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# High-Level Psychophysical Tuning Curves: Simultaneous Masking With Different Noise Bandwidths

**David A. Nelson**
**Todd W. Fortune**
*Hearing Research Laboratory*
*Departments of Otolaryngology and Communication Disorders*
*University of Minnesota, Minneapolis*

Simultaneous-masked psychophysical tuning curves were measured with narrow-band noise maskers varying in bandwidth from 40 Hz to 800 Hz to determine the masker bandwidths at which combination-band detection cues no longer influence tuning-curve shapes. Tuning curves were obtained at 1000 and 4000 Hz from normal-hearing listeners using high-level (60 dB SPL) probe tones in quiet and in the presence of a broadband background noise to eliminate combination bands and other off-frequency listening cues that exist at high levels. High-level tuning curves revealed notches on the low-frequency sides. Those notches were eliminated with broad-band background noise, which indicates that combination bands can strongly influence the shapes of high-level tuning curves obtained with narrow-band maskers, primarily by steepening the low-frequency and tail slopes. Combination-band detection cues had a stronger influence at 4000 Hz than at 1000 Hz. As masker bandwidth increased, combination bands had less influence on tuning-curve shapes. These results suggest a possible relation between masker bandwidth and auditory critical bandwidth: combination bands affected the low-frequency sides of the tuning curves only when the masker bandwidth was less than the auditory critical bandwidth.

**KEY WORDS: frequency resolution, high sound pressures, sensorineural hearing loss, cochlear hearing loss, psychophysical tuning curves**

In a companion paper, Nelson and Fortune (1991) showed that combination-band detection cues can strongly influence the shapes of high-level simultaneous-masked psychophysical tuning curves (PTCs). Using 100-Hz-wide noise bands as maskers, they showed that the influence of combination-band detection cues on the shapes of high-level PTCs depended on test frequency. At 1000 Hz, PTC shapes changed only slightly when a background noise was added to mask combination-band detection cues. At 4000 Hz, the addition of a background noise eliminated large "notches" on the low-frequency sides of the PTCs and flattened the shapes of the PTCs. It was apparent that combination-band detection cues strongly affected PTC shapes at 4000 Hz, but had less of an effect at 1000 Hz. The reason for this difference across test frequency is not immediately clear, although it was noted that at the higher test frequency the masker bandwidth was a much smaller proportion of auditory critical bandwidth. For example, at 1000 Hz where combination bands did not influence PTC shape, the 100-Hz-wide masker was approximately 62% of auditory critical bandwidth (Zwicker & Terhardt, 1980). At 4000 Hz, where the detection of combination bands sharpened the PTC considerably, the 100-Hz-wide masker was only 15% of auditory critical bandwidth. It may be that the relative size of masker bandwidth and auditory critical bandwidth is the principal determinant of whether or not combination-band detection cues will influence PTC shape. If so, then the use of a masker bandwidth that is some proportion of the normal auditory critical bandwidth might provide a convenient and clinically practical way to measure tuning at high levels without the

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influence of combination bands. To investigate this possibility further, PTCs were obtained from normal-hearing listeners using narrow-band maskers that ranged in bandwidth from less than the auditory critical bandwidth to greater than the auditory critical bandwidth. PTCs were obtained in quiet and in the presence of a broad-band background noise adjusted to mask the most salient combination bands.

## Methods

Simultaneous-masked PTCs were obtained from 3 normal-hearing listeners with thresholds for 200-ms tone bursts between 125 and 8000 Hz that were less than 10 dB HL (ANSI, 1969). Listeners were tested at 1000 Hz and 4000 Hz using narrow-band (NB) maskers and high-level probe tones. One listener was tested at both frequencies the other two were tested only at one frequency. The high-level probe tones were presented at 60 dB SPL. Narrow-band maskers had bandwidths of 40, 200, and 400 Hz at a test frequency of 1000 Hz; and 40, 200, 400, and 800 Hz at a test frequency of 4000 Hz. The narrow-band maskers were produced by multiplying a low-pass noise with a sinusoidal carrier. Cut-off frequencies for the low-pass noises (3-dB down) were half the desired bandwidth of the NB masker. Filter slopes for the low-pass noises were 96 dB/octave. Masker frequencies for the NB maskers were specified as the edge frequency of the noise (at −3 dB) that was nearest to the probe frequency.

Maskers were gated on for 500 ms and probe stimuli were gated on for 250 ms during the temporal center of the masker. Both stimuli were gated with a 10-ms squared cosine ramp. Pure-tone probe tones and the sinusoidal carriers for the masking bands were produced by a digital-to-analog converter running at a sample rate of 20 kHz and low-pass filtered at 4.7 kHz. The low-pass noises were multiplied with the carrier tones using an analog multiplier. Whenever masker and probe were at the same frequency, the phase of the probe tone relative to the phase of the sinusoidal carrier for the NB masker was 90°. Masker levels and probe levels were attenuated with programmable attenuators controlled by a computer.

During the broad-band background noise (BBN) condition, a white noise ranging from 100–10,000 Hz was gated concurrently with the masker. The level of the BBN background was adjusted to a level that was 10 dB less intense than the level of noise required to mask the 60-dB-SPL probe tone. Independent noise generators were used to construct the BBN background and the NB maskers.

A three-interval three-alternative forced-choice adaptive procedure was used to adjust the level of the masker required to mask the fixed-level probe tone. Initial step sizes of 8 dB were used to reach the target region quickly, and were ignored for threshold calculations. After two reversals, the step size was reduced to 2 dB. Masked thresholds were estimated by averaging the last 10 out of 12 reversals in an adaptive procedure that used a 2-up/1-down stepping rule to track 71% correct. Correct answer feedback was given.

Stimuli were delivered to a single ear via a TDH-49 earphone mounted in an MX-41/AR cushion. The listener sat in a sound-treated booth. Test sessions lasted about 30–45 minutes, after which time the listener took a short break. All thresholds reported here are the mean thresholds from at least three threshold estimates for each condition. Ninety-one percent of the standard deviations of those means were less than 3 dB, 96% were less than 4 dB.

Each tuning curve was fitted, using least-squares procedures, with three straight-line segments to estimate various tuning-curve characteristics. The procedure for fitting the curves and specifying the various tuning-curve characteristics is described in detail in Nelson and Fortune (1991). The three-segment fits are shown on the graphs by solid lines. Masker frequencies not included in the fits are connected by dashed lines.

## Results and Discussion

### *Masker-Bandwidth Effects of 1000 Hz*

Figure 1 shows the results at 1000 Hz. Two tuning curves are shown in each panel. For each of three masker bandwidths, PTCs obtained in quiet (inverted triangles) are compared with PTCs obtained in a background noise (squares).

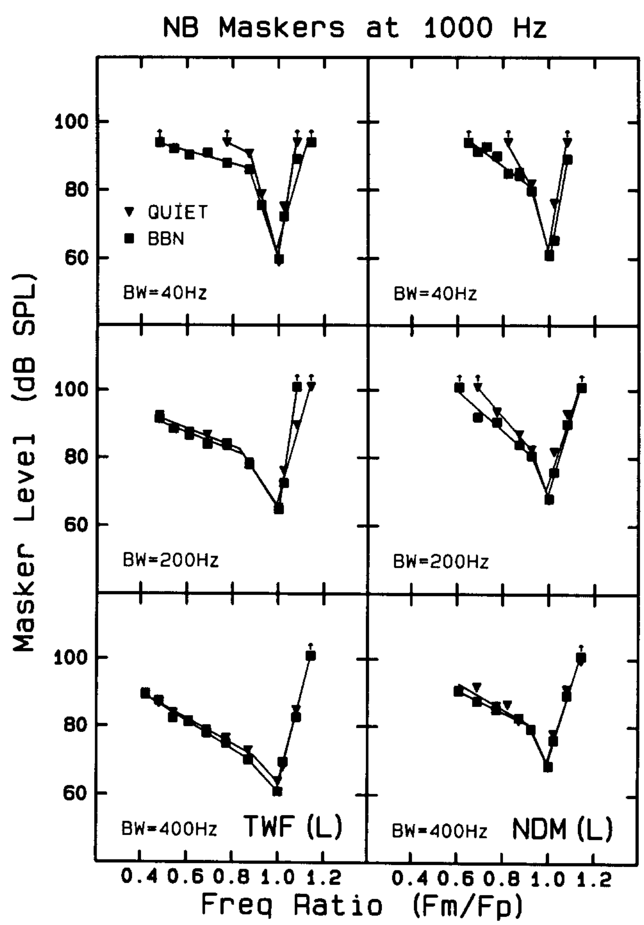


**FIGURE 1. High-level PTCs at 1000 Hz obtained with 40-, 200-, and 400-Hz-wide narrow-band maskers from 2 normal-hearing listeners. PTCs in quiet (triangles) are compared with PTCs in a BBN background to mask combination-bands and off-frequency listening.**

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Results from the left ear of Subject TWF are shown in the left column of panels, results from the left ear of Subject NDM are shown in the right column of panels. In each panel, the differences between the two curves show the extent to which, in quiet, the presence of combination-band detection cues resulted in higher masker levels on the low-frequency side of the tuning curve.

For the 40-Hz-wide NB maskers, comparisons of tuning curves obtained in quiet with those obtained in the BBN background indicate that combination-band detection cues influenced the shapes of the tuning curves. This is shown in the top of two panels of Figure 1 on the low-frequency sides of the tuning curves for both subjects. Higher masker levels were required to mask the probe tone in the quiet background than in the BBN background condition. At some masker frequencies, the limits of the equipment were reached in the quiet condition but not in the BBN background condition. Those limits were also reached at lower masker frequencies in the BBN background than in quiet. For both conditions, testing at masker frequencies further removed from the probe frequency did not yield any masker-level thresholds below the limits of the equipment.

This indicates that the subjects heard a cue in the quiet condition, which was not available during the BBN background. The most likely cue is from the detection of combination bands at $(n + 1)f_1$-$nf_2$ frequencies, where $f_2$ is the frequency of the probe tone and $f_1$ frequencies are the individual components of the NB masker, which lead to combination bands of order $n$ below the NB masker. The most likely combination band is the first order cubic-difference band at $2f_1$-$f_2$ frequencies, because it is the most salient (Greenwood, 1971, 1972). However, higher-order combination bands may also have contributed to the results (Kramer & Greenwood, 1973).

For the 200-Hz-wide NB maskers, shown by the middle row of panels, the influence of combination-band detection cues was not obvious. In Subject TWF, there were no differences between the masker levels required on the low-frequency side of the tuning curves in quiet versus the BBN background. In Subject NDM, there were some small differences, but they were much smaller than those seen for 40-Hz-wide NB maskers and occurred much further up on the tail of the tuning curve.

For the 400-Hz-wide NB masker, shown by the lower row of panels, we see that there were no differences between the tuning curves obtained in quiet or in the BBN background. At this bandwidth, neither subject heard any combination-band detection cues that influenced the shape of the tuning curve obtained in quiet.

These results are consistent with the results for 100-Hz-wide NB maskers reported previously (Nelson & Fortune, 1991). Very little difference was demonstrated between PTCs obtained in quiet and PTCs obtained in background noise for the 200- and 400-Hz-wide NB maskers (middle and bottom panels of Figure 1). As shown in Table 1, these observations are supported by similar tail slopes, $Q_{10dB}$ values, and Weber fractions for PTCs obtained in quiet and in the BBN background. Both of these NB maskers had bandwidths that were greater than critical bandwidth at 1000 Hz (about 160 Hz, from Zwicker & Terhardt, 1980), and the resulting PTCs did not demonstrate an appreciable influence of combination-band detection cues.

By contrast, the PTCs at 1000 Hz for the 40-Hz-wide NB maskers, with bandwidths about 25% of auditory critical

**TABLE 1. Tuning-curve characteristics for high-level PTCs (60-dB-SPL probe tones) obtained with narrow-band noise maskers of different bandwidths at 1000-Hz and 4000-Hz probe frequencies.**

| Background condition | Masker bandwidth | $L_p$-$L_m$ | $S_t$ * | $S_{lf}$ * | $S_{hf}$ * | $Q_{10dB}$ |
|---|---|---|---|---|---|---|
| Mean PTC Characteristics at 1000 Hz ($N$ = 2) | | | | | | |
| Quiet | 40 Hz | 0.15 | −29.9 | −131.5 | 404.2 | 15.8 |
| BBN | 40 Hz | −0.22 | −13.7 | −113.1 | 301.5 | 12.8 |
| | | | Change factor (BBN at 60 vs. Quiet at 60) = | | | −0.19** |
| Quiet | 200 Hz | −6.56 | −20.8 | −73.7 | 226.2 | 8.6 |
| BBN | 200 Hz | −6.42 | −17.4 | −67.4 | 345.4 | 9.0 |
| | | | Change factor (BBN at 60 vs. Quiet at 60) = | | | 0.05** |
| Quiet | 400 Hz | −6.04 | −15.4 | −54.2 | 238.6 | 7.1 |
| BBN | 400 Hz | −4.69 | −15.0 | −54.3 | 247.6 | 7.2 |
| | | | Change factor (BBN at 60 vs. Quiet at 60) = | | | 0.01** |
| Mean PTC Characteristics at 4000 Hz ($N$ = 2) | | | | | | |
| Quiet | 40 Hz | 1.95 | −69.6 | −94.5 | 266.8 | 11.0 |
| BBN | 40 Hz | 0.93 | −27.4 | −39.8 | 208.0 | 5.7 |
| | | | Change factor (BBN at 60 vs. Quiet at 60) = | | | −0.48** |
| Quiet | 200 Hz | −5.14 | −72.0 | −58.4 | 258.0 | 8.0 |
| BBN | 200 Hz | −4.48 | −23.3 | −42.9 | 178.3 | 5.8 |
| | | | Change factor (BBN at 60 vs. Quiet at 60) = | | | −0.27** |
| Quiet | 400 Hz | −2.63 | −60.5 | −50.1 | 267.3 | 7.2 |
| BBN | 400 Hz | −3.97 | −27.0 | −38.3 | 218.9 | 5.6 |
| | | | Change factor (BBN at 60 vs. Quiet at 60) = | | | −0.22** |
| Quiet | 800 Hz | −4.52 | −22.6 | −44.0 | 223.8 | 6.3 |
| BBN | 800 Hz | −4.35 | −22.9 | −40.6 | 274.6 | 6.1 |
| | | | Change factor (BBN at 60 vs. Quiet at 60) = | | | 0.03** |

*slopes given in dB per octave. **$Q_{10dB}$ change factor = [(BBN 60)/(QUIET 20) − 1.0]

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bandwidth, did demonstrate the influence of combination-band detection cues. For masker frequencies at 0.85Fp and below, masker levels in quiet were greater than in background noise, although the true magnitude of the differences could not be assessed because the intensity limits of the system were reached in quiet at masker frequencies below 0.7Fp. Those limits were not reached in the presence of background noise, presumably because the most salient combination-bands were masked by the background noise. Table 1 shows that $Q_{10dB}$ values were reduced by 19% and tail slopes were reduced by the BBN background to less than half of what they were in a quiet background.

These results support a relative bandwidth supposition that the amount of influence combination-band detection cues have on PTC shapes may depend upon the relative sizes of masker bandwidth and auditory critical bandwidth. The masker bandwidth that showed strong evidence of combination-band detection was only 25% of the auditory critical bandwidth at 1000 Hz. The masker bandwidths that did not show strong evidence of combination-band detection were 123% and 247% of auditory critical bandwidth.

### *Masker-Bandwidth Effects at 4000 Hz*

This proposed relationship between masker bandwidth and auditory critical bandwidth is more obvious in the results obtained at 4000 Hz, where auditory critical bandwidth is much broader (about 680 Hz, from Zwicker & Terhardt, 1980). Those results are shown in Figure 2 for 40-, 200-, and 400-Hz masker bandwidths. The differences between PTCs in quiet and background noise were appreciable at this frequency for masker bandwidths between 40 and 400 Hz, indicating that the detection cues offered by combination bands were much more salient at 4000 Hz than they were at 1000 Hz. Consequently, the shapes of PTCs in quiet were influenced more strongly by combination bands at 4000 Hz than at 1000 Hz. As indicated in Table 1, $Q_{10dB}$ values were reduced by 22%–44% and tail slopes were appreciably flattened by the introduction of the BBN background. In this case the masker bandwidths were 6%, 29%, and 59% of the critical bandwidth at 4000 Hz, for 40- 200- and 400-Hz-wide NB maskers, respectively, which supports the relative bandwidth supposition.

In Figure 2, the dependence of the apparent salience of combination-band cues upon masker bandwidth is demonstrated further at 4000 Hz by the observation that the region of the notch became smaller as the bandwidth of the NB masker increased from 40 Hz up to 400 Hz. For 40-Hz-wide maskers, the region of differences between masker levels in quiet and in background noise extended to masker frequencies well below 0.6Fp, where masker levels at the limits of the equipment could not mask the probe because of strong combination-band cues. For 200-Hz-wide maskers, the PTC tail was observable in quiet for Subject ACW(L), suggesting less salient combination bands at those masker frequencies, and in the other subject there was little change on the low-frequency side of the PTC. For 400-Hz-wide maskers, neither subject demonstrated combination-band detection at masker frequencies below 0.6Fp, but they did above 0.6Fp.

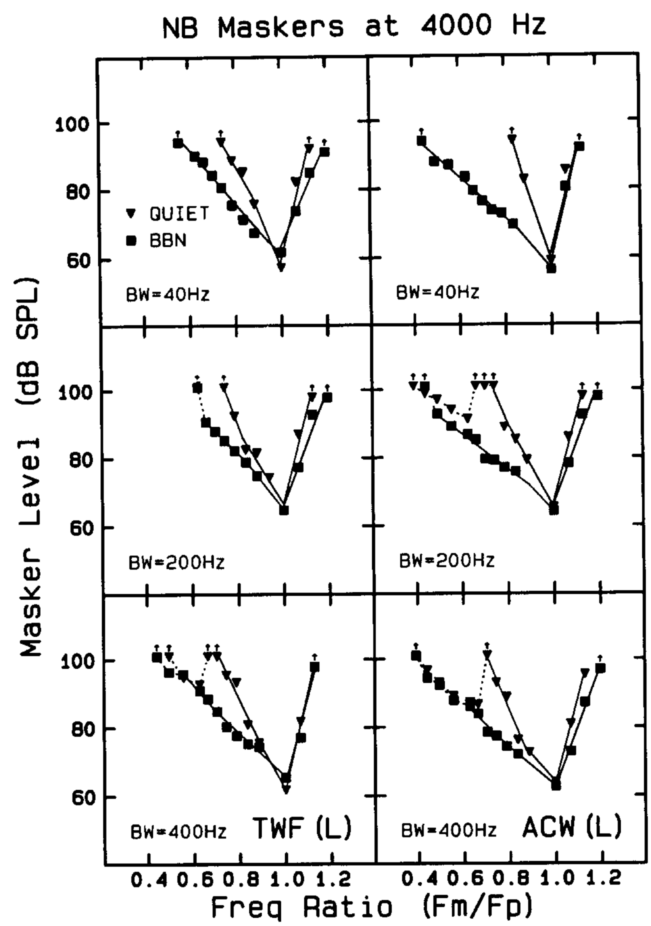


**FIGURE 2. High-level PTCs at 4000 Hz obtained with 40-, 200-, and 400-Hz-wide narrow-band maskers from 2 normal-hearing listeners. Legend as in Figure 1.**

Figure 3 shows the results for the 800-Hz-wide NB maskers. With the 800-Hz-wide NB masker there were no consistent differences between tuning curves obtained in quiet and those obtained in the BBN background. Table 1 shows that the tuning characteristics were not appreciably different for PTCs obtained in quiet or the BBN background. Essentially, there were no changes in the shapes of PTCs when the BBN

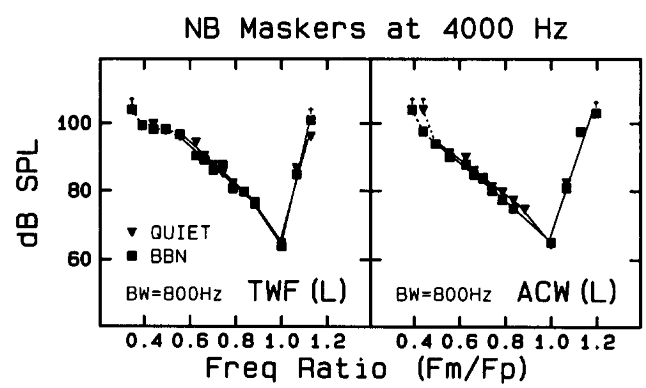


**FIGURE 3. High-level PTCs at 4000 Hz obtained with 800-Hz-wide narrow-band maskers from 2 normal-hearing listeners. Legend as in Figure 1.**

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background was presented to mask any potential combination-band detection cues. In this case, where the 800-Hz-wide NB masker was 118% of auditory critical bandwidth at 4000 Hz, there were no effects attributable to combination-band detection cues.

Here, it is important to point out that a tuning curve obtained in broad-band background noise may not be completely free from the influence of combination-band detection cues. We have shown that the most obvious effects of combination-band detection cues, those that are manifested by obvious notches on the low-frequency side of the PTC, can be removed with broad-band background noise or with a narrow-band masker wider than auditory critical bandwidth. However, the low-frequency slope of the PTC could still be influenced by the detection of higher-order combination tones at very low frequencies, where the extra-cochlear broadband masking noise is rendered less effective at masking intracochlear events by the low-frequency response characteristic of the ear. Some evidence for this word of caution can be seen on the high-frequency sides of masking patterns for supra-critical bands of noise reported by Greenwood (1971, see Figure 22). At higher masker levels, some unusual notches appeared on the high-frequency side of the masked audiogram from 1 of Greenwood's subjects when the masker was a 300-Hz-wide narrow-band noise centered at 1000 Hz.

### *Clinical Implications*

One of the motivations for this investigation was to examine simultaneous-masking measures of tuning in normal-hearing listeners, which might be used to define abnormal tuning in hearing-impaired listeners. Because hearing-impaired ears may not generate or detect combination tones (Smoorenburg, 1972), it was suggested previously (Nelson & Fortune, 1991) that estimates of normal tuning that are influenced by combination-tone or combination-band cues would not provide an appropriate comparison. A more appropriate estimate of normal tuning, one that could be used to evaluate tuning in impaired ears, would be one that is influenced very little or not at all by combination-tone or combination-band detection cues. The current results suggest that one can obtain PTCs relatively free from the influence of combination-band detection cues, if masker bandwidths wider than normal auditory critical bandwidth are used at each test frequency. Therefore, PTCs obtained with masker bandwidths wider than normal auditory critical bandwidths may provide the estimates of normal tuning needed to appropriately define abnormal tuning in cochlear-impaired listeners. This would, of course, require some estimate of auditory critical bandwidth across test frequency in normal-hearing listeners. We have used critical bandwidth estimates from the equation reported by Zwicker and Terhardt (1980), although estimates derived from the equivalent rectangular bandwidth equation reported by Moore and Glasberg (1983, 1987) might serve as well. However, it should be cautioned that it has not yet been shown that critical bandwidth estimates change as dramatically with level as suggested by PTCs obtained in the presence of background noise (Nelson & Fortune, 1991). Clearly, further research is required before this line of reasoning could result in a clinically practicable procedure for estimating abnormal tuning.

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## References

**American National Standards Institute.** (1969). *Specifications for audiometers* (ANSI S3.6-1969). New York: ANSI.

**Greenwood, D. D.** (1971). Aural combination tones and auditory masking. *Journal of the Acoustical Society of America, 50,* 502–543.

**Greenwood, D. D.** (1972). Masking by combination bands: Estimation of the levels of the combination bands $(n + 1)f_1 - nf_h$. *Journal of the Acoustical Society of America, 52,* 1144–1154.

**Kramer, F. G., & Greenwood, D. D.** (1973). Role of difference tone $f_2$-$f_1$ in masking. *Journal of the Acoustical Society of America, 54,* S42(A).

**Moore, B. C. J., & Glasberg, B. R.** (1983). Suggested formulae for calculating auditory-filter shapes and excitation patterns. *Journal of the Acoustical Society of America, 74,* 750–753.

**Moore, B. C. J., & Glasberg, B. R.** (1987). Formulae describing frequency selectivity as a function of frequency and level, and their use in calculating excitation patterns. *Hearing Research, 28,* 209–225.

**Nelson, D. A., & Fortune, T. W.** (1991). High-level psychophysical tuning curves: simultaneous masking by pure tones and 100-Hz-wide noise bands. *Journal Speech and Hearing Research, 34,* 360–373.

**Smoorenburg, G. F.** (1972). Combination tones and their origin. *Journal of the Acoustical Society of America, 52,* 615–632.

**Zwicker, E., & Terhardt, E.** (1980). Analytical expressions for critical band rate and critical bandwidth as a function of frequency. *Journal of the Acoustical Society of America, 68,* 1523–1525.

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Requests for reprints should be sent to David A. Nelson, Ph.D., University of Minnesota, Department of Otolaryngology Medical School, 2630 University Avenue, S.E., Minneapolis, MN 55414.

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