Temporal overshoot in simultaneous-masked psychophysical tuning curves from normal and hearing-impaired listeners

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Simultaneous-masked psychophysical tuning curves (PTCs) were obtained from normal-hearing and sensorineural hearing-impaired listeners. The 20-ms signal was presented at the onset or at the temporal center of the 400-ms masker. For the normal-hearing listeners, as shown previously [S. P. Bacon and B. C. J. Moore, J. Acoust. Soc. Am. **80**, 1638–1645 (1986)], the PTCs were sharper on the high-frequency side for a signal in the temporal center of the masker. For the hearing-impaired listeners, however, the shape of the PTC was virtually independent of the temporal position of the signal. These data suggest that the mechanisms responsible for sharpening the PTC with time in normal-hearing listeners are ineffective in listeners with moderate-to-severe sensorineural hearing loss

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INTRODUCTION

Zwicker (1965a,b) observed that a brief signal was more easily masked if it occurred at the onset rather than at the temporal center of a longer duration masker. The magnitude of that effect was as large as 15 dB. He called it the "overshoot" phenomenon. Many authors have subsequently characterized, in great detail, the overshoot phenomenon in normal-hearing listeners (see Bacon and Viemeister, 1985a, for a review). The time course of temporal overshoot was studied by Elliott (1967), Green (1969), Bacon and Viemeister (1985b), and by Bacon and Moore (1986b). The frequency dependence was investigated by Green (1969), Leshowitz and Cudahy (1975), Bacon and Viemeister (1985a,b), and Bacon and Moore (1986b). Bacon and Viemeister (1985a,b) examined overshoot by comparing the amount of masking produced by a gated masker with that produced by a continuous masker. Their results showed that a gated 50-ms masker produced up to 20 dB more masking than a continuous masker. This gated-continuous threshold difference occurred primarily when the masker frequency was above the signal frequency.

Bacon and Moore (1986a) examined the frequency dependence of the overshoot phenomenon further. They obtained simultaneous-masked psychophysical tuning curves (PTCs) from three normal listeners for a 20-ms signal that occurred either at the beginning, in the temporal center, or at the end of a 400-ms masker. The PTCs were sharpest when the signal was at the temporal center of the masker, and broadest when it was at the beginning of the masker. Their results showed that most masking occurs at masker onset. The biggest effect of signal temporal position was on the high-frequency side (i.e., where the masker frequency is above the signal frequency).

Since the temporal overshoot phenomenon was first observed, there have been many conjectures about the mechanisms underlying it. Green (1969) considered three possibilities: (1) that the auditory filter becomes more highly tuned with time after onset of stimulation, (2) that spectral splatter occurring at the onset of a masker causes a transient increase in masking, and (3) that neural adaptation or "equilibration" accounts for the phenomenon.

The idea that the auditory filter requires time to develop fine tuning was supported by Scholl (1962) and Elliott (1967) but was seriously questioned by Zwicker and Fastl (1972). Later, Moore *et al.* (1987) questioned that explanation further. They derived auditory filter shapes in simultaneous masking for brief signals at the beginning, at the temporal center, or at the end of notched-noise maskers. The derived filter shapes did not change shape consistently with signal temporal position.

The idea that spectral splatter is responsible for temporal overshoot was addressed directly by Bacon and Viemeister (1985a). They found that the contribution of splatter to temporal overshoot was very small provided that the rise time of the masker was greater than 5 ms.

Physiological data supporting the neural-adaptation explanation have been reported by Smith and co-workers (1971, 1975, 1979), although there are no data indicating a frequency-dependent adaptation (Abbas, 1979; Harris, 1977; Smith, 1979), which would be necessary to account for the psychophysical data (Bacon and Viemeister, 1985a,b; Bacon and Moore, 1986a,b). In addition, recent psychophysical data (Bacon and Jesteadt, 1987) suggest that adaptation cannot account for the frequency-dependent temporal overshoot effect. Bacon and Moore (1986b) have suggested that an interaction between adaptation and some other process, like suppression, might possibly account for the frequency-dependent overshoot.

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The purpose of this study was to characterize the nature of temporal overshoot in ears with demonstrably abnormal frequency resolution, as reflected by shallow high-frequency slopes of simultaneous-masked PTCs. Since the largest temporal overshoot effects are seen on the high-frequency side of tuning curves of normal listeners, which is the steep-sloped segment most likely related to sharp active tuning mechanisms in the cochlea, we postulated that the temporal overshoot phenomenon might be dependent upon the integrity of the physiological mechanisms underlying that sharp tuning. This reasoning would predict that the temporal overshoot phenomenon would be absent in cochlear hearing-impaired listeners who have relatively flat PTCs and therefore, presumably, impaired cochlear tuning mechanisms.

I. METHODS

Two normal-hearing listeners and two moderate-to-severe sensorineural hearing-impaired listeners participated in the experiment. The normal-hearing listeners had thresholds less than 10 dB HL from 125 Hz to 6 kHz. Table I shows the absolute sensitivity thresholds of the hearing-impaired listeners for 200-ms tones, obtained using the adaptive procedure described below. All subjects had extensive experience with the psychophysical task prior to testing.

Sinusoidal signals and maskers, generated from separate frequency synthesizers, were gated on and off with 10-ms raised-cosine ramps. The signal had a total duration, from onset to offset, of 20 ms; the total masker duration was 400 ms. When masker and signal frequencies were identical, the two signals were added in phase. A mathematical correction was applied to the data obtained under those conditions to calculate the masker levels that correspond to a quadrature-phase relation between signal and masker.[1]

TABLE I. Thresholds from hearing-impaired listeners (dB SPL).

Listener	Test frequency 250 Hz	300 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz
MGR	63	64	57	54	62	73
RAL	51	55	64	57	59	57

Simultaneous-masked PTCs were measured for two temporal relations between masker and signal. In one, called the onset condition, both the signal and masker were gated on together with identical onset ramps. In the other, called the centered condition, the signal was gated on at the temporal center of the 400-ms masker. The signal was presented at a low sensation level (8–15 dB SL) for normal-hearing and hearing-impaired listeners. A four-interval, four-alternative, forced-choice adaptive procedure was used to determine the level of the masker that was required to just mask the fixed-level signal. Each trial consisted of a 500-ms warning light followed by four 400-ms observation intervals, each separated by a 250-ms silent interval. Feedback was provided after each response. The adaptive procedure used a two-up/one-down stepping rule to estimate the masker level necessary for 71% correct decisions. Threshold was defined as the average of the last 6 out of 12 level reversals in the adaptive procedure. Step size was 4 dB for the first six reversals and 2 dB during the last six reversals. All thresholds reported here are the average of three or more threshold determinations for each condition. Signal frequencies of 500, 1000, and 3000 Hz were tested with the normal-hearing listeners. One of the hearing-impaired listeners was tested at 500 and 1000 Hz, the other was tested at 1000 Hz only.

II. RESULTS

A. Normal-hearing listeners

PTCs from the normal-hearing listeners are shown by the three double-panel graphs in Fig. 1 for listener BPK and in Fig. 2 for listener TRC. Data for the equal onset condition

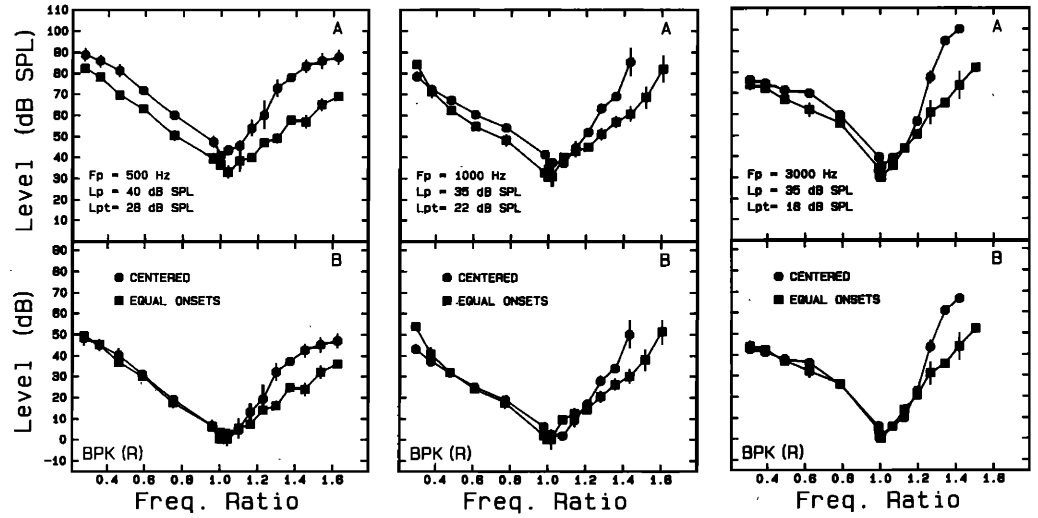

FIG. 1. Comparisons of simultaneous-masked PTCs from normal-hearing listener BPK when the signal is centered in the masker (circles) or is at the onset of the masker (squares). Panel A: masker levels in dB SPL. Panel B: masker levels normalized to the masker level at the minimum masker-level frequency in order to remove a component of temporal overshoot that is constant across masker/signal frequency ratio. After normalization, the remaining differences between the tuning curves are characterized by slope differences on the high-frequency sides. *Fp* is the frequency of the probe (signal); *Lp* is the level of the probe (signal) in dB SPL; and *Lpt* = threshold of the probe (signal) in dB SPL.

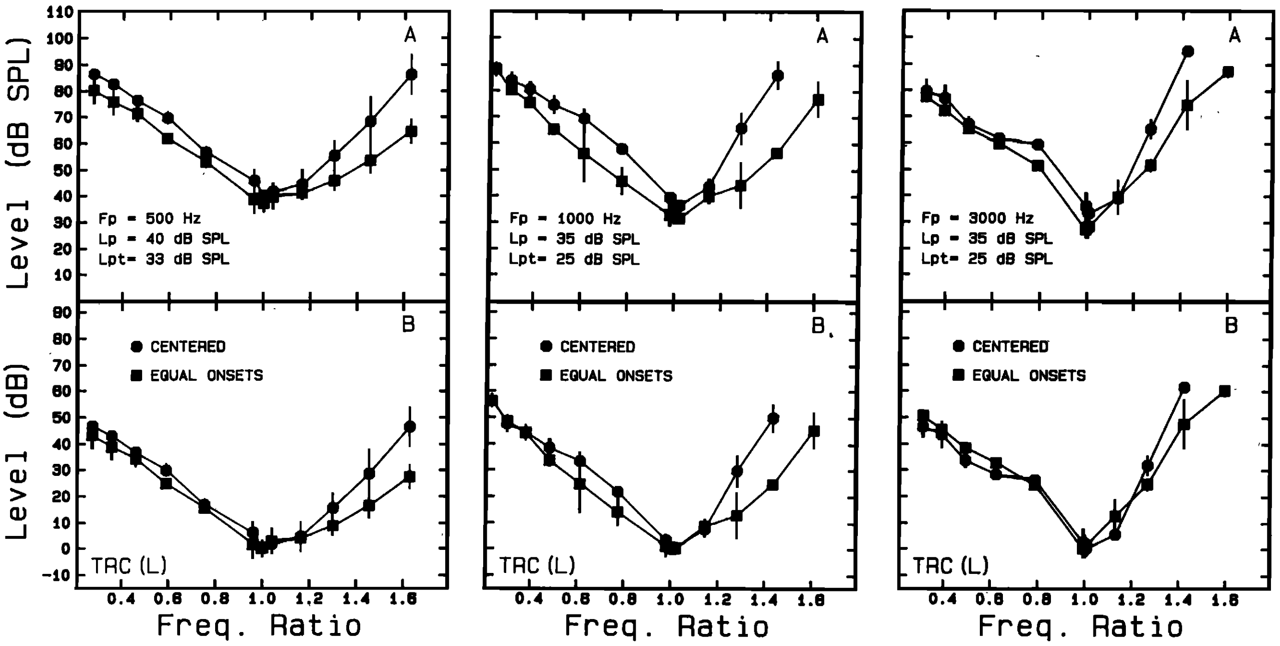

FIG. 2. Comparisons of simultaneous-masked PTCs from normal-hearing listener TRC when the signal is centered in the masker (circles) or is at the onset of the masker (squares). Caption as in Fig. 1.

are represented by closed squares; those for the temporally centered condition are shown by closed circles. The top panel of each graph (labeled A) shows PTCs with masker level in dB SPL on the ordinate and frequency ratio between masker and signal on the abscissa. Data for the three test frequencies (500, 1000, and 3000 Hz) are shown from left to right.

Careful examination of the PTCs for both subjects shows what appears to be two components to the temporal overshoot phenomenon: *a constant component* that is independent of masker frequency, and a *frequency-dependent component* that is restricted mostly to the high-frequency sides of the PTCs. The constant component is seen most easily in the curves for listener BPK, in Fig. 1, at a test frequency of 500 Hz (upper left-hand graph). As seen in panel A, the masker levels for the onset condition (squares) are all at lower SPLs than for the centered condition (circles), indicating that the signal was easier to mask in the onset condition than in the centered condition. Differences between the two curves vary between 5–10 dB over a wide range of masker/signal frequency ratios from 0.25 up to about 1.15.

At masker/signal frequency ratios of 1.2 and larger, the difference between the two curves becomes progressively larger with increasing frequency ratio; i.e., there appears to be an additional temporal overshoot effect that is strongly frequency dependent. This is similar to what has been recently reported by Bacon and Viemeister (1985a,b) and by Bacon and Moore (1986a,b) at masker/signal frequency ratios of 1.2 and larger.

To focus on the frequency-dependent component, while minimizing the constant component of temporal overshoot, we have normalized the two PTCs to the masker level existing at the minimum masker-level frequency for each curve. The results of this normalization process are shown in the bottom panel of each graph (labeled B). For listener BPK in Fig. 1, the normalization process effectively eliminates any differences between the two curves for masker/signal frequency ratios below 1.2. For listener TRC in Fig. 2, only slight differences remain after normalization, and those occur for only two masker frequencies at the 1000-Hz test frequency. The values of the constant differences between each pair of PTCs ranged between 5.9 and 9.4 dB, as indicated in Table II. The average difference is 7 dB for both normal-hearing listeners.

With the constant temporal overshoot effects minimized, the true magnitude of the frequency-dependent effect can be examined. Here, as in the data of Bacon and Moore (1986a), the high-frequency side of the PTC grows steeply with increased frequency ratio for the centered condition. For the onset condition, the high-frequency side of the PTC grows much more gradually with increased frequency ratio.

This frequency-dependent component of temporal overshoot can be most easily characterized by the slopes of the

TABLE II. Tuning curve parameters from normal-hearing listeners.

Listener	Signal frequency (Hz)	Constant overshoot (dB)	High-frequency slopes Onset (dB/oct)	Centered (dB/oct)	Reduction factors
BPK	500	9.0	61	101	0.60
	1000	6.0	64	136	0.47
	3000	6.5	102	243	0.42
TRC	500	7.0	51	89	0.57
	1000	9.4	77	145	0.53
	3000	5.9	108	192	0.56

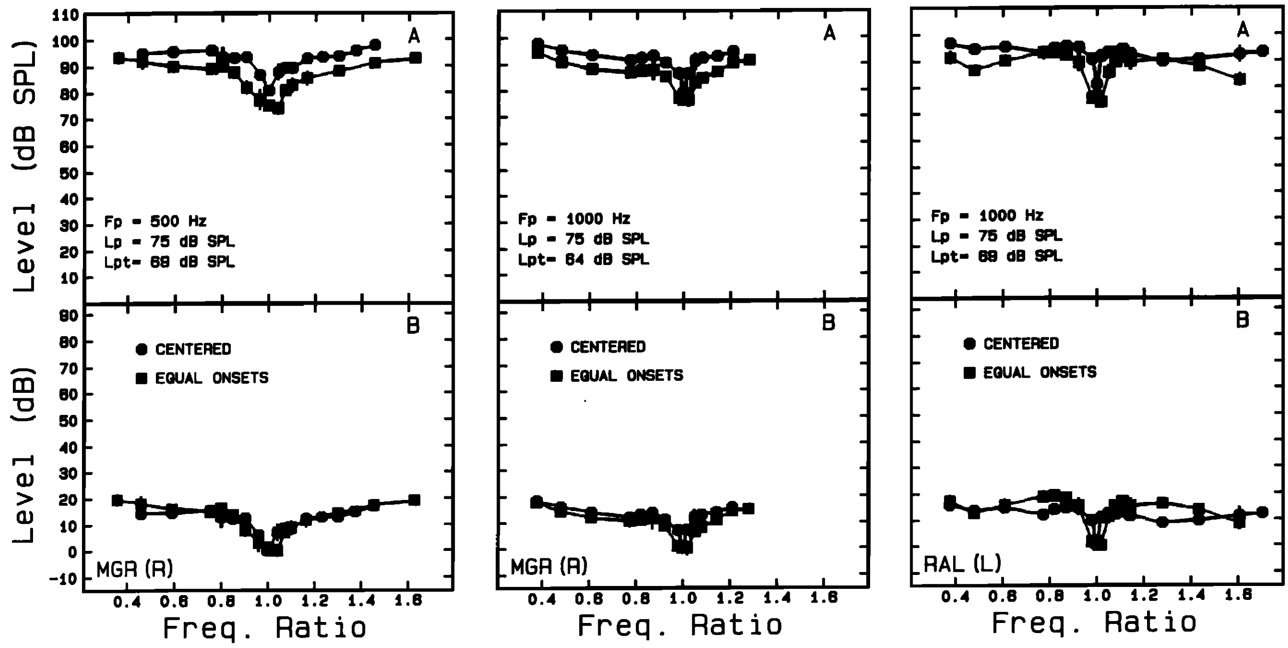

FIG. 3. Comparisons of simultaneous-masked PTCs from hearing-impaired listeners MGR and RAL when the signal is centered in the masker (circles) or is at the onset of the masker (squares) as in Fig. 1. In contrast to the normal-hearing listeners, after normalization in panel B, for hearing-impaired listeners there are no substantial differences remaining between the two tuning curves.

high-frequency sides of the two PTCs,[2] and the magnitude of the differences between those slopes is well specified by the ratios of the two slopes. These are given in Table II. For example, with listener BPK at a signal frequency of 500 Hz, the high-frequency slope for the centered condition is about 101 dB per octave, while the slope for the onset condition is only 61 dB per octave. In the last column of Table II, the ratio of the two slopes is given. For this listener at 500 Hz, the high-frequency slope of the PTC was changed by a factor of 0.60, when the signal was moved from the center to the onset of the masker. As indicated in Table II, those slope-reduction factors varied between 0.42 and 0.60 across signal frequencies and between listeners. The mean slope-reduction factor is about 0.53, when averaged across test frequencies and listeners.

In summary, there appear to be two components to the temporal overshoot phenomenon in normal-hearing listeners, one that is constant across masker frequency and another that is dependent upon masker/signal frequency ratio. The constant temporal overshoot, which is independent of masker/signal frequency ratio, is about 7 dB for these particular listening conditions. The frequency-dependent component, which is restricted to the high-frequency side of the PTC, can be described as a reduction in the high-frequency slope of the PTC by an average factor of 0.53.

B. Hearing-impaired listeners

PTCs from the two hearing-impaired listeners are shown in Fig. 3 by three double-panel graphs. PTCs for signal frequencies at 500 and 1000 Hz were obtained from listener MGR; a signal frequency of 1000 Hz was used for listener RAL. Listener MGR is a 27-year-old male with Alport's Syndrome, which is characterized by a combination of progressive sensorineural hearing loss and renal failure. His sensorineural loss stabilized 7 years ago after renal transplantation. Listener RAL is a 35-year-old male, who has a progressive sensorineural loss of unknown etiology.

Three general features of the results from the hearing-impaired listeners are noteworthy. First, their PTCs are uniformly flat compared with those from the normal-hearing listeners. This, of course, was by design, since it was our purpose to examine temporal overshoot in hearing-impaired listeners with abnormal frequency resolution. Second, sizable temporal overshoot effects are seen in both listeners. Third, when the two different curves are normalized to the masker level at the minimum masker-level frequency, as in panel B, no frequency-dependent temporal overshoot effects are seen.[3] All of the differences between masker levels for the centered and onset conditions are apparently frequency independent, and those frequency-independent differences (5.8 to 7.0 dB) are similar in size to those seen in the normal-hearing listeners (compare Table III with Table II).

III. DISCUSSION

Two general findings emerge from these results. First, for normal-hearing listeners, there appear to be two components to the temporal overshoot phenomenon. One is roughly constant across masker/signal frequency ratio, and is demonstrated by an approximate 7-dB increase in the effectiveness of the masker when the signal is at the onset of the masker as compared to the temporal center of the masker. The other component is frequency dependent, and occurs primarily when the masker frequency is above the signal frequency. When the signal is at the onset of the masker, the slope of the high-frequency side of the PTC is approximately half of what it is when the signal is temporally centered in the masker. The two components of temporal overshoot we pro-

TABLE III. Tuning curve parameters from hearing-impaired listeners.

Listener	Signal frequency (Hz)	Constant overshoot (dB)	High-frequency slopes Onset (dB/oct)	High-frequency slopes Centered (dB/oct)
MGR	500	7.0	18	15
	1000	5.8	29	18
RAL	1000	5.8	−5	0

pose here are also observable in the reconstructed PTCs for continuous versus gated maskers reported by Bacon and Viemeister (1985a) and in the PTCs for onset versus centered signals reported by Bacon and Moore (1986a).

Second, in hearing-impaired listeners with cochlear hearing losses and abnormally flat PTCs, the constant component of temporal overshoot remains about the same as in normal-hearing listeners, while the frequency-dependent component on the high-frequency side of the PTC is absent. This finding is similar to that of Carlyon and Sloan (1987), who showed about 5 dB of temporal overshoot for broadband maskers in both normal-hearing and sensorineural hearing-impaired listeners. Our data are also similar to those of Bacon *et al.* (1987), who showed that the size of the overshoot decreases, but is not eliminated, when masker and signal (with a fixed masker/signal frequency ratio of 1.2) are moved from a region of normal hearing into a region of sensorineural hearing loss.

The physiological mechanism responsible for the constant component of temporal overshoot might well be related to what Green (1969) referred to as "equilibration" and what we refer to as short-term neural adaptation. Using a neural threshold criterion that required a constant percentage change in spike rate for detection, Smith and Zwislocki (1971, 1975) have shown, by calculation, that the threshold for a tone increment would be about 5 dB higher when the increment is at the beginning of a masker than when it occurs later in a masker, where substantial neural adaptation has occurred. This adaptation, as mentioned in the Introduction, almost certainly is not frequency dependent, and thus an additional physiological mechanism must be postulated to explain the frequency-dependent component.

The explanation based upon short-term neural adaptation clearly implies that what should be constant (across masker frequency) is *signal detectability*, not *masker level* as we observe. The two are equivalent, however, if growth of masking is independent of the frequency relation between masker and signal. Although growth of masking is known to vary with masker/signal frequency ratio (e.g., Wegel and Lane, 1924), the change may be relatively small for the small amounts of masking (8–15 dB) obtained here (see Bacon and Viemeister, 1985a).

The finding reported here, that the constant component of temporal overshoot is not substantially affected by significant cochlear hearing loss, is also consistent with neural adaptation, since, to the best of our knowledge, there have been no substantial findings of decreased short-term neural adaptation in neural recordings from damaged cochleas.

Recall that the rationale for testing hearing-impaired listeners in this experiment was to determine whether or not temporal overshoot is demonstrable in listeners with abnormal frequency resolution, presumably associated with dysfunctions in the sharp tuning mechanism of the cochlea. We found that the constant component of temporal overshoot was present, but that the frequency-dependent component was not. From this finding we can *speculate* that the frequency-dependent component may be associated with the active nonlinear tuning mechanisms that lead to sharp tuning in normal cochleas. However, a more definitive association might be observed from a population of impaired ears with a range of frequency-resolution deficits that are not quite as extreme as shown here. Finally, it is interesting to note that many other cochlear nonlinearities, such as two-tone suppression and combination-tone generation, also disappear with impaired frequency resolution.

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[1] When masker and signal are at the same frequency, masked thresholds are strongly dependent upon the phase relation between masker and signal. In this experiment, for conditions in which the masker and signal were at the same frequency, masker-level thresholds were obtained using a zero-degree phase relation between masker and signal, which results in amplitude summation rather than intensity summation. Since we wished to compare those masker-level thresholds with conditions in which the masker and signal are at different frequencies, it seemed more appropriate to specify the masker-levels in terms of a quadrature phase relation between masker and signal, which results in intensity summation between masker and signal similar to the case for different masker and signal frequencies. This was done using Eq. (1) listed below, where Im_0 and Is are the intensities of masker and signal obtained at masked threshold for zero-phase addition, and Im_{90} is the masker intensity that would be required to achieve the same ratio of signal-to-masker intensity for quadrature-phase addition as was obtained for zero-phase addition:

$$Im_{90} = Is/[(Is/Im_0) + 2(Is/Im_0)^{0.5}]. \quad (1)$$

The effect of converting zero-phase masker levels to equivalent quadrature-phase masker levels was to decrease the masker levels at the tips of PTCs by about 10 dB. This conversion to quadrature-phase masker levels is equivalent to one used by Vogten (1972, 1978). A recent demonstration of the phase insensitivity of intensity increment threshold supports the validity of this conversion (Weber, 1987).

[2] Slope values were taken from linear least-squares fits of the masker levels on the high-frequency sides of PTCs as a function of the logarithm of masker frequency, and were specified as dB per octave. Masker levels near the tips of the PTCs were not used in those fits. For normal-hearing listeners, only masker/probe frequency differences of 50 Hz or larger were used; for hearing-impaired listeners, the small tip region was ignored, and only the flat high-frequency "tail" portions of the PTCs were fitted.

[3] This lack of a frequency-dependent effect almost certainly cannot be attributed to the fact that the signal was presented at higher SPLs in the hearing-impaired listeners, since the temporal overshoot effect typically *increases* with increases in signal level (Bacon and Viemeister, 1985a).

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