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High-Level Psychophysical Tuning Curves: Simultaneous Masking by Pure Tones and 100-Hz-Wide Noise Bands

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Simultaneous-masked psychophysical tuning curves were obtained from normal-hearing listeners using low-level (20–25 dB SPL) probe tones in quiet and high-level (60 dB SPL) probe tones, both in quiet and in the presence of a broad-band background noise. The background noise was introduced to eliminate combination tones or combination bands and other off-frequency listening cues that exist at high levels. Tuning curves were obtained using pure-tone maskers and 100-Hz-wide narrow-band noise maskers for probe tones at 1000 and 4000 Hz. High-level tuning curves for pure-tone maskers demonstrated large discontinuities or "notches" on the low-frequency sides of the tuning curves. Broad-band background noise eliminated those notches, indicating that the notches were due to the detection of off-frequency listening cues at combination-tone frequencies. High-level tuning curves for 100-Hz-wide narrow-band maskers also demonstrated notches on the low-frequency sides. Those notches were eliminated with broad-band background noise, which indicates that combination bands strongly influenced the shapes of high-level tuning curves obtained with narrow-band maskers. The influence of combination bands was dependent upon test frequency. At 1000 Hz, combination bands had very little influence on the shapes of high-level tuning curves. At 4000 Hz, where the masker bandwidth was substantially less than the critical bandwidth, combination bands strongly affected the low-frequency sides of the tuning curves. In 2 subjects tested at a probe frequency of 2000 Hz with 100-Hz-wide masking bands, combination bands also influenced the low-frequency sides of high-level tuning curves. The presence of combination-tone or combination-band cues essentially steepened the low-frequency slopes of tuning curves, resulting in sharper estimates of tuning. Comparisons of tuning curves obtained with pure-tone maskers and narrow-band maskers, in the same listeners, revealed that pure-tone maskers were more effective than narrow-band maskers when the masker frequencies were in the tail region of the tuning curve. The results of these experiments support the notion that tuning in the normal auditory system broadens notably with stimulus level, once off-frequency listening cues such as combination tones or combination bands are eliminated. The low-level simultaneously masked tuning curve demonstrates a sharp bandpass tuning characteristic, whereas the high-level simultaneously masked tuning curve in background noise demonstrates a broad low-pass tuning characteristic. It is argued that comparisons of tuning in impaired ears with tuning in normal ears should be made using estimates of tuning in normal ears that are not influenced by combination-tone or combination-band detection cues.

KEY WORDS: psychophysical tuning curves, high-level tuning, frequency resolution, sensorineural hearing loss, masking

Simultaneous-masking psychophysical tuning curves (PTCs) have frequently been used to assess frequency resolution in sensorineural hearing-impaired listeners (Carney & Nelson, 1983; Davidson & Melnick, 1988; Florentine, Buus, Scharf, & Zwicker, 1980; Florentine & Houtsma, 1983; Goldstein, Karlovich, Tweed, & Kile,

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1983; Hoekstra & Ritsma, 1977; Leshowitz & Lindstrom, 1977; Stelmachowicz, Jesteadt, Gorga, & Mott, 1985; Thornton & Abbas, 1980; Turner, Burns, & Nelson, 1983; Turner & Nelson, 1982; Tyler & Summerfield, 1980; Tyler, Wood, & Fernandez, 1983; Van Tasell & Turner, 1984; Wightman, McGee, & Kramer, 1977; Zwicker & Schorn, 1978). By necessity, high-level probe tones must be used with hearing-impaired listeners just to overcome their hearing losses. When high-level probe tones have been used to obtain PTCs from normal-hearing listeners, some investigators have found PTCs to be broader than when low-level probe tones were used (Vogten, 1978a,b; Zwicker, 1974). Because of this, concerns have arisen about how comparisons between PTCs from normal and impaired ears are made. If PTCs broaden with stimulus level in the normal-hearing ear, it would be misleading to compare (sharp) low-level PTCs obtained from normal-hearing listeners with (broad) high-level PTCs obtained from hearing-impaired listeners. It would be more appropriate to make comparisons between normal and impaired ears at equivalent levels. That is, PTCs obtained from hearing-impaired listeners using high-level probe tones should be compared with PTCs obtained from normal-hearing listeners using the same high-level probe tones.

Two investigations of PTCs in hearing-impaired listeners have attempted to make such equivalent-level comparisons. Carney and Nelson (1983) used pure-tone maskers and Stelmachowicz et al. (1985) used narrow-band noise maskers; both tested their listeners with high-level probe tones. Their results, however, led to slightly different conclusions about tuning in impaired ears.

Carney and Nelson (1983) tested their listeners with probe tones at about 60 dB SPL. They found high-frequency PTC slopes that were abnormally flat in impaired ears. They also found low-frequency PTC slopes that were flatter than normal; however, low-frequency PTC slopes in normal ears demonstrated discontinuities that were not present in impaired ears. Because of this, the authors questioned the validity of those apparent differences in low-frequency PTC slopes. Following the interpretation of Greenwood (1971) and Leshowitz and Lindstrom (1977), the presence of discontinuities in normal ears was attributed to the detection of cubic difference tones at $2f_1$-f_2 frequencies, where f_1 is the frequency of the masker (Fm), f_2 is the frequency of the probe (Fp), and $f1 < f2$. The absence of those discontinuities in listeners with cochlear dysfunction was attributed to the absence of detectable combination tones in those ears (Smoorenburg, 1972b). It was suggested that if combination-tone detection cues were not available to the normal ear, the PTC discontinuities would disappear and much broader tuning curves might result at high probe SPLs. They speculated that without the influence of combination-tone detection in normal ears, comparisons between PTCs from normal and impaired ears might only reflect significant differences in tuning on the high-frequency side of the PTC.

Stelmachowicz et al. (1985) also compared PTCs from hearing-impaired listeners with PTCs from normal-hearing listeners (Stelmachowicz & Jesteadt, 1984), using high-level probe tones. For normal ears, using 100-Hz wide narrow-band noise maskers, they found that PTCs did not change shape at high levels (Stelmachowicz & Jesteadt, 1984). They found that tuning characteristics in normal-hearing ears, such as Q_{10dB}, were relatively independent of probe level. Comparisons between PTCs from normal-hearing and hearing-impaired listeners showed significantly flatter low-frequency slopes for PTCs from impaired ears, in addition to flatter high-frequency slopes similar to those reported earlier by Carney and Nelson (1983).

These two PTC studies came to the same conclusion about high-frequency PTC slopes: impaired ears showed significantly flatter high-frequency PTC slopes with tip frequencies shifted toward higher frequencies, which is a demonstration of *abnormal downward spread of masking*. The two studies reached different conclusions about low-frequency PTC slopes. Stelmachowicz et al. (1985) showed significantly flatter low-frequency PTC slopes in impaired than in normal ears. If low-frequency PTC slopes reflect the spread of excitation from low frequencies toward higher frequencies, their results imply that impaired ears demonstrate *abnormal upward spread of masking*. Carney and Nelson (1983) also showed significantly flatter low-frequency PTC slopes in impaired ears, but they reasoned that low-frequency PTC slopes without the influence of combination-tone detection cues might well be just as flat in normal as in impaired ears. If that reasoning is correct, the spread of excitation from low to high frequencies may not be different in impaired ears; only the nonlinearities responsible for combination-tone generation might be different.

From the data available so far, the question about whether impaired ears demonstrate significantly flatter low-frequency PTC slopes because of abnormal upward spread of masking or because of the lack of combination-tone detection cues remains open to question. Carney and Nelson's speculations about the influence of combination-tone detection cues on low-frequency PTC slopes deserve further investigation. The elimination of combination-tone or combination-band detection cues from PTCs obtained with pure-tones or narrow-band noise may indicate that high-level PTCs from normal ears have flatter low-frequency slopes than previously reported.

In addition, these two studies used maskers with different types of amplitude envelopes. Carney and Nelson (1983) used pure-tone maskers with flat amplitude envelopes, whereas Stelmachowicz et al. (1985) used 100-Hz-wide narrow-band maskers that had fluctuating envelopes. Early studies (Egan & Hake, 1950) and more recent ones (Buus, 1985; Mott & Feth, 1986; Weber & Patterson, 1984) have demonstrated differences between the masking patterns of sinusoids and narrow-band noises, differences that suggest there may be something fundamentally different about the mechanisms underlying detection with pure-tone maskers and narrow-band maskers. Comparisons of PTCs for pure-tone maskers with PTCs for narrow-band maskers, under conditions where the contribution of combination tones or combination bands are minimized, may provide some insight into these issues.

At this point, more research into tuning at high SPLs is warranted before valid conclusions can be reached about frequency resolution in the impaired ear. Towards that end, we carried out replications of the Hoekstra and Ritsma (1977) demonstration, in which an additional background noise was used to mask combination tones or combination bands. One of our goals was to determine the extent to which low-frequency PTC slopes obtained in background noise (without combination-tone cues) are flatter than they are in quiet (with combination-tone cues), and to extend Hoekstra and Ritsma's demonstration (with a 30-dB SPL probe tone at 2000 Hz) to a higher probe SPL, to additional frequencies and to additional subjects. Also, because Stelmachowicz et al. found no level effects for narrow-band maskers in normal-hearing listeners, we wished to examine whether or not PTCs obtained with narrow-band maskers might also be contaminated by the detection of combination bands, as might be expected from Greenwood's (1971, 1972) experiments.

Two experiments are reported here. They were carried out to examine high-level tuning in normal-hearing listeners, as reflected by simultaneous-masking PTCs. Experiment 1 examined 1000-Hz and 4000-Hz PTCs obtained with pure-tone maskers, both in quiet and in the presence of a broad-band background noise, to determine the extent to which PTCs obtained with pure-tone maskers might be influenced by combination-tone detection cues. Experiment 2 examined 1000-Hz and 4000-Hz PTCs obtained with 100-Hz-wide narrow-band maskers, both in quiet and in the presence of a broad-band background noise, to determine the extent to which PTCs obtained with 100-Hz-wide narrow-band maskers might be influenced by combination-band detection cues. In addition, 2000-Hz PTCs were obtained with 100-Hz-wide masking bands in 2 subjects to further explore the effects of probe frequency suggested by the results at 1000 and 4000 Hz.

Methods

Stimuli

Two different types of gated maskers were employed: pure-tone (PT) maskers and narrow-band (NB) noise maskers. The NB maskers were 100-Hz-wide multiplied noises, produced by multiplying a low-pass noise with a sinusoid (carrier). Cut-off frequencies for the low-pass noises (3-dB down) were half the desired bandwidths of the NB maskers. Filter slopes for the low-pass noises were 48 dB/oct. For most of the listeners, masker frequencies were chosen in integer steps per octave, both below and above the probe frequency. Generally, 6 steps per octave were used for masker frequencies below the probe frequency, and 12 steps per octave were used for masker frequencies above the probe. In some cases, the number of steps per octave was doubled to achieve higher-resolution PTCs. For some of the listeners, masker frequencies were chosen in integer steps per Hz. Masker frequencies below the probe were separated by 10% of the probe frequency, and those above the probe were separated by 5% of the probe frequency. Masker frequency for NB maskers was designated as the edge frequency of the noise that was nearest to the probe frequency (3-dB down).

Probe stimuli were gated sinusoids with a total duration of 250 ms. They were temporally centered in gated maskers that had total durations of 500 ms. Both probe-tones and maskers were gated with 10-ms rise and decay times. A non-linear ramp, approximating a squared cosine, was used to gate stimuli. Probe frequencies were at 1000, 2000, or 4000 Hz.

Whenever the masker and probe were at the same frequency, the sinusoid used for a probe tone was phase-locked to the sinusoid used to generate the PT or NB maskers. The phase of the probe relative to the masker was at zero degrees, which results in amplitude summation between two sinusoids of equal frequency. Because we wished to express masked thresholds based upon intensity summation between masker and probe, the zero-phase masker levels obtained for pure-tone maskers were converted to quadrature-phase masker levels using the equation reported by Kimberley, Nelson, and Bacon (1989). That conversion is similar to those used by Bos and deBoer (1966) and Vogten (1972, 1978b). Consequently, the tips of the pure-tone PTCs shown in the figures are effectively based upon quadrature phases between masker and probe.

In both experiments, during the broad-band noise (BBN) background condition, a white noise ranging from 100–10,000 Hz was gated concurrently with the masker. For each listener, the BBN background was adjusted to a level that was 10 dB less intense than the level of noise required to mask a 60-dB-SPL probe tone. Whenever the BBN background was employed with narrow-band noise maskers, two independent noise generators were used.

Subjects

Eight normal-hearing listeners participated as subjects. Four of them participated in both experiments at a test frequency of 1000 Hz and the other 4 participated later at a test frequency of 4000 Hz. All of the listeners, except one, were in their 20s and had thresholds for 200-ms tone bursts, between 125 and 8000 Hz, which were within 10 dB of our laboratory norms for young healthy ears without history of noise exposure. The one exception was listener DAN(L), the first author, who was in this mid-forties and demonstrated a mild sloping high-frequency hearing loss above the 1000-Hz frequency at which he was tested. He had normal hearing at 1000 Hz and below, with a loss that grew to 25 dB at 4000 Hz and above.

Threshold Tracking Procedures

Simultaneous-masking tuning curves (PTCs) were obtained for a probe stimulus (signal) that was fixed at either a low level (20 dB SPL) or a high level (60 dB SPL). The level of the masking stimulus was adjusted until it masked the fixed-level probe. Such "masker-level thresholds" are referred to here, for convenience, as "masked thresholds." All masked thresholds were estimated by averaging the last 10 out of 12 reversals in a four-interval, four-alternative, forced-choice adaptive procedure. The adaptive procedure used a 2-up/1-down stepping rule and a 2-dB step size to track 71% correct (Levitt, 1971; Zwislocki, Maire, Feldman, & Rubin, 1958). The first two reversals used an 8-dB step size to reach the target region quickly, and were ignored in the threshold calculation. Each threshold reported here was based on the

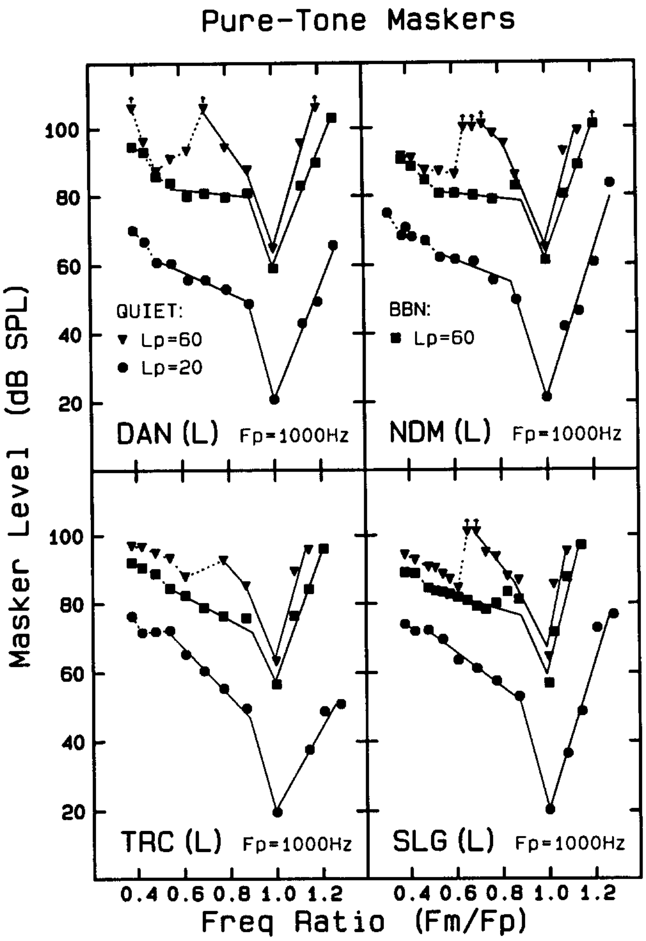

FIGURE 1. PTCs at 1000 Hz obtained with pure-tone maskers from four normal-hearing listeners in Experiment 1. Low-level PTCs for 20-dB-SPL probe tones (circles) are compared with high-level PTCs for 60-dB-SPL probe tones in QUIET (triangles) and in the presence of a BBN background (squares). The BBN background was presented at 10 dB below the level required to mask a 60-dB-SPL 1000-Hz probe tone. PTCs from individual normal-hearing listeners are shown in separate panels.

mean of at least three threshold determinations. The standard deviations of those means were less than 3 dB for 90% and less than 4 dB for 97% of the threshold determinations.

Tuning Curve Parameters

In an attempt to provide an objective analysis of tuning-curve parameters, PTCs were fitted with three straight-line segments: a high-frequency segment, a low-frequency segment, and a tail segment. This was done using least-squares procedures. For each segment a slope value was used to describe the tuning characteristic; steeper slopes indicate sharper tuning. The slope of the high-frequency segment (S_{hf}) was calculated using masker frequencies (Fm) at and above the probe frequency (Fp). The slope of the low-frequency segment near the PTC tip (S_{lf}) was calculated using masker frequencies between about 0.8Fp and 1.0Fp, including Fp. The slope of the tail segment (S_t) was calculated using masker frequencies near 0.8Fp and below. This three-segment fitting procedure is similar to that employed by Stelmachowicz and Jesteadt (1984) to describe PTCs obtained with 100-Hz-wide narrow-band noise maskers. However, a significant departure from their general procedure was required for some PTCs. At low masker frequencies, on the tail of the PTC, some tuning curves could not be well described by a single tail segment because masker levels at lower masker frequencies increased or decreased rapidly with decreasing masker frequency. In those cases, the slope of the tail segment was calculated using masker frequencies on the more linear portion of the tail between about 0.5Fp and 0.8Fp. For other PTCs a notch precluded a single tail-slope calculation. When a definite notch existed in the PTC, low-frequency slopes and tail slopes were calculated using only those masker frequencies on the high-frequency side of the notch (the negative slope region of the notch). The three-segment fits are shown in the graphs by straight (solid) lines through the data. Those points not included in the fits are connected by dotted lines. Slope values were calculated in dB-per-octave using Fp as a reference for S_{hf} and S_{lf}, and 0.8Fp as a reference for S_t. PTC bandwidths, 10 dB above the masker level at Fm = Fp, were calculated using the values for S_{hf} and S_{lf}. The "quality factor" for the auditory filter at 10 dB of attenuation (Q_{10dB}) was specified as the ratio of Fp to PTC bandwidth.

Results and Discussion

EXPERIMENT 1: HIGH-LEVEL PTCS FOR PURE-TONE MASKERS

Low-Level Versus High-Level Tuning Curves

Figure 1 shows 1000-Hz PTCs obtained with low-level (20 dB SPL) probe tones and with high-level (60 dB SPL) probe tones both in quiet and in a BBN background. Each panel shows the results for different listeners. The lower curve in each panel (circles) shows the low-level PTCs, which are typical of those obtained from normal-hearing listeners.[1] They are well described by three slope segments: a steep

[1]For the PTCs displayed in the figures we have avoided masker frequencies any closer to the probe frequency than 10%; therefore, the very sharp tips sometimes evident in simultaneous-masking PTCs for pure-tone maskers are not seen here. When masker frequencies very close to the probe frequency are tested, very sharp PTC tips can be observed (Vogten, 1978a); in some cases Q_{10dB} values as high as 40 are seen. However, for masker frequencies closer than 10% of the probe frequency, it is apparent that masked thresholds are influenced by amplitude-envelope fluctuations inherent in the interactions between masker and probe stimuli, which may represent a different detection strategy (modulation detection) than the presumed detection strategy involved when masker and probe are at the same frequency (energy detection). For some PTCs, the high-frequency slope was sufficiently steep to require inclusion of masker frequencies closer than 1.10Fp in order to provide a sufficient number of data points for a valid straight-line fit of the high-frequency segment. In those cases, the slope of the auditory filter may be sufficiently steep to preclude modulation detection from influencing the slope calculation appreciably. Significant questions remain about the validity of using masker frequencies very close to the probe frequency to obtain estimates of auditory filtering characteristics. They will not be addressed in this paper.

high-frequency slope (S_{hf}), a steep low-frequency (S_{lf}) near the tip, and a more gradual low-frequency slope on the tail (S_t). Straight (solid) lines through the data depict those three slope segments; the corresponding slope values, averaged across the four listeners, are given in Table 1. Points not fit by the three slope segments are connected by dotted lines. The slope values for these low-level PTCs are generally consistent with slope values reported by others for narrow-band noise maskers and low-level probe tones (Stelmachowicz & Jesteadt, 1984). Similarly, the quality factors of the PTCs (Q_{10dB}) are close to values reported by others.

The upper curve in each panel (inverted triangles) shows the PTCs obtained with a high-level probe. As indicated in Table 1, they have an average high-frequency slope that is 46% steeper than for a low-level probe. That apparent increase in S_{hf} with probe level is consistent with a 53% increase reported by Stelmachowicz & Jesteadt (1984) for a comparable range of probe levels (20–60 dB SPL) at 2000 Hz. The high-level PTCs have flatter low-frequency slopes than the low-level PTCs. Together, the high-frequency and low-frequency slopes yield an average Q_{10dB} value of 10.1 for the high-level probe, which is the same as the average Q_{10dB} value obtained with the low-level probe. This result is consistent with the finding of Stelmachowicz & Jesteadt (1984) that Q_{10dB} at 2000 Hz was relatively independent of probe level for 100-Hz-wide NB maskers in a quiet background.

If masker frequencies below about 0.7Fp had not been tested because the equipment limits were exceeded (indicated by small arrows), one might conclude that the high-level PTCs are very similar to the low-level PTCs, except that the tail segments are steeper for the high-level PTCs. One might then proceed to compare these high-level PTCs from normal-hearing listeners with (high-level) PTCs from hearing-impaired listeners. However, in this case masker frequencies below 0.7Fp were tested, and the results revealed notches in the PTC tail regions below about 0.9Fp. The notch in the PTC tail region can be seen in the high-level PTC (inverted triangles) from each of the four listeners. For example, in Figure 1A, moving from the PTC tip toward lower masker frequencies, the notch is defined by a negative slope between 0.9Fp and 0.7Fp, a positive slope between 0.7Fp and 0.56Fp, and a negative slope for masker frequencies below 0.56Fp.

Notches in PTCs have been reported in previous studies (Carney & Nelson, 1983; Chistovich, 1957; Hoekstra & Ritsma, 1977). Similar notches to those seen here were reported in three additional listeners by Carney and Nelson (1983). They found notches in high-level PTCs at probe frequencies of 1000, 2000, and 4000 Hz, but not at 500 Hz. Hoekstra and Ritsma (1977) proposed an explanation for these notches, namely that the masker levels for frequencies just below the probe (between 0.56Fp and 0.9Fp in this case) were excessively high because of the production and detection of combination tones, which is the same explanation used earlier by Greenwood (1970, 1971) to explain notches on the high-frequency sides of frequency masking patterns. For example, in the upper PTC of subject DAN(L) in Figure 1, at the peak of the notch (Fm/Fp = 0.7) the combination tone that is likely to have provided the most salient detection cue is the cubic difference tone at a $2f_1$-f_2 frequency of 414 Hz, which would have been produced by the 707-Hz masker and the 1000-Hz probe. As the 707-Hz masker is increased in level from inaudibility, it does indeed mask the 1000-Hz probe tone at some masker level; however, at that masker level the 414-Hz cubic difference tone is still audible when the probe tone is presented together with the masker. Therefore, the level of the 707-Hz masking tone must be increased further until it either masks the 414-Hz combination tone or, as occurred in this case, the intensity limits of the equipment are reached (indicated by small upward arrow).

Presumably, obvious notches are not seen in low-level PTCs because combination tones are very weak or are not intense enough to be heard when the probe tone is at a low sensation level (10–15 dB SL). Because we did not specifically test for combination-tone detection cues at low levels with appropriate background noise, the fact remains that the low-level PTCs reported here could have been influenced slightly by combination tone cues and other off-frequency listening cues. Suggestions have been made in the past that the lack of an observable notch may not be sufficient evidence to conclude that masking-pattern slopes are not influenced by combination tones, even at low levels (Greenwood, 1971; Zwicker, 1968).

TABLE 1. Tuning-curve characteristics for pure-tone maskers. Mean PTC characteristics at 1000 Hz are from four normal-hearing listeners. Mean PTC characteristics at 4000 Hz are from the same four normal-hearing listeners. PTC characteristics are given for low-level probe tones and for high-level probe tones in quiet (QUIET) and in the presence of a broad-band noise (BBN) background.

Background Condition	Probe dB SPL	L_p-L_m	S_t *	S_{lf} *	S_{hf} *	Q_{10dB}
		Mean PTC Characteristics at 1000 Hz (N = 4)				
QUIET	20	−0.44	−18.0	−120.8	177.4	10.1
QUIET	60	−4.36	−32.5	−86.0	259.7	10.1
BBN	60	1.62	−7.1	−84.6	201.0	9.0
Change Factor (BBN at 60 vs. QUIET at 20)**			−10.9	−36.2	+23.6	−0.11***
		Mean PTC Characteristics at 4000 Hz (N = 4)				
QUIET	20–25	3.33	−22.1	−130.5	206.2	11.4
QUIET	60	−0.41	−96.3	−131.3	260.4	12.5
BBN	60	1.32	−17.3	−40.3	227.9	5.8
Change Factor (BBN at 60 vs. QUIET at 20)**			−4.8	−90.2	+21.7	−0.49***

*slopes given in dB per octave. **Sign of slope differences indicates direction of change ("+" = steeper; "−" = flatter). ***Q_{10dB} change factor = [(BNN 60)/(QUIET 20) − 1.0].

PTCs in Broad-Band Background Noise

To examine the notion that the notches in the low-frequency tails of the high-level PTCs were due to the detection of combination tones, a broad-band masking noise (BBN) was introduced into the PTC experiment, as was done by Hoekstra and Ritsma (1977). The BBN background was intended to mask combination-tone cues, as well as other off-frequency cues that might influence the shape of the high-level PTC (Glasberg & Moore, 1982; Johnson-Davies & Patterson, 1979; Moore, Glasberg, & Roberts, 1984; O'Loughlin & Moore, 1981). The BBN background was first adjusted to a level that would just mask the 60-dB-SPL probe tone. The level of the BBN background was then reduced by 10 dB, and during the acquisition of the PTC the BBN background was gated concurrently with the pure-tone masker. With this procedure, the 60-dB-SPL probe tone was effectively at 10 dB SL in noise. If the notch was due to the detection of combination tones, it was expected that the BBN noise would mask those combination tones and eliminate the notch.

The PTCs obtained in the BBN background are shown in Figure 1 by squares. The difference between the squares and inverted triangles shows the effects of introducing the background noise. The most obvious was the elimination of the notch on the tail of the high-level PTC. At some of the masker frequencies, the masker levels were reduced by as much as 25 dB by the addition of the BBN background. The detection cues responsible for the notch in the high-level PTC were reduced or minimized by the BBN background condition. The most straightforward explanation for these results is provided by the detection of cubic-difference-tone cues at $2f_1$-f_2, at least for the peak of the notch.

The background noise also reduced the masker levels at and around the probe frequency for each listener. The reduced masker levels at the probe frequency are indicated in Table 1 by the average differences between probe level and masker level at the PTC tip frequency (Lp-Lm). Those differences were smaller in the BBN background than in quiet. This suggests that the background noise produced a change in the detection criterion at the output of the auditory filter, which could be due either to increased intensity fluctuations at the output of the auditory filter, or to the elimination of off-frequency listening at higher frequencies. In either case, the change in the detection cue was reflected by a general reduction in overall masker level for maskers near to the probe frequency. Whether it also contributed to the reduction in masker levels within and below the notch region cannot be determined from these data, although it is unlikely that those changes in detection cues can account for the dramatic change in masker levels that occurred within the peak of the notch region.

Furthermore, other combination tones such as the simple difference tone at f_2-f_1 might also have influenced the tail segments (Greenwood, 1971, 1972). In some cases, difference tones may not have been masked by the broad-band background noise, such as when the difference tone occurred at a frequency below about 250 Hz where the audibility curve may limit the effectiveness of the broad-band noise. This would correspond to masker frequencies between 0.75Fp and 1.0Fp.

High-Level PTCs at 4000 Hz

To extend these findings to a higher test frequency, simultaneous-masking PTCs were obtained from four normal-hearing listeners at a probe frequency of 4000 Hz. Those results are shown in Figure 2. The same general findings are seen at 4000 Hz that were demonstrated at 1000 Hz. High-level PTCs exhibited strong notches, which were eliminated by the BBN background. However, there are some significant differences across test frequency that deserve closer attention.

At 4000 Hz, the shapes of high-level PTCs appear to be more strongly influenced by cubic-difference-tone cues and off-frequency-listening cues than at 1000 Hz. The high-level PTCs at 4000 Hz in quiet (inverted triangles) have the same general characteristics seen previously for high-level PTCs at 1000 Hz in quiet. Considering only those masker frequencies above 0.7Fp, the Q_{10dB} values in Table 1 would lead to the conclusion that high-level PTCs in quiet are as sharply tuned as they are at low levels. However, testing at masker

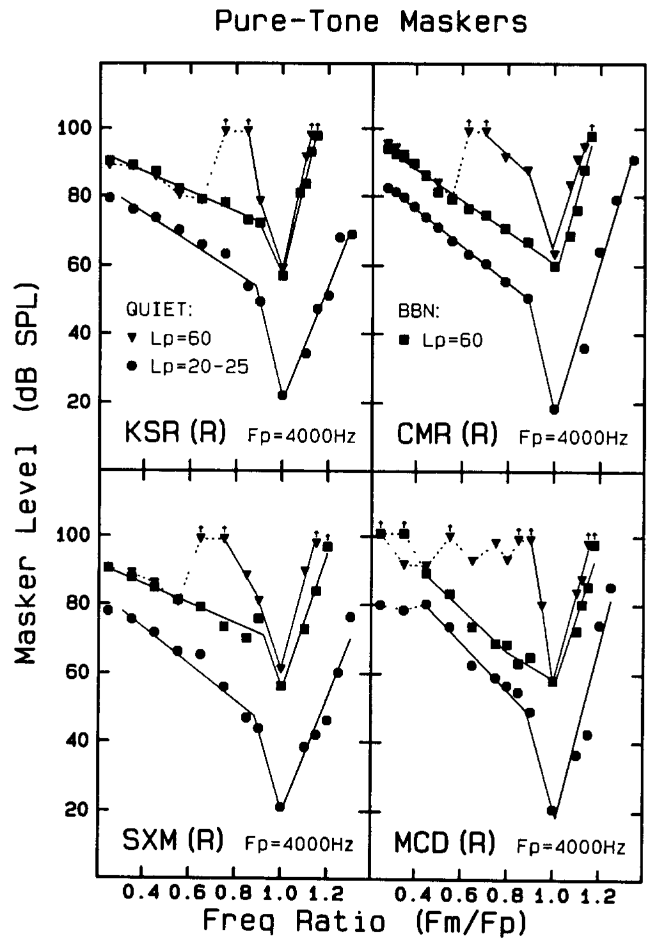

FIGURE 2. PTCs at 4000 Hz obtained with pure-tone maskers in Experiment 1. Legend as in Figure 1.

frequencies below 0.7Fp revealed the characteristic notches in the PTCs that reflect the influence of combination-tone cues. The maximum masker levels within those notch regions for 4000-Hz PTCs ranged between 0.6Fp and 0.8Fp, just as they did at 1000 Hz. This indicates that combination tones were heard over a wider frequency range (in absolute Hz) at 4000 Hz (800–2400 Hz) than they were at 1000 Hz (200–600 Hz), which is consistent with previous findings that the audibility region for combination tones is a constant fraction of the low-frequency primary (Goldstein, 1967; Smoorenburg, 1972a). Consequently, high-level PTCs were influenced by combination-tone detection cues over a wider range of masker frequencies at 4000 Hz than at 1000 Hz.

This was particularly evident with the introduction of broadband background noise, which had a more dramatic effect on the shapes of PTCs at 4000 Hz than at 1000 Hz. The background noise eliminated the notches, just as it did at 1000 Hz, but as seen in Figure 2 and Table 1, it appreciably reduced the low-frequency segment of the high-level PTCs, which also reduced the quality factor from what it was without the BBN background. As indicated in Table 1, the reduction in quality factor at high probe levels was also associated with an increase in average high-frequency slope of +21.7 dB/oct at 4000 Hz.[2]

When comparing low-level PTCs in quiet with high-level PTCs in noise, without the influence of combination tones or off-frequency listening, PTCs at 4000 Hz were more broadly tuned at high levels than at low levels. As indicated in Table 1, Q_{10dB} values at high probe levels in the BBN background were reduced from what they were at low probe levels by 11% and 49%, at 1000 Hz and 4000 Hz, respectively. This reduction in quality factor at high probe levels in noise was associated with a decrease in low-frequency slope of −36.2 and −90.2 dB/oct at 1000 Hz and 4000 Hz, respectively. Thus, it appears that the tuning characteristics of high-level PTCs in quiet were more strongly influenced by combination-tone cues at 4000 Hz than they were at 1000 Hz.

The introduction of background noise had a larger effect on the sharply tuned PTC tip at 4000 Hz than it did at 1000 Hz. At 4000 Hz, the sharp tip region was essentially eliminated in 3 subjects. At 1000 Hz, the background noise had very little effect on the sharp tip region. Once the influence of combination tones and off-frequency listening were minimized by background noise, it appears that high-level PTCs changed shape with test frequency. PTCs at 1000 Hz retained their gradual tail segment and a well-defined tip region, whereas PTCs at 4000 Hz demonstrated a single-sloped low-frequency segment without a well-defined tip region. The appropriate interpretation of this difference with test frequency is not clear. One might argue that combination-tone cues were more robust at 1000 Hz than at 4000 Hz, and that the background noise did not mask combination-tone cues at 1000 Hz as effectively as it did at 4000 Hz. With these assumptions, one might conclude that PTC characteristics are indeed similar across test frequencies but that the influence of combination tones is harder to remove at lower test frequencies. Because the range of masker frequencies over which PTCs were influenced by combination-tone cues was greater (in Hz) at higher test frequencies, this line of reasoning does not seem particularly productive. It does not seem likely that, where the existence region for combination-tone generation is the broadest, combination tones would be the most susceptible to masking by a background noise. On the other hand, one might reason that the background noise did mask the influence of combination-tone detection cues and off-frequency listening at both test frequencies, and therefore, the remaining PTC tip at 1000 Hz and the lack of a residual PTC tip at 4000 Hz indicated that there were indeed dramatic differences in the shapes of high-level PTCs across test frequency. In either case, for high-level probe tones, differences between tuning in quiet and tuning in background noise were greater at the higher test frequency.

EXPERIMENT 2. HIGH-LEVEL PTCS FOR 100-HZ-WIDE NARROW-BAND MASKERS

The changes in PTC shapes with probe level observed in the presence of the BBN background in Experiment 1 were notably different from those reported by Stelmachowicz and Jesteadt (1984). For probe levels between 20 and 60 dB SPL, their mean Q_{10dB} values increased with level by +33% at 2000 Hz, compared with the decreases with level of −11% and −49% in Q_{10dB}, at 1000 and 4000 Hz respectively, observed in Experiment 1 with pure-tone maskers when combination-tone cues were masked. Because their PTCs were obtained in quiet and with 100-Hz-wide narrow-band noise maskers, it is not immediately clear why they found PTC tuning to increase with probe level. Their results are consistent with the results reported in Experiment 1 for high-level PTCs in quiet, which were shown to be influenced by combination-tone and other off-frequency cues. However, they also used narrow-band-noise maskers instead of the pure-tone maskers used in Experiment 1. Therefore, a second experiment was carried out to investigate high-level PTCs obtained with 100-Hz-wide narrow-band noise maskers.

High-Level PTCs at 1000 Hz

Simultaneous-masking PTCs at 1000 Hz were obtained from 4 normal-hearing listeners using 100-Hz-wide narrow-band-noise maskers. As in the previous experiment, PTCs were obtained at low probe levels (Lp = 20 dB SPL) in quiet, and at high probe levels (Lp = 60 dB SPL) both in quiet and in the presence of a broad-band masking noise that was 10

[2]The observed change in Q_{10dB} by −49% at 4000 Hz may not seem consistent with an decrease in S_{lf} by −90.2 dB/oct and an increase in S_{hf} by +21.7 dB/oct. This is because the slope values are reported here in dB/oct, whereas Q_{10dB} is directly related to dB per frequency ratio (dB/Hz * Fp). PTC slopes were actually calculated using masker/probe frequency ratio as the independent variable, which is displayed on the abscissa in the figures, and Q_{10dB} values were derived from those slopes The slopes were converted to dB/oct for presentation in tables in order to be consistent with previous studies (e.g., Stelmachowicz & Jesteadt, 1984). To convert back to slopes relating masker levels to frequency ratio, the slopes reported here in dB/oct units need only be multiplied by the constants 2.5, 2.0, and 1.0 for S_t, S_{lf}, and S_{hf}, respectively. In terms of the slope values reported here in dB/oct, $Q_{10dB} = 1/\{10/S_{hf} - 10/2S_{lf}\}$. From this relation, it is apparent that the decrease in S_{lf} of −90.2 dB/oct (from Table 1) has more than twice the effect on Q_{10dB} as the increase in S_{hf} of +21.7 dB/oct; therefore the net effect is a reduction in quality factor

dB below the level needed to just mask a 60-dB-SPL probe tone. The results are shown in Figure 3, and the mean PTC characteristics are given in Table 2.

From Figure 3 it can be seen that, at 1000 Hz, high-level PTCs in quiet (inverted triangles) are only slightly more sharply tuned than low-level PTCs (circles). This is mainly due to a change in the steepness of S_{hf} with probe level. Mean slope calculations in Table 2 indicate that S_{hf} increased from 156 dB/oct at low probe levels to 308 dB/oct at high probe levels. Because S_{lf} also decreased from −129 dB/oct to −104 dB/oct, the net effect on Q_{10dB} was a 27% increase from 9.7 for low-level probes to 12.3 for high-level probes. This increase in sharpness of tuning with probe level is comparable with the 33% increase evident in the data reported by Stelmachowicz and Jesteadt (1984).

In Figure 3, high-level PTCs in quiet (inverted triangles) are also compared with high-level PTCs in a BBN background (squares). It can be seen that very little change in the overall shapes of high-level PTCs occurred with the

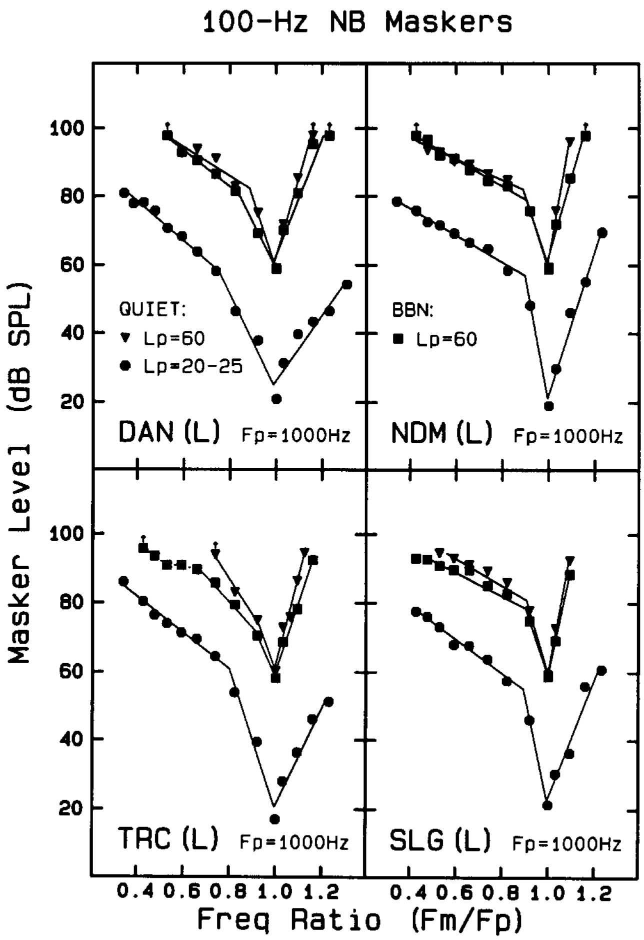

FIGURE 3. PTCs at 1000 Hz obtained with 100-Hz-wide narrow-band (NB) maskers from four normal-hearing listeners in Experiment 2. Low-level PTCs for 20-dB-SPL probe tones (circles) are compared with high-level PTCs for 60-dB-SPL probe tones in QUIET (triangles) and in the presence of a BBN background (squares). The BBN background was presented at 10 dB below the level required to mask a 60-dB-SPL 1000-Hz probe tone. Data are shown for individual listeners in separate panels.

introduction of a BBN background designed to mask combination-band and off-frequency-listening cues, although there were some decreases in absolute slope values. Table 2 indicates that a slight reduction occurred in mean S_{lf} and a more noticeable reduction occurred in mean S_{hf}. The net effect on Q_{10dB} was a reduction from 12.3 in quiet to 10.2 in the BBN background, which is similar to the Q_{10dB} obtained at low probe levels.

Table 2 also shows that the mean probe-masker difference at the PTC tip did not change when the probe level varied from 20 dB SPL (+0.46 dB) to 60 dB SPL (+0.48 dB). This indicates that very little off-frequency listening occurred above the probe frequency. When the broad-band background noise was introduced, the probe-masker difference at the tip frequency increased to 1.39 dB, indicating that the background noise probably added additional fluctuations to the 1000-Hz auditory filter, thereby raising the intensity increment threshold slightly.

These results indicate that, at 1000 Hz, high-level PTCs obtained with 100-Hz-wide narrow-band noise are influenced very little by combination-band detection cues. High-level PTCs obtained in background noise were as sharply tuned as low-level PTCs, indicated in Table 2 by a change in Q_{10dB} of only +5%, even though low-frequency slopes decreased with probe level by −40.5 dB/oct and high-frequency slopes increased with probe level by +89.3 dB/oct. Tail slopes were only slightly flatter at high than at low probe levels, and were not changed substantially by the background noise.

High-Level PTCs at 4000 Hz

Simultaneous-masking PTCs at 4000 Hz were obtained from four additional normal-hearing listeners. As before, PTCs were obtained for a low-level probe (Lp = 20 dB SPL) in quiet and for a high-level probe (Lp = 60 dB SPL) both in quiet and in the presence of a broad-band background noise at 10 dB below the level of the noise needed to just mask a 60-dB-SPL probe tone. Figure 4 shows the results.

At 4000 Hz, high-level PTCs obtained with 100-Hz-wide narrow-band maskers exhibited effects similar to those demonstrated earlier at both 1000 and 4000 Hz with pure-tone maskers. For pure-tone maskers, those effects were attributed to combination-tone detection cues. In this case, with 100-Hz-wide narrow-band maskers, the detection cues are assumed to be due to combination bands at $(n + 1)f_1\text{-}nf_2$ frequencies, where f_2 is the frequency of the probe tone and f_1 frequencies are the individual components of the 100-Hz-wide narrow-band masker, leading to combination bands of order n below the narrow-band masker. As shown in Figure 4, at 4000 Hz, high-level PTCs in quiet exhibited higher masker levels on the low-frequency sides between 0.6Fp and 0.8Fp than high-level PTCs in a BBN background. Those higher masker levels in quiet are most likely due to the detection of combination bands at frequencies below the masker frequencies. The most likely combination band is the first order cubic-difference band at $2f_1\text{-}f_2$ frequencies, because it has been shown to be the most salient of the combination bands (Greenwood, 1971, 1972, 1983). However, higher-order combination bands may have contributed

TABLE 2. Tuning-curve characteristics for 100-Hz-wide narrow-band noise maskers. Mean PTC characteristics at 1000 Hz are from four normal-hearing listeners. Mean PTC characteristics at 4000 Hz are from the same four normal-hearing listeners. Mean PTC characteristics at 2000 Hz from two additional normal-hearing listeners.

Background Condition	Probe dB SPL	L_p-L_m	S_t *	S_{lf} *	S_{hf} *	Q_{10dB}
		Mean PTC Characteristics at 1000 Hz (N = 4)				
QUIET	20	0.46	−19.9	−129.3	156.0	9.7
QUIET	60	0.48	−21.5	−104.5	308.3	12.3
BBN	60	1.39	−20.1	−88.8	245.3	10.2
Change Factor (BBN at 60 vs. QUIET at 20)**			+0.2	−40.5	+89.3	+0.05***
		Mean PTC Characteristics at 4000 Hz (N = 4)				
QUIET	20–25	−0.35	−23.6	−126.3	208.7	11.4
QUIET	60	−2.68	−81.8	−101.3	265.1	11.3
BBN	60	−3.29	−18.5	−52.9	227.8	7.1
Change Factor (BBN at 60 vs. QUIET at 20)**			−5.1	−73.4	+19.1	−0.38***
		Mean PTC Characteristics at 2000 Hz (N = 2)				
QUIET	20	−3.15	−19.8	−114.5	177.8	9.8
QUIET	60	−4.95	−32.8	−95.5	229.9	10.0
BBN	60	−4.99	−26.6	−71.3	224.0	8.5
Change Factor (BBN at 60 vs. QUIET at 20)**			+6.8	−43.2	+46.2	−0.13***

*slopes given in dB per octave. **Sign of slope differences indicates direction of change ("+" = steeper; "−" = flatter). ***Q_{10dB} change factor = [(BNN 60)/(QUIET 20) − 1.0].

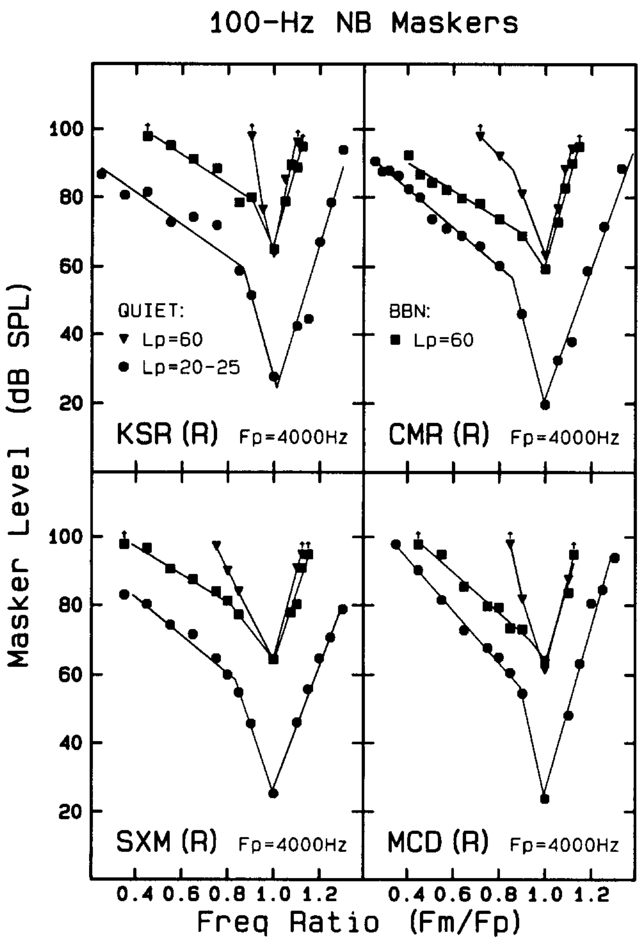

FIGURE 4. PTCs at 4000 Hz obtained with 100-Hz-wide NB maskers from four normal-hearing listeners in Experiment 2. Legend as in Figure 3.

to the width and breadth of the notch, and difference bands of the order f_2-f_1 may also have been involved at these high levels when the masker edge was closer to the probe than about 0.7Fp (Kramer & Greenwood, 1973).

Table 2 shows the corresponding changes in PTC tuning characteristics that occurred with the addition of background noise. The largest effect of the background noise was seen on the low-frequency sides of the PTCs. The BBN background flattened the low-frequency slope at 4000 Hz. A direct analog of this result with 2000-Hz frequency masking patterns, using low-pass noise instead of broad-band noise, can be seen in Greenwood (1971, Figure 11). Once the major effects of combination-band detection cues were removed by the BBN background, a comparison with Q_{10dB} estimates for low-level probes reveals a 38% decrease in tuning with probe level at 4000 Hz (Table 2). When compared to the 5% increase in tuning with probe level seen previously at 1000 Hz, this indicates that estimates of tuning obtained with a 100-Hz-wide narrow-band masker were more strongly influenced by combination-band detection cues at 4000 Hz than at 1000 Hz.

High-Level PTCs at 2000 Hz

The above results suggest that the influence of combination bands on tuning-curve shapes is dependent upon probe frequency. Combination-band detection cues strongly influenced 4000-Hz tuning curves but had little effect at 1000 Hz. As mentioned earlier, a thorough study of high-level PTCs in normal-hearing listeners was previously carried out by Stelmachowicz and Jesteadt (1984). They used 100-Hz-wide narrow-band noise maskers in order to reduce the effects of beats and combination bands. The results presented above suggest that their 100-Hz-wide maskers might have produced audible combination-band detection cues that could have influenced the estimates of tuning they reported. However, their test frequency was 2000 Hz, so the present data are not immediately generalizable. Therefore, we tested two additional normal-hearing listeners with a probe frequency of 2000 Hz, using 100-Hz-wide narrow-band noise maskers. All other conditions were the same as described above for 1000-Hz and 4000-Hz probe frequencies.

Figure 5 shows the results obtained with 100-Hz-wide maskers at 2000 Hz. Similar to the results described above at 4000 Hz, high-level PTCs revealed steeper low-frequency slopes in quiet than in the BBN background. The tuning-curve parameters for 2000 Hz, listed in Table 2, indicate that the high-level PTCs in background noise, without combination-band detection cues, were more broadly tuned than low-level PTCs or high-level PTCs in quiet. From this it appears that 100-Hz-wide narrow-band maskers and 2000-Hz probe tones do produce audible combination-band detection cues that influence estimates of PTC tuning at 2000 Hz.

COMPARISONS OF PTCS OBTAINED WITH PURE-TONE AND 100-HZ-WIDE MASKERS

In Experiment 1, high-level PTCs obtained with pure-tone maskers were influenced by combination-tone detection cues at 1000 Hz and 4000 Hz. In Experiment 2, high-level PTCs obtained with 100-Hz-wide narrow-band maskers were influenced by combination-band detection cues at 4000 Hz, but not at 1000 Hz. Apart from this difference in the influence of combination tones versus combination bands at 1000 Hz, it is of interest to determine whether there are any other consistent differences between PTCs obtained with pure-tone (PT) and narrow-band (NB) maskers. Because one motivation for this research was to find appropriate ways to compare high-level PTCs in hearing-impaired and normal-hearing ears, and hearing-impaired ears may not generate or hear combination tones (Smoorenburg, 1972b), we will focus our comparisons on PTCs that are influenced minimally by combination tones or combination bands, that is, those obtained in the presence of BBN background.

Figures 6 and 7 compare PTCs obtained using pure-tone

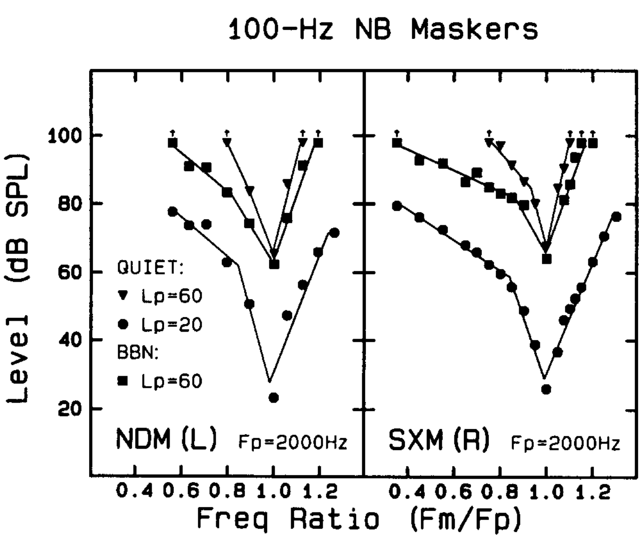

FIGURE 5. PTCs at 2000 Hz obtained with 100-Hz-wide NB maskers from two additional normal-hearing listeners. Legend as in Figure 3.

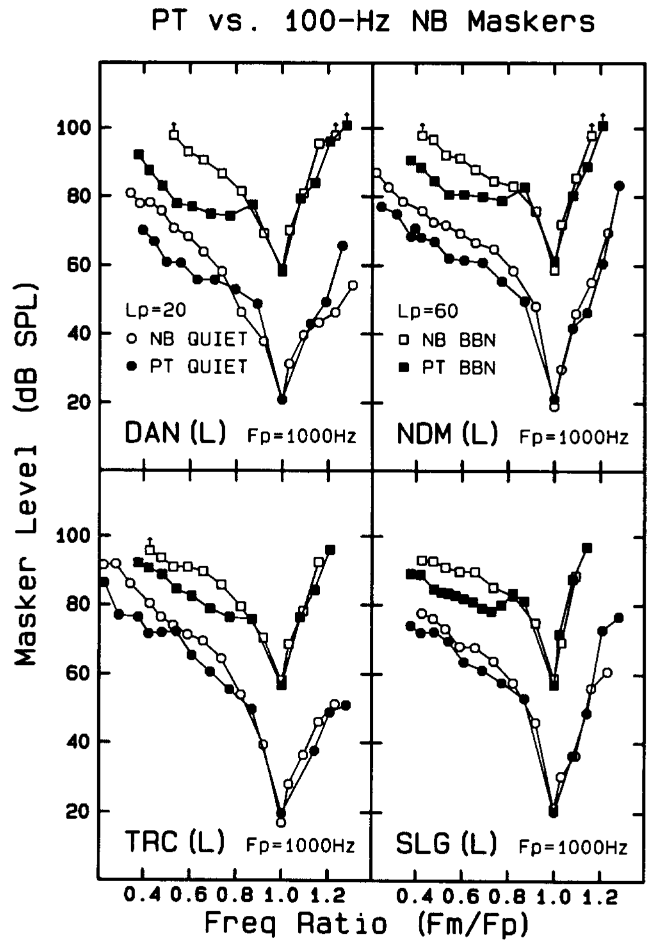

FIGURE 6. A comparison of PTCs at 1000 Hz obtained with pure-tone maskers (filled symbols) and 100-Hz-wide narrow-band maskers (open symbols). Low-level 20-dB-SPL probe tones (circles): PTCs for pure-tone maskers (filled) are compared with PTCs for 100-Hz-wide narrow-band maskers (open). High-level 60-dB-SPL probe tones (squares): PTCs for pure-tone maskers (filled) are compared with PTCs for 100-Hz-wide narrow-band maskers (open).

(PT) maskers with PTCs obtained using 100-Hz-wide narrow-band (NB100) maskers, both at low levels in quiet and at high levels in background noise. Figure 6 presents the results at 1000 Hz and Figure 7 shows the results at 4000 Hz. To the extent discussed previously, these curves are relatively free of the influence of combination-tone or combination-band detection cues and they are relatively free from the influence of off-frequency listening cues.

Comparisons at Low Probe Levels

Low-level PTCs at 1000 Hz from four normal-hearing listeners are shown in Figure 6 for PT maskers (filled circles) and NB100 maskers (open circles). Comparisons across masker type for these low-level PTCs revealed similar tuning for both PT and NB100 maskers. This observation is supported by similar high-frequency, low-frequency, and tail slopes, as indicated in Table 1 and 2. Mean Q_{10dB} values

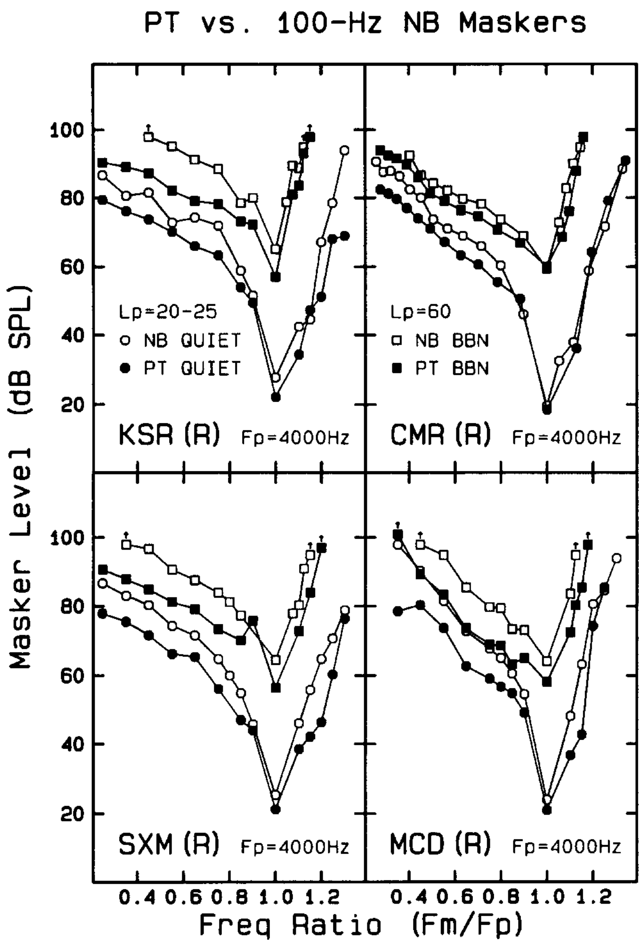

FIGURE 7. A comparison of PTCs at 4000 Hz obtained with pure-tone maskers and 100-Hz-wide narrow-band maskers. Legend as in Figure 6.

were 10.1 and 9.7 for the PT and NB100 maskers, respectively. Masker/probe ratios at the PTC tips were also similar, being within 0.90 dB of one another (−0.44 for PT and +0.46 for NB100).

The major differences between PT and NB100 maskers occurred on the tails of the PTCs. For masker frequencies below about 0.8Fp, the NB100 maskers were 5–10 dB less effective than the PT maskers. This difference in masking effectiveness below 0.8Fp was demonstrated in all four listeners.

Figure 7 shows low-level PTCs at 4000 Hz. Comparisons across masker type reveal the same findings seen at 1000 Hz for low-level probes. PT and NB100 PTCs were tuned the same at 4000 Hz: Q_{10dB} was 11.4. The major differences were again seen below 0.8Fp, where NB100 maskers were 5–15 dB less effective than PT maskers.

The finding that PT and NB100 maskers were equally effective above 0.8Fp suggests, for both types of maskers, that at masker frequencies above 0.8Fp the auditory system detects the probe tone by detecting a change in the intensity at the output of the auditory filter tuned to the probe frequency. At face value, this result may appear inconsistent with results from Weber and Patterson (1984), who reported that narrow-band noise maskers were more effective than pure-tone maskers for masker frequencies near Fp. In their case, they compared the two types of maskers at masker frequencies that were 5 Hz above and below the probe frequency. Therefore, as they point out, the effective cue for the pure-tone masker was probably dependent upon amplitude summation between masker and probe (involving beat detection), whereas the cue for the narrow-band masker was probably dependent upon intensity summation between masker and probe (involving intensity increment detection).

Comparisons at High Probe Levels

High-level PTCs at 1000 Hz in background noise, from four normal-hearing listeners, are shown in Figure 6. Comparisons across masker type for high-level probe tones revealed similar tuning for PT maskers (filled squares) and NB100 maskers (open squares), just as with low-level PTCs, except that both low-frequency and high-frequency slopes were slightly steeper for NB100 maskers than for PT maskers. Mean Q_{10dB} values at 1000 Hz were 9.0 and 10.2 for PT and NB100 maskers, respectively. Again, the major differences between the two types of maskers occurred on the tails of the PTCs. At masker frequencies below 0.8Fp, NB100 maskers were less effective than PT maskers. At high levels, this difference was more robust, because for all four listeners the magnitude of the differences were larger at high probe levels. In one listener, the NB100 masker was more than 20 dB less effective at some masker frequencies. Comparisons across masker type at 4000 Hz are shown in Figure 7. It can be seen that the differences between PT and NB100 masker levels appear slightly larger at 4000 Hz than at 1000 Hz. However, if the masker levels are specified relative to the masker level at the PTC tip, then the differences between PT and NB100 masker levels would actually be smaller at 4000 Hz than at 1000 Hz.

Release From Masking Below 0.8Fp

The finding that NB100 maskers are less effective than PT maskers, for masker frequencies below 0.8Fp, is essentially a demonstration of more upward spread of masking for a pure-tone masker than for a narrow-band-noise masker having the same overall power (e.g., Egan & Hake, 1950, Figure 7; Greenwood, 1971, Figure 12). The same result was demonstrated for fixed-level maskers more recently by Buus (1985) and by Mott and Feth (1986). Buus described the difference in masking effectiveness between pure-tone and narrow-band-noise maskers as a release from masking for narrow-band-noise maskers compared to pure-tone maskers. This release from masking suggests that a detection strategy (or strategies) other than intensity increment detection may be involved at masker frequencies below 0.8Fp.

One difference between the PT and NB100 maskers, other than their spectral width, was their envelope shape. The envelopes of the PT maskers were flat throughout the 500-ms stimulus interval, while the envelopes of the NB100 maskers fluctuated dramatically over the same period of time. Because the NB100 maskers were produced by multiplying a low-pass noise (f_c = 50 Hz) with a sinusoid, the resulting envelopes had periodic peaks and zeros, with zeros occurring at an average rate of $1.155f_c$ = 58 Hz (Rice, 1954; p. 139). This difference in envelope shape for PT and NB maskers may be particularly relevant to the observed release from masking.

The exact detection strategies responsible for the release from masking for fluctuating-envelope maskers are not yet well understood. To explain the release from masking associated with envelope fluctuations, some investigators have proposed across-channel mechanisms that involve subtraction of envelopes from different auditory channels (Buus, 1985) or correlation between envelopes from different channels (Hall, Haggard, & Fernandes, 1984). Others have proposed within-channel cues that involve temporal weighting functions determined by forward- and backward-masking time constants (Fastl, 1975; Zwicker & Schötte, 1973), "listening in the valleys" of fluctuating-envelope maskers using a short time window (Buus, 1985; Mott & Feth, 1986), or modulation of phase locking (Moore & Glasberg, 1987). Furthermore, it would seem that all of these mechanisms should be dependent upon the temporal resolving capability of the auditory system, which is best at slower fluctuation rates (Viemeister, 1977, 1979).

Summary and Conclusions

In Experiment 1, comparisons of high-level PTCs obtained with pure-tone maskers, both in quiet and in the presence of different background noises that selectively masked combination-tones and other off-frequency detection cues, demonstrated that the shapes of high-level PTCs for pure-tone maskers obtained in quiet are strongly influenced by combination-tone detection cues. Furthermore, the influence of combination-tone detection cues was dependent upon test frequency. It was greater for probe frequencies at 4000 Hz than it was at 1000 Hz. Combination-tone detection cues tended to sharpen a high-level PTC by producing an artificially steep low-frequency slope and a well-defined notch on the tail. High-level PTCs in quiet, which were influenced by combination-tone detection cues, had average Q_{10dB} values that were essentially the same as those for low-level PTCs. Therefore, tuning in quiet appeared to be relatively independent of probe level. On the other hand, when a BBN background masked the most salient combination-tone cues, tuning was strongly dependent on level. High-level PTCs in background noise had Q_{10dB} values of 9.0 and 5.8 at 1000 and 4000 Hz, which were broader than Q_{10dB} values for low-level PTCs by 11%, and 49% at the two test frequencies, respectively. These results indicate that, when adequate precautions are taken to avoid inappropriate detection cues, tuning at high levels is considerably less sharp than it is at low levels.

In Experiment 2, comparisons of high-level PTCs obtained with 100-Hz-wide narrow-band maskers, both in quiet and in a broadband background noise to mask combination bands, demonstrated that combination-band detection cues can strongly influence the shapes of high-level PTCs (in quiet), depending upon the test frequency. At 1000 Hz, high-level PTCs in quiet were only slightly influenced by combination bands. At 4000 Hz, high-level PTCs in quiet demonstrated obvious notches that were removed by a background noise, which indicates a stronger influence by combination-band detection cues at higher test frequencies. Because the 100-Hz-wide narrow-band maskers are smaller fractions of the critical bandwidth at higher frequencies, this dependence on test frequency may be related to the relative bandwidths of the maskers and the underlying auditory filters.

The stimulus conditions examined in 2 subjects in Experiment 2, at a test frequency of 2000 Hz, were very similar to those used by Stelmachowicz and Jesteadt (1984) to collect normative data they later used to evaluate tuning in impaired ears (Stelmachowicz, et al., 1985). They measured PTCs at 2000 Hz for various probe levels using 100-Hz-wide narrow-band noise maskers, without any background noise. They concluded that Q_{10dB} did not change appreciably with level. In the present study, when high-level PTCs were obtained in quiet at 2000 Hz, without background noise, Q_{10dB} remained about the same, which is essentially a replication of their results. However, the introduction of background noise in the present study changed Q_{10dB} by -15%, an appreciable decrease in tuning at high levels, which was due to masking of combination-band detection cues. These results imply that the normal-hearing data reported by Stelmachowicz and Jesteadt (1984) were probably influenced by combination-band detection cues and consequently overestimated the sharpness of tuning at 2000 Hz.

High-level tuning curves obtained in broad-band background noise indicate that when combination tones and other off-frequency cues are minimized, the steep low-frequency side of a PTC flattens or disappears and a much broader tuning characteristic is revealed. This implies that the tuning characteristic of the normal ear, without the strong influence of combination-tone or combination-band detection cues, is considerably broader at high intensities than it is at low intensities. Because of this, it would seem prudent, for comparing tuning in normal-hearing and hearing-impaired subjects, to avoid a measure of tuning that is strongly influenced by combination-tone or combination-band detection cues in the normal ear. For simultaneous-masking procedures, it appears that this can be done by obtaining normal estimates of tuning in a broad-band background noise.

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