similar findings for the localization of octave-band signals in broadband noise. Thus the available data suggest that, for band-limited noise, detection and localization thresholds are comparable, and are independent of stimulus frequency.

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 there was some degree of binaural unmasking. Two factors suggest, however, that the contribution of unmasking to the observed developmental changes would be negligible. First, very little unmasking occurs when the spectrum level of the masker is as low as in the present experiment (see Durlach & Colburn, 1978, p. 437). Second, Nozza (1987) and Schneider, Bull, & Trehub (1988) have shown that binaural unmasking occurs in infants, but 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.

The present results are consistent with the findings of Oshio (1985) and Irwin et al. (1986) in indicating that the width of the critical band changes very little from infancy to adulthood. If this is true, then how do we account for the higher masked thresholds in children compared with adults? Even if we assume that the infant's critical band is 50% larger than that of the adult, this increase in the critical band size should result in a mere 1.75-dB increase in threshold. In the present experi-
Figure 7. Spectral density for 1/3-octave, 0.8-kHz signal and for two maskers with nominal bandwidths of 0 and 100 Hz.

iment, however, as in others (Bull et al., 1981; Irwin et al., 1986; Nozza & Wilson, 1984; Olsho, 1985; Schneider et al., 1989; Trehub et al., 1981), the child–adult difference in masked thresholds is on the order of 8–15 dB. Clearly, changes in critical band size can account for no more than 1–2 dB of this difference.

Schneider et al. (1989) argue that the most likely source of these developmental changes is a nonlinear change in the representation of intensity, given that the size of the critical band does not change substantially with age. Their argument is based on the following observations. First, linear changes at any stage in the auditory processing chain cannot account for changes in masked threshold. For example, consider a simple change in the mechanical efficiency with which signals are delivered to the basilar membrane. If the efficiency, say, of the outer and middle ear improves by 10 dB from childhood to adulthood, this improvement would not change the signal-to-noise ratio in a masking experiment because the improved efficiency would enhance both signal and 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, one can conclude that linear changes in sensitivity could not affect masked threshold because such changes leave the signal-to-noise ratio unchanged.

Child–adult differences could also be due to differential motivation and attention. However, differential attention should affect not only the threshold but also the slopes of the psychometric functions. But Schneider et al. (1989) found no differences in the slopes of the psychometric functions between children over 1 year of age and adults. This finding, in conjunction with the fact that highly motivated older children could not match adult performance, suggests that attention and motivation cannot account for much of this adult–child difference.

If linear changes in sensitivity, motivational and attentional factors, and changes in critical band size do not account for the observed differences in masked threshold, then the source of the differences must lie in nonlinear changes in signal processing. Because the peripheral auditory system is essentially linear, the locus of these nonlinear changes is likely to be found in more central processes. It would be of considerable interest to explore the nature of these changes and their relation to maturational changes in the nervous system.

References


Schneider, B. A., & Trehub, S. E. (1985). Behavioral assessment of basic auditory abilities. In S. E. Trehub & B. A. Schneider (Eds.),


Received October 4, 1988
Revision received June 16, 1989
Accepted July 19, 1989