Interactions of forward and simultaneous masking in intensity discrimination[a)]

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Intensity coding mechanisms are explored in a paradigm involving both forward and simultaneous masking. For intensity discrimination of 1000-Hz pure tone in quiet, a near-miss to Weber's law is observed. However, as more stimulus components are added to this relatively simple experiment, interactions among components produce a more complex pattern of results. An intense forward masker, while not causing any threshold shift for the test tone, produces a nonmonotonic intensity discrimination function [''the midlevel hump,'' Zeng *et al.*, Hearing Res. **55**, 223–230 (1991)]. The midlevel hump can be removed by the presence of additional notched noise [Plack and Viemeister, J. Acoust. Soc. Am. **92**, 1902–1910 (1992)] or narrow-band noise whose level is increased along with the test tone's standard level. The same midlevel hump can also be enhanced by a fixed-low-level notched noise or a high-level, high-pass noise which causes minimal masking at the test frequency. Interactions of forward masking and simultaneous masking present a serious problem for a clear interpretation of these results. For example, the notched noise was originally intended to restrict off-frequency listening, but on-frequency masking compromised this original purpose and confounded the interpretation of the notched noise effects. By measuring systematically the growth-of-masking functions, the present study identified various interactions of forward and simultaneous masking and clarified the role of off-frequency listening in forward-masked intensity discrimination. Both peripheral and central mechanisms may have contributed to the occurrence, reduction and enhancement of the midlevel hump under these masking conditions. © *1998 Acoustical Society of America.* [S0001-4966(98)01404-0]

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INTRODUCTION

The peripheral auditory system is often modeled as a bank of tuned filters that perform frequency analysis on sounds. The high-frequency selectivity of the auditory filter is accomplished by a passive resonance of the basilar membrane coupled with an active process linked to the nonlinear motor activity of outer hair cells (e.g., Allen and Neely, 1992). Because of this nonlinearity, the output of the array of auditory filters or ''the excitation pattern'' generated by an acoustic stimulus is also highly nonlinear as a function of stimulus level. Both psychophysical and physiological data indicate that for sinusoidal stimuli at low stimulus levels, localized activity occurs over a small range of filters tuned around the stimulus frequency, but as the level is increased, the excitation spreads towards filters with higher and lower center frequencies, particularly on the high-frequency side of the excitation pattern (e.g., Egan and Hake, 1950; Kim and Molnar, 1979).

Auditory discrimination of intensity and frequency has been modeled using both a single-filter model in which the filter is located at the frequency where the largest difference in excitation occurs (Zwicker, 1970) and a multi-filter model in which information from all excited filters is combined either in an optimal fashion (Florentine and Buus, 1981) or in a nonoptimal, unweighted fashion (Moore and Sek, 1994). The ability to use information in different frequency regions to improve auditory performance is often termed ''off-frequency listening.'' Off-frequency listening has been shown to be involved in a wide range of psychophysical measures including intensity discrimination (Viemeister, 1972; Moore and Raab, 1974), the slope of loudness growth functions (Hellman, 1978), differences in temporal integration between normal and impaired listeners (Hall and Fernandes, 1983), and differences in tuning curves obtained in simultaneous and forward masking (O'Loughlin and Moore, 1981).

Attempts to restrict off-frequency listening have used a notched or band-stop noise masker (e.g., Viemeister, 1974; Moore *et al.*, 1985; Schneider and Parker, 1987; Plack and Viemeister, 1992a,b). In these experiments, as the signal level is increased, the level of the notched noise is also increased to restrict off-frequency listening. This increase in the notched-noise level elevates the signal threshold so that intensity discrimination is measured at low sensation levels for all standard levels. To reduce this masking problem, alternative approaches have been used to restrict off-frequency listening. Hellman (1978) used a high-pass noise to mask a 100-Hz tone and reasoned that the high-pass noise would limit off-frequency listening at high frequencies while the apical edge of the basilar membrane would limit naturally

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off-frequency listening at low frequencies. Viemeister (1972) measured intensity discrimination for a tone in high-pass noise and suggested that the ''near-miss'' to Weber's law reflects the observer's use of information of aural harmonics; on the other hand, Moore and Raab (1974) compared intensity discrimination results from relatively low-level, wide-band, high-pass, and notched noises, and found that information from both low- and high-frequency sides of the test tone, not just the aural harmonics, contributes to intensity discrimination at high levels. Florentine (1983) controlled the audibility of very high frequencies (6–19 kHz) using either a high-pass noise or the high threshold naturally present in normal-hearing listeners and found that intensity discrimination for a 1000-Hz tone at 80–90 dB SPL was related to the ability to hear at these very high frequencies. Additional studies found similar results using cochlear-impaired listeners with normal hearing at the test frequency and significant hearing loss in regions of excitation spread (e.g., Penner *et al.*, 1974; Zeng and Turner, 1991).

Because the excitation spreads more toward high frequencies, the low-pass band in a notched noise may play a smaller role than the high-pass band in restricting off-frequency listening. On the other hand, the low-pass noise spreads to the signal frequency and actually interferes with the excitation pattern at the signal frequency. Schlauch (1994) measured intensity discrimination using only a high-pass noise presented at a fixed high level for all standard levels. This high-pass noise masker produced a minimal threshold elevation at the signal frequency but significantly elevated thresholds for higher frequencies in the noise pass band. Under these conditions, Schlauch showed that intensity discrimination and loudness are unaffected for standard levels below 40 dB SPL. However, for standard levels above 40 dB SPL, intensity discrimination is degraded and loudness is reduced, indicating a significant role for off-frequency listening at these higher levels.

The present study evaluates the role of off-frequency listening in intensity discrimination under forward masking. Zeng *et al.* (1991, 1992, 1995) showed that, for a brief pure tone following a high-level masker, intensity discrimination is degraded significantly at medium levels, but by little or not at all at low and high levels, a pattern termed the ''midlevel hump.'' Plack and Viemeister (1992a) used a notched noise in an attempt to restrict off-frequency listening and suggested that ''limiting the intensity information to neurons tuned close to the pedestal frequency should, if anything, increase the magnitude of the effect.'' Instead, Plack and Viemeister found that the notched-noise masker actually reduced the midlevel hump. Although the original motivation for the Plack and Viemeister study was to use the notched noise to restrict off-frequency listening, the apparent contradiction to their original prediction of the notched-noise effects led them to conclude that ''the notched noise obviously does more than limit off-frequency listening, the role of this later process in the original Zeng *et al.* experiment is still unclear (Plack and Viemeister, 1992a, p. 1902).''

In particular, the present study addresses the issue of on-frequency masking caused by the notched noise. Indeed, threshold data from a single subject in the Plack and Viemeister study indicated that the notched noise produced significant masking at the signal frequency so that intensity discrimination was measured at sensation levels between 5 and 15 dB for all standard levels. This on-frequency masking problem, also noted by Plack and Viemeister (1992a), compromised their original purpose of using the notched noise to restrict off-frequency listening and possibly confounded their interpretation of the data. In this paper, three experiments were conducted in an attempt to separate the effects of on-frequency masking and off-frequency listening on forward-masked intensity discrimination. The first experiment used a notched noise to replicate the Plack and Viemeister study; in addition, this experiment extended their study by systematically measuring the growth-of-masking function for a tone in the notched noise in both the presence and absence of forward masking. The second experiment used a narrow-band noise to match threshold shifts caused by the notched noise to study whether the on-frequency masking at the threshold level by itself can remove the midlevel hump at the suprathreshold level. The third experiment used a high-pass noise to reduce the on-frequency masking while limiting effectively off-frequency listening on the high-frequency side of the excitation pattern.

I. GENERAL METHOD

A. Subjects

Six experienced listeners, two females and four males, participated in the present study. Three subjects participated in experiment 1 and the other three participated in experiments 2 and 3. They were between 25 and 30 years old at the time of the experiment. All had normal hearing with less than 10 dB HL thresholds at frequencies of 125, 250, 500, 1000, 2000, and 5000 Hz. For all measurements, subjects were seated in a double-walled, sound-treated booth and tested individually.

B. Stimuli

Figure 1 shows the temporal and spectral configurations of the three experiments. In all three experiments, the forward masker was a 1000-Hz sinusoid of 100 ms in duration. The test tone was a 1000-Hz sinusoid of 25 ms in duration. There was a 100-ms delay between the offset of the masker and the onset of the tone, at which the average threshold shift due to the forward masker was negligible. In noise conditions, the 25-ms test tone was presented simultaneously at the temporal center of a noise. Unless otherwise noted, the noise had a duration of 125 ms. The noise was a notched noise (experiment 1), a narrow-band noise (experiment 2), or a high-pass noise (experiment 3). All durations included 2.5-ms cosine-squared rise and fall ramps.

All tonal stimuli were digitally generated by an IBM-PC computer using a 16-bit D/A converter at a sampling rate of 20 kHz (TDT model QDA2, Tucker-Davis Technologies). The stimuli were smoothed by an anti-aliasing filter (TDT model FLT3) with a cutoff frequency of 8 kHz. The forward masker was always presented at 90 dB SPL. The level of the standard tone varied from 30 to 90 dB SPL in steps of 10 dB.

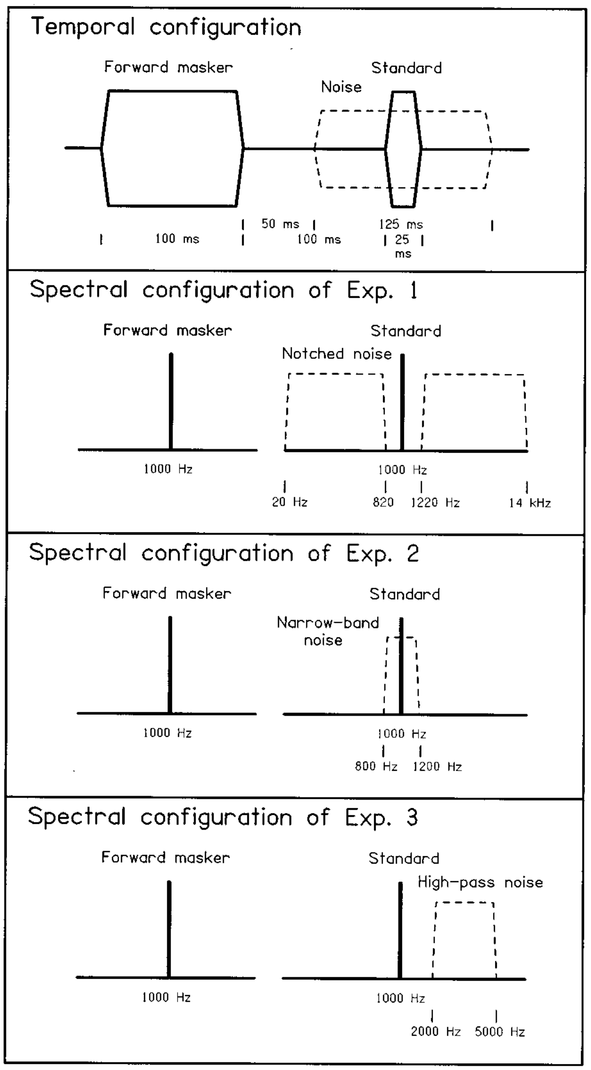

FIG. 1. The top panel shows the temporal configuration of stimuli in experiments 1, 2, and 3. A notched noise was used in experiment 1, a narrow-band noise was used in experiment 2, and a high-pass noise was used in experiment 3. All stimuli were turned on and off with 2.5-ms cosine-squared ramps. The second, third, and bottom panel shows spectral configurations for the stimuli in experiment 1, 2, and 3, respectively.

The levels of the masker and the test tone were separately controlled by two programmable attenuators (TDT model PA3).

All noise stimuli were produced by passing a white noise (TDT model WG1) through a dual-channel filter with a nominal attenuation slope of 135 dB/oct (Stewart VBF-10M). The timing of the noise was controlled by an electronic switch (TDT model SW1). In experiment 1 (the second panel in Fig. 1), the notched noise was similar to the one in Plack and Viemeister's study (1992a) and consisted of a low-pass noise (3-dB cutoff frequencies: 20–820 Hz) and a high-pass noise (1220–14 000 Hz). In experiment 2 (the third panel of Fig. 1), the bandpass noise had a width of 400 Hz with 3-dB down points at 800 and 1200 Hz, respectively. In experiment 3 (the bottom panel of Fig. 1), the high-pass noise (relative to the 1000-Hz signal frequency) had a width of 3000 Hz with 3-dB down points at 2000 and 5000 Hz, respectively. The stimuli in experiment 1 were delivered through an ER-2 insert earphone and calibrated periodically by a B&K sound level meter using a Zwislocki coupler. The ER-2 earphone had a relatively flat frequency response up to 16 kHz. The stimuli in experiments 2 and 3 were delivered through TDH-49 headphones mounted in an MX41/AR cushion and calibrated by the B&K sound level meter using an NBS-9A coupler. Monaural stimulation of the right ear was used for all subjects.

C. Procedure

A two-interval, two-alternative, forced-choice, adaptive procedure was employed to measure the increment in intensity that produces a 79.4% correct response level (3-down, 1-up rule, Levitt, 1971). The two observation intervals were indicated visually on a computer monitor and separated by 650 ms. The silent interval from trial to trial was about 2 s plus the subject's response time. During each trial, the observer had to indicate which one of two intervals contained the signal in the detection experiment or the louder sound in the discrimination experiment. The signal was randomly presented in either one of the two intervals. Visual feedback was provided indicating the correct response. The starting level for the test tone was 20 dB above the estimated threshold in the detection experiment and 10 or 20 dB higher than the standard tone in the discrimination experiment. An initial 5-dB step size was reduced to 1 dB after the first four reversals. Testing continued until 12 reversals had occurred or 60 trials were completed. At the end of each run, intensity discrimination in units of $10 \log(1+\Delta I/I)$ was taken as the mean of the values for the last eight reversals. The result from a run was discarded if less than 10 reversals were obtained or the standard deviation was greater than 5 dB in the run. Three-to-eight runs were obtained for each data point. Following Buus and Florentine's (1991) suggestion, intensity discrimination data in terms of level difference in dB will be plotted on a logarithmic scale.

II. THE NOTCHED-NOISE EXPERIMENT

A. Rationale and method

To measure systematically the degree of on-frequency masking caused by the notched noise, the growth-of-masking function was measured for a 25-ms, 1000-Hz tone as a function of the notched-noise level from −10 to 50 dB in 10 steps. The growth-of-masking function was obtained in both the presence and absence of forward masking in all three subjects. In addition, two control masking functions were obtained in one subject. The ''gated'' control represents a condition where the notched noise had a duration of 25 ms and was gated simultaneously with the 25-ms tone (experiment 2C in Plack and Viemeister, 1992a). Threshold elevations caused by the ''gated'' notched noise were presumably due to suppression (Costalupes *et al.*, 1984). In contrast to the ''gated'' control, the ''fringe-only'' control represents a condition where the notched noise was turned off in the presence of the test tone but was on for 50 ms before the onset of the tone and for 50 ms after the offset of the tone. Threshold

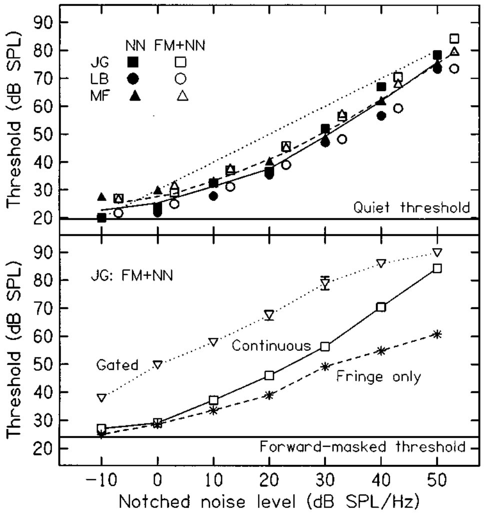

FIG. 2. Growth-of-masking function for a 1000-Hz tone in a notched noise with and without forward masking (upper panel). Individual data are represented by symbols and average data are represented by lines. The dotted line represents a hypothetical linear growth-of-masking function. Growth-of-masking functions for an individual subject obtained with three notched-noise conditions in the presence of forward masking (lower panel). The ''Continuous'' data were the same as in the upper panel. The ''Gated'' data were obtained when the notched noise was gated simultaneously with the test tone. The ''Fringe only'' data were obtained under a condition opposite to the ''Gated'' condition.

elevations caused by the ''fringe-only'' condition were mainly due to adaptation (Smith, 1979; Costalupes *et al.*, 1984).

Forward-masked intensity discrimination was measured first using a paradigm identical to Plack and Viemeister (1992a). The standard level for the tone varied from 30 to 80 dB SPL in 10-dB steps. The notched noise level was increased by 10 dB whenever the standard level was increased by the same amount, in an attempt to keep a constant 30-dB ratio between the tonal standard level and the spectrum level of the notched noise. Data at the 90 dB SPL standard level were not collected because all subjects reported that the 60-dB notched noise was uncomfortably loud. In addition, the forward-masked intensity discrimination function was measured for a fixed notched-noise level at −10, 10, 30, or 50 dB.

B. Results and discussion

The upper panel of Fig. 2 displays the growth-of-masking functions obtained in the continuous notched-noise condition. The filled symbols represent individual data and the solid line represents the averaged data for the notched-noise alone condition; the open symbols represent individual data and the dashed line represents the averaged data for the notched noise plus forward-masking condition. The error bar represents the size of one standard deviation. To reduce overlap between the two data sets in this display, the data in the notched-noise plus forward-masking condition are shifted by 3 dB on the x axis. The horizontal solid line represents the averaged tonal threshold in quiet (19 dB SPL). The diagonal dotted line represents a hypothetical linear growth-of-masking function, in which a 1-dB increment in the notched-noise level would result in a 1-dB threshold elevation for the test tone.

A nonlinear, increasingly steep, growth-of-masking function is clearly noted for the detection of the 1000-Hz test tone in both the notched-noise alone and the notched-noise plus forward-masking conditions. The forward masker appears to produce an additional 2–3 dB threshold elevation, mostly at low and medium notched-noise levels, compared with the masking function in the notched-noise alone condition. It is also noted that the single subject's data in the Plack and Viemeister (1992a) study were very similar to subject LB's threshold data (open circles) in the present study. To demonstrate quantitatively the nonlinear growth-of-masking function, the slope of the masking function was calculated using a linear regression analysis at low notched-noise levels (−10, 0, and 10 dB) and at high noise levels (30, 40, and 50 dB), respectively. For the notched-noise alone condition, the slope averaged across three subjects was 0.43 ($r=0.97$) at low notched-noise levels and 1.32 ($r=0.99$) at high levels; whereas for the notched-noise plus forward-masking condition, the slope was 0.51 ($r=0.99$) at low notched-noise levels and 1.26 ($r=1.00$) at high levels. This increasing steep masking function in notched noise is similar to the ''upward spread of masking'' typically observed for masker frequencies well below the signal (e.g., Egan and Hake, 1950; Oxennam and Moore, 1995) and likely reflects the growth of suppression of the auditory nerve activity (Delgutte, 1990a, b).

The lower panel of Fig. 2 displays three growth-of-masking functions obtained from subject JG only, and representing the ''Continuous'' notched-noise condition (open squares, same as in the upper panel), the ''Gated'' condition (inverted triangles), and the ''Fringe only'' condition (asterisks). The increasingly steep ''Continuous'' masking function is sandwiched between the more linear ''Gated'' and ''Fringe only'' masking functions. A linear regression analysis across all notched-noise levels reveals a slope of 0.89 ($r=0.99$) for the ''Gated'' condition and 0.67 ($r=0.99$) for the ''Fringe only'' conditions. In other words, a 60-dB increment in the notched-noise level results in an approximately 54-dB and 42-dB overall threshold elevation for the ''Gated'' and the ''Fringe only'' conditions, respectively. The threshold difference between the ''Gated'' and the ''Continuous'' conditions shows the classic level-dependent overshoot effect, in which the gated (or onset) threshold is greater than the continuous (or steady-state) threshold at low and medium levels than at high levels (Bacon, 1990). To summarize, the present data show that the notched-noise produced considerable on-frequency masking, even under conditions where the notched noise did not overlap with the test tone either spectrally or temporally (the ''Fringe only'' condition).

Figure 3 shows both individual (JG, LB, and MF) and average data that were obtained using the Plack and Viemeister paradigm (experiment 1, 1992a). The intensity discrimination function in the quiet condition is plotted as a shaded area (mean plus one standard deviation) and the forward-masked intensity discrimination function is plotted

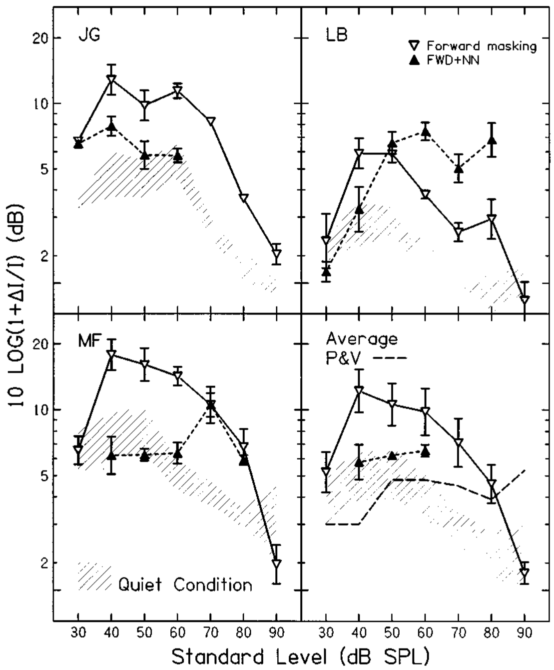

FIG. 3. Replication of the Plack and Viemeister study (1992a), in which the notched-noise level was increased along with the tonal standard level.

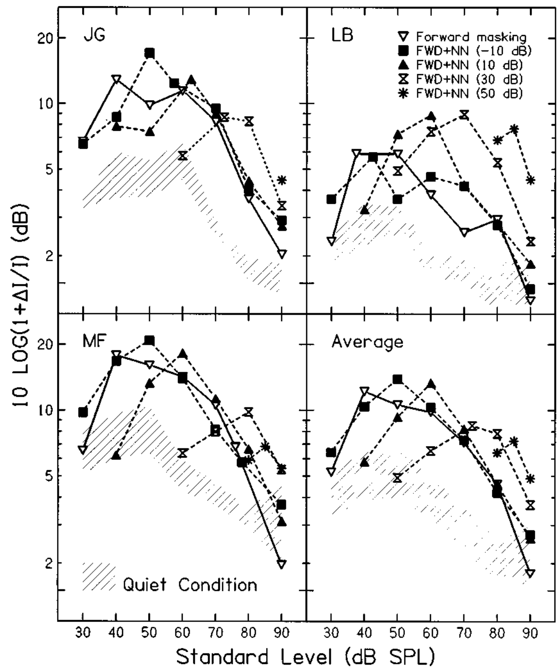

FIG. 4. Forward-masked intensity discrimination functions as a function of the fixed noise level. Note both consistent shift for the hump position and the change for the hump size as a function of the notched-noise level. Some data points are shifted by -2 and 2 dB along the x axis to avoid overlap.

as inverted triangles connected by solid lines. The forward-masked intensity discrimination function in the notched-noise condition is plotted as filled triangles connected by dotted lines. Note the missing data points at 70 and 80 dB SPL for subject JG and at 30 dB SPL for subject MF, because the combination of the forward masker and the notched noise elevated the tonal threshold above these standard levels (see Fig. 2, lower panel). Plack and Viemeister's results are converted from Weber fractions in dB to level differences in dB and are plotted as a dashed line on the ''Average'' panel.

Figure 3 shows that intensity discrimination in quiet followed the ''near-miss'' to Weber's law (e.g., McGill and Goldberg, 1968) and that the forward masker produced a nonmonotonic intensity discrimination function (Zeng *et al.*, 1991). The addition of the notched noise essentially removed the midlevel hump, with the exception of subject LB, who had the smallest hump in the forward masking alone condition and appeared to shift the peak of the ''hump'' from 40 to 60 dB SPL. Although only three data points (at 40, 50, and 60 dB SPL) were averaged from all three subjects, the removal of the midlevel hump could be observed in the average data between present study and the Plack and Viemeister (1992a) study. The 1–2 dB overall elevation in the average data for the present study could be due to a procedural difference (2IFC vs 3IFC) between the two studies.

Figure 4 shows individual forward-masked intensity discrimination functions measured at fixed noise levels of -10, 10, 30, and 50 dB SPL, which is represented by squares, triangles, ''hour glasses,'' and asterisks, respectively. For subject JG, only the 90 dB SPL data point was collected at the 50-dB notched-noise level because of his high threshold under this condition (86 dB SPL, see Fig. 2). Shown again in Fig. 4 are the quiet and forward-masked intensity discrimination functions without the notched noise. Despite individual variability, both individual and average data show a consistent peak shift as a function of the notched-noise level: the peak of the ''midlevel hump'' shifted from 40 dB SPL in the forward-masking alone condition to about 50, 60, 70, and 85 dB SPL at the notched-noise level of -10, to 10, 30, and 50 dB, respectively. The size of the ''hump'' was increased usually at low notched-noise levels (-10 dB for JG and MF, and 10 and 30 dB for LB), and decreased at high noise levels (30 dB for JG, and 30 and 50 dB for MF). The average data show a similar trend in the peak shift and the dependence of the hump size on the notched-noise level. Note also in the average data that the reduced hump at 30-dB notched-noise level is consistent with Plack and Viemeister's observation (1992a) at the same fixed notched-noise level.

In terms of the average data, the present experiment (Fig. 3 and the 30-dB notched-noise condition in Fig. 4) replicated the Plack and Viemeister result (1992a) that the notched noise removed or reduced the midlevel hump. In addition, the present experiment also measured forward-masked intensity discrimination functions at other fixed notched-noise levels from -10 to 50 dB in 20-dB steps. The results indicate that the notched noise did not always remove the midlevel hump, but rather produced level-dependent dual effects on forward-masked intensity discrimination. At low notched-noise levels where on-frequency masking was negligible, the notched noise actually increased the size of the midlevel hump in all three listeners. At high notched-noise levels where significant on-frequency masking occurred, the notched noise decreased the size of the midlevel hump. These new data (Figs. 2 and 4) suggest a close association

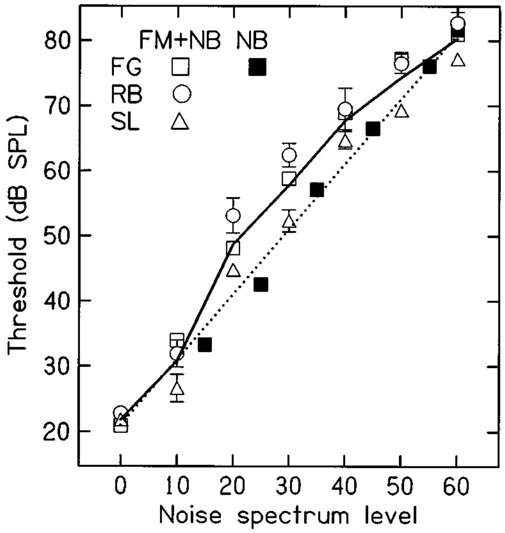

FIG. 5. Growth-of-masking function for a 1000-Hz tone in a narrow-band noise with forward masking: individual data (symbols) and the average data (solid line). The filled squares represent the measured growth-of-masking in noise without forward masking from a single listener and the dotted line represents predicted linear masking function. Bars on each data point represent the size of one standard deviation.

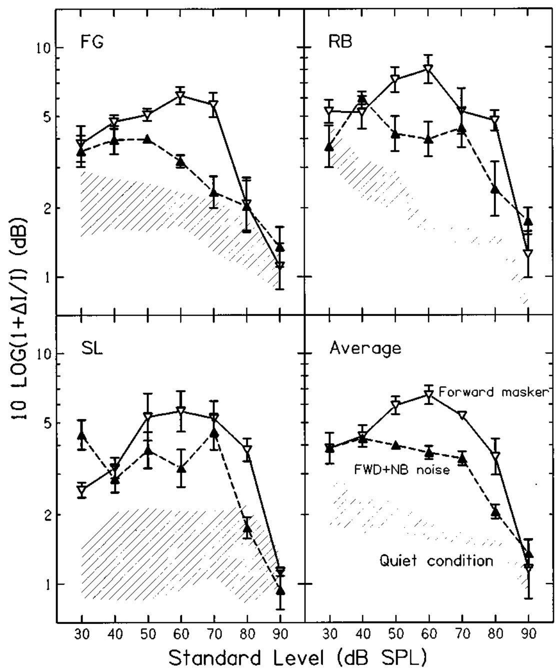

FIG. 6. Effects of the narrow-band noise on intensity discrimination under forward masking (solid triangles). Also shown are the intensity discrimination functions under the quiet control condition (shaded areas) and the forward-masking control condition (open, inverted triangles).

between the removal of the midlevel hump and the on-frequency masking caused by the notched noise.

III. THE NARROW-BAND NOISE EXPERIMENT

A. Rationale and method

A direct test of the relation between on-frequency masking at the threshold level and reduction in the midlevel hump by the notched noise would be to use a narrow-band noise centered on the test frequency. The narrow-band noise would produce direct excitatory masking at the test frequency in contrast to the remote ‘‘suppressive’’ masking caused by a notched noise (Delgutte, 1990a, b). Thresholds for the 25-ms, 1000-Hz tone were first measured in both the narrow-band noise only condition and the noise masker plus the forward-masker condition. A 400-Hz bandwidth of the ‘‘narrow-band’’ noise was chosen to fill in the ‘‘notch’’ in the Plack and Viemeister study. It was noted that 400 Hz was about three times the ‘‘equivalent-rectangular-bandwidth’’ at 1000 Hz (Moore and Glasberg, 1983b) and 2.5 times of the critical bandwidth at 1000 Hz (Zwicker and Fastl, 1990). Thus the present narrow-band noise may limit to some degree the off-frequency listening. The noise spectrum levels ranged from 0 to 60 dB in 10-dB steps. Once the growth-of-masking function was obtained, a narrow-band noise level was selected individually for each subject to approximate the threshold shift caused by the equivalent notched noise in the Plack and Viemeister study (1992a).

B. Results and discussion

Figure 5 shows the growth-of-masking function for the 1000-Hz tone in the narrow-band noise condition with and without forward masking. The open symbols represent individual data and the thick solid line represents the average data in forward masking. The solid squares represent the measured growth-of-masking function in the noise alone condition from a single subject (FG). The dotted line represents predicted thresholds (21 dB above the noise spectrum level) based on the 130-Hz auditory bandwidth at 1000 Hz (Moore and Glasberg, 1983b). Note the consistency between the measured and predicted threshold data.

Similar to previous observations made by Carlyon and Beveridge (1993), the forward masker caused additional masking at medium narrow-band noise levels but not much at low and high noise levels. This nonlinear, *decreasingly* steep (except for narrow-band noise levels between 0 and 10 dB) growth-of-masking function in the narrow-band condition contrasts sharply with the *increasingly* steep growth-of-masking function in the notched-noise condition (Fig. 2). Using the same linear regression analysis, the average slope of the growth-of-masking function was estimated to be 1.34 ($r=0.97$) at low narrow-band noise levels (0, 10, and 20 dB) and 0.63 ($r=1.00$) at high noise levels (40, 50, and 60 dB). These slope values were almost reversed from the values at low and high notched-noise levels. These slope differences may reflect two different physiological mechanisms: a suppressive masking caused by the notched noise and an excitatory masking caused by the narrow-band noise (Delgutte, 1990a, b).

Figure 6 shows individual and average intensity discrimination data in the forward masker plus the narrow-band noise condition (solid triangles) as well as data in two additional control conditions. The quiet control condition produced an intensity discrimination function abiding by the near-miss to Weber’s law. The forward-masking alone control condition produced a nonmonotonic intensity discrimination with a midlevel hump which was similar in magnitude to that found in the original Zeng *et al.* study (1991) but smaller than that found in the Plack and Viemeister study (1992a) and the present experiment 1. Similar to the notched noise, the narrow-band noise also removed the midlevel hump. Both noise data suggest that on-frequency masking, independent of its origin, can remove or reduce the midlevel hump.

IV. THE HIGH-PASS NOISE EXPERIMENT

A. Rationale and method

The fixed-low-level, notched-noise data (Fig. 4) indicate that, under conditions where on-frequency masking was minimized, limiting off-frequency listening could increase the midlevel hump as Plack and Viemeister (1992a) originally predicted. To further separate the interactions between off-frequency listening and on-frequency masking, the present experiment used a high-level, high-pass noise to produce minimal on-frequency masking while effectively limiting off-frequency listening on the high-frequency side of the excitation pattern.

First, a forward-masking pattern of the 1000-Hz pure tone was measured to avoid common problems such as combination tones and beats in tone-on-tone simultaneous masking (Egan and Hake, 1950). The forward masker was a 1000-Hz tone and had a duration of 100 ms. Thresholds were measured for a 5-ms test tone with 1-ms signal delay. Test frequencies were at 500, 1000, 1500, 2000, 3000, and 4000 Hz. All stimuli had cosine-squared 2.5-ms ramps. A masking pattern measured under these conditions has been referred as the ''internal representation'' of the forward masker (Bacon and Brandt, 1982; Sidwell and Summerfield, 1985), and can be used to derive the actual ''excitation pattern'' by taking into account the nonlinear characteristics of forward masking (Moore and Glasberg, 1983a).

Second, a simultaneous masking pattern of the high-level, high-pass noise was obtained by measuring thresholds of a 25-ms test tone presented at the temporal center of the high-pass noise. The signal frequency was chosen at 1000, 1250, 1500, 2000, 3000, and 4000 Hz. The forward masker was also included in this experiment, but its effect seemed to be negligible because the obtained masking pattern was very similar to that of Schlauch (1994) in the absence of forward masker. Finally, forward-masked intensity discrimination was measured in the presence of this additional high-level, high-pass noise masker.

B. Results and discussion

Figure 7 shows the average data of the three subjects, except for the 60 dB SPL tonal forward-masking pattern which is based on the data of a single subject (SL). The absolute thresholds of the tonal stimuli are represented by the dotted line and marked as ''Quiet threshold.'' The forward-masking patterns of the 1000-Hz tone (solid lines) show broad excitation areas across frequency, particularly at the high level (90 dB) and toward the high-frequency side. The high-pass noise simultaneous masker caused a 10-dB threshold shift for the 1000-Hz tone, while elevating the threshold to 60 dB SPL for the 1500-Hz tone and to about 80 dB SPL

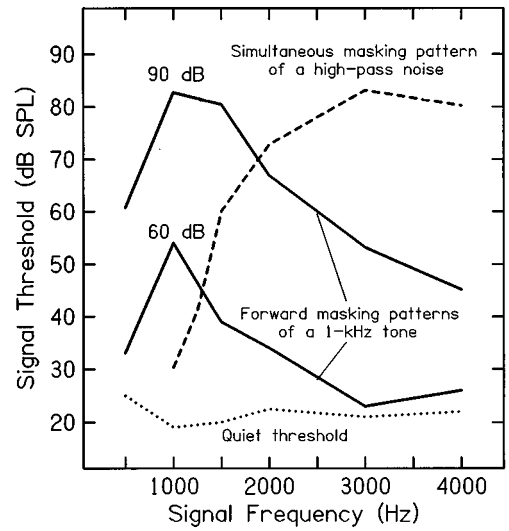

FIG. 7. Forward-masking patterns for the 1000-Hz test tone at 60 and 90 dB SPL (two solid lines). A simultaneous masking pattern for a high-pass noise presented at a 50-dB spectrum level (the dashed line). Absolute thresholds in the quiet condition (the dotted line).

for frequencies higher than 2500 Hz (dashed line). The data suggest that the present high-pass noise can effectively limit off-frequency listening on the high-frequency side while producing minimal on-frequency masking.

Figure 8 shows forward-masked intensity discrimination data in the presence of the high-pass noise (solid triangles). The same two control conditions as in the narrow-band noise experiment are also included. Both individual and average data show degraded intensity discrimination performance at medium and high standard levels in the high-pass noise condition, and the same or slightly better performance at low

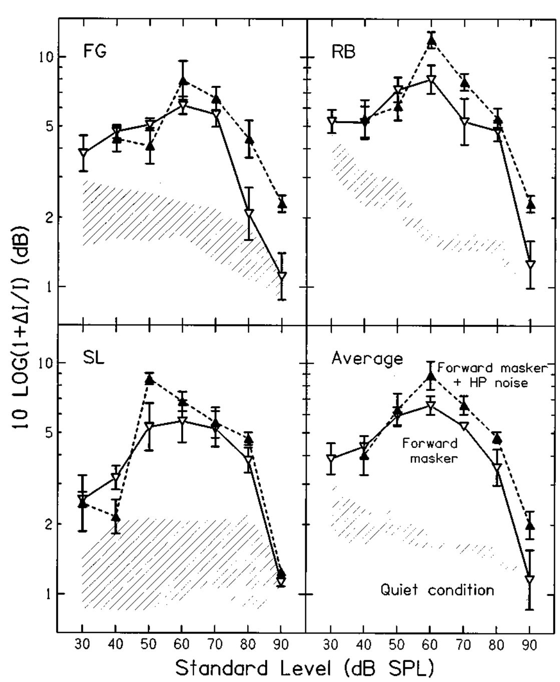

FIG. 8. Effects of the high-pass noise on intensity discrimination under forward masking (solid triangles). Also shown are the same two control conditions as in Fig. 6.

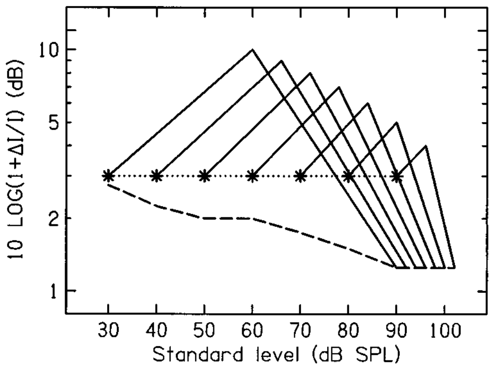

FIG. 9. A schematic model to show how on-frequency masking at the threshold level can remove the midlevel hump in forward-masked intensity discrimination. The dashed line represents the intensity discrimination function in quiet. Solid lines represent a family of forward-masked intensity discrimination functions with successive signal threshold shifts caused by the noise simultaneous masker. Asterisks connected by the dotted line represent the intensity discrimination function under a condition similar to that in the Plack and Viemeister study (1992a).

levels. In contrast to the removal of the midlevel hump by the notched noise and narrow-band noise, a greater midlevel hump is observed in the high-pass noise condition than in the control condition.

The present results indicate a clear role of off-frequency listening in forward-masked intensity discrimination: Under conditions where the on-frequency masking problem is controlled, indeed as Plack and Viemeister (1992a) suggested, limiting the off-frequency listening cue ''should, if anything, increase the magnitude of the effect.'' The increased midlevel hump under limited off-frequency listening conditions adds another piece of evidence to the body of literature demonstrating the role of off-frequency listening in auditory perception. Consistent with previous studies without forward masking (Schlauch, 1994), the present result also shows that the effect of off-frequency listening is greater at moderate and high levels than at low levels. An obvious interpretation for this level effect is that a low-level tone generates localized excitation around the test frequency while moderate to high level tones cause excitation to spread to other frequency regions, which causes minimal effect of the high-pass noise on intensity discrimination at low levels and a significant effect at moderate to high levels.

V. FINAL REMARKS

The most important finding in the present study is the clarification of the role of off-frequency listening in forward-masked intensity discrimination. If the on-frequency masking is minimized by using a low-level notched noise or a high-level high-pass noise, then limiting off-frequency listening does indeed increase the magnitude of the midlevel hump in forward masking. In addition, based on the systematic measurement of the growth-of-masking functions, the present study also shows that the removal of the midlevel hump by the notched noise or the narrow-band noise is always associated with significant on-frequency masking.

Figure 9 presents the data (Fig. 4) in a schematic fashion to demonstrate at a phenomenological level how on-frequency masking could reduce the midlevel hump in forward masking. The dashed line represents the near-miss to Weber's law, or the intensity discrimination function in quiet. The solid lines represent a family of ''idealized'' forward-masked intensity discrimination functions, which from left to right reflect an increasingly elevated threshold at the test frequency (on frequency masking) as a function of the noise level. The asterisk symbol on each function represents intensity discrimination performance measured at the lowest standard level. Figure 9 indicates that the notched noise, when presented at a fixed level, did not actually remove the midlevel hump but rather shifted the hump position to higher levels. However, when the noise level was increased along with the standard level (asterisks connected by the dashed line), the noise appeared to ''remove'' the midlevel hump due to the increased on-frequency masking.

Peripheral mechanisms like adaptation and suppression can account for the removal of the midlevel hump by the notched and narrow-band noises. Based on a differential recovery from prior stimulation by low- and high-threshold auditory neurons (Relkin and Doucet, 1991), Zeng *et al.* (1991) proposed that the midlevel hump is a result of an intensity coding gap at moderate levels in which the high-threshold neurons that normally code intensity at these moderate levels are not recovered whereas the recovered low-threshold neurons are saturated. By shifting the neural dynamic range (Geisler and Sinex, 1980; Palmer and Evans, 1982; Delgutte, 1990a), the notched noise effectively shifts the coding gap and its resulting midlevel hump towards high levels (Fig. 4). The narrow-band noise also shifts the neural dynamic range but not as effectively as the notched noise (Gibson *et al.*, 1985), and accordingly reduces the midlevel hump (Fig. 6) but to a lesser degree than the notched noise (Fig. 3).

Central mechanisms like profile analysis in the frequency domain (Green, 1988) and a similar mechanism in the time domain, namely, ''referential coding'' (Plack *et al.*, 1995; Plack, 1996) can also account for the removal of the midlevel hump by the notched and narrow-band noises. The central hypothesis explains the reduced hump at low sensation levels due to relative comparisons across frequency and time that are more effective when the signal and the noise ''context'' are closer in level (Durlach and Braida, 1969; Green and Kidd, 1983). When the noise level was increased along with the signal, both the temporal and spectral profiles of the signal-noise complex were kept constant at the same favorable level, resulting in a removal of the midlevel hump by the noise.

At present, there is a body of evidence for a central origin of the midlevel hump, for example, the greater midlevel hump in backward masking than in forward masking (Plack and Viemeister, 1992b), the presence of a midlevel hump in cochlear implant users (Zeng and Shannon, 1995), or the greater midlevel hump with a shorter forward masker (Schlauch *et al.*, 1997). On the other hand, there is also a body of evidence for a peripheral origin of the midlevel hump (Turner *et al.*, 1992; Zeng and Shannon, 1995; Schlauch and Clement, 1997; Zeng *et al.*, 1996). In particular, Schlauch and Clement (1997) took advantage of a binaural hearing phenomenon in which a 80 dB SPL sound was perceptually unnoticeable in the simultaneous presence of a 93 dB SPL sound in the contralateral ear. However, Schlauch found that this unnoticeable 80-dB forward masker in the ipsilateral ear produced a significant midlevel hump even though the contralateral 93-dB forward masker alone did not produce a midlevel hump. It appears that both peripheral and central mechanisms are involved in the midlevel hump in nonsimultaneous masking and the removal of the midlevel hump by the simultaneous noise masker. Quantitative contributions of these peripheral and central mechanisms to the nonmonotonic intensity discrimination function in forward masking remains to be evaluated.

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Allen, J. B., and Neely, S. T. (**1992**). ''Micromechanical models of the cochlea,'' Phys. Today **7**, 40–47.

Bacon, S. P. (**1990**). ''Effect of masker level on overshoot,'' J. Acoust. Soc. Am. **88**, 698–702.

Bacon, S. P., and Brandt, J. F. (**1982**). ''Auditory processing of vowels by normal-hearing and hearing-impaired listeners,'' J. Speech Hear. Res. **25**, 339–347.

Buus, S., and Florentine, M. (**1991**). ''Psychometric functions for level discrimination,'' J. Acoust. Soc. Am. **90**, 1371–1380.

Carlyon, R. P., and Beveridge, H. A. (**1993**). ''Effects of forward masking on intensity discrimination, frequency discrimination, and the detection of tones in noise,'' J. Acoust. Soc. Am. **93**, 2886–2895.

Costalupes, J. A., Young, E. D., and Gibson, D. J. (**1984**). ''Effects of continuous noise backgrounds on rate responses of auditory nerve fibers in cat,'' J. Neurophysiol. **51**, 1326–1344.

Delgutte, B. (**1990a**). ''Physiological mechanisms of psychophysical masking: Observation from auditory-nerve fibers,'' J. Acoust. Soc. Am. **87**, 791–809.

Delgutte, B. (**1990b**). ''Two-tone suppression in auditory-nerve fibers: Dependence on suppresser frequency and level'' Hearing Res. **40**, 225–246.

Durlach, N. I., and Braida, L. D. (**1969**). ''Intensity perception. I. Preliminary theory of intensity resolution,'' J. Acoust. Soc. Am. **46**, 372–383.

Egan, J. P., and Hake, H. W. (**1950**). ''On the masking pattern of a simple auditory stimulus,'' J. Acoust. Soc. Am. **22**, 622–630.

Florentine, M. (**1983**). ''Intensity discrimination as a function of level and frequency and its relation to high-frequency listening,'' J. Acoust. Soc. Am. **74**, 1375–1379.

Florentine, M., and Buss, S. (**1981**). ''An excitation-pattern model for intensity discrimination,'' J. Acoust. Soc. Am. **70**, 1626–1654.

Geisler, C. D., and Sinex, D. G. (**1980**). ''Responses of primary auditory fibers to combined noise and tonal stimuli,'' Hearing Res. **3**, 317–224.

Gibson, D. J., Young, E. D., and Costalupes, J. A. (**1985**). ''Similarity of dynamic range adjustment in auditory nerve and cochlear nuclei,'' J. Neurophysiol. **53**, 940–958.

Green, D. M. (**1988**). *Profile analysis: Auditory Intensity Discrimination* (Oxford U.P., Oxford, England).

Green, D. M., and Kidd, G. Hr. (**1983**). ''Further studies of auditory profile analysis,'' J. Acoust. Soc. Am. **73**, 1260–1265.

Hall, J. W., and Fernandes, M. A. (**1983**). ''Temporal integration, frequency resolution, and off-frequency listening in normal-hearing and cochlear-impaired listeners,'' J. Acoust. Soc. Am. **74**, 1172–1177.

Hellman, R. P. (**1978**). ''Dependence of loudness growth on the skirts of excitation patterns,'' J. Acoust. Soc. Am. **63**, 1114–1119.

Kim, D. O., and Molnar, C. E. (**1979**). ''A population study of cochlear nerve fibers: Comparison of spatial distribution of average-rate and phase-locking measures of responses to single tones,'' J. Neurophysiol. **42**, 16–30.

Levitt, H. (**1971**). ''Transformed up-down methods in psychoacoustics,'' J. Acoust. Soc. Am. **49**, 467–477.

McGill, W. J., and Goldberg, J. P. (**1968**). ''A study of the near-miss involving Weber's law and pure-tone intensity discrimination,'' Percept. Psychophys. **4**, 105–109.

Moore, B. C. J., and Glasberg, B. R. (**1983a**). ''Masking patterns of synthetic vowels in simultaneous and forward masking,'' J. Acoust. Soc. Am. **73**, 906–917.

Moore, B. C. J., and Glasberg, B. R. (**1983b**). ''Suggested formulae for calculating auditory-filter shapes and excitation patterns,'' J. Acoust. Soc. Am. **74**, 750–753.

Moore, B. C. J., and Raab, D. H. (**1974**). ''Pure-tone intensity discrimination: Some experiments relating to the ''near-miss'' to Weber's law,'' J. Acoust. Soc. Am. **55**, 1049–1054.

Moore, B. C. J., and Sek, A. (**1994**). ''Effects of carrier frequency and background noise on the detection of mixed modulation,'' J. Acoust. Soc. Am. **96**, 741–751.

Moore, B. C. J., Glasberg, B. R., Hess, R. F., and Birchall, J. P. (**1985**). ''Effects of flanking noise bands on the rate of growth of loudness of tones in normal and recruiting ears,'' J. Acoust. Soc. Am. **77**, 1049–1054.

O'Loughlin, B. J., and Moore, B. C. J. (**1981**). ''Off-frequency listening: Effects on psychoacoustical tuning curves obtained in simultaneous and forward masking,'' J. Acoust. Soc. Am. **69**, 1119–1125.

Oxenham, A. J., and Moore, B. C. J. (**1995**). ''Overshoot and the 'severe departure' from Weber's law,'' J. Acoust. Soc. Am. **97**, 2442–2453.

Palmer, A. R., and Evans, E. F. (**1982**). ''Intensity coding in the auditory periphery of the cat: Responses of cochlear nerve and cochlear nucleus neurons to signals in the presence of bandstop masking noise,'' Hearing Res. **7**, 305–323.

Penner, M. J., Leshowitz, B., Cudahy, E., and Richard, G. (**1974**). ''Intensity discrimination for pulsed sinusoids of various frequencies,'' Percept. Psychophys. **15**, 568–570.

Plack, C. J. (**1996**). ''Temporal factors in referential intensity coding,'' J. Acoust. Soc. Am. **100**, 1031–1042.

Plack, C. J., and Viemeister, N. F. (**1992a**). ''The effects of notched noise on intensity discrimination under forward masking,'' J. Acoust. Soc. Am. **92**, 1902–1910.

Plack, C. J., and Viemeister, N. F. (**1992b**). ''Intensity discrimination under backward masking,'' J. Acoust. Soc. Am. **92**, 3087–3101.

Plack, C. J., Carlyon, R. P., and Viemeister, N. F. (**1995**). ''Intensity discrimination under forward and backward masking: Role of referential coding,'' J. Acoust. Soc. Am. **97**, 1141–1149.

Relkin, E. M., and Doucet, J. R. (**1991**). ''Recovery from prior stimulation. I. Relationship to spontaneous firing rates of primary auditory neurons,'' Hearing Res. **55**, 215–222.

Schlauch, R. S. (**1994**). ''Intensity discrimination and loudness in high-pass noise,'' J. Acoust. Soc. Am. **95**, 2171–2179.

Schlauch, R. S., and Clement, B. R. (**1997**). ''Mechanisms underlying nonmonotonic Weber functions in forward-masked intensity discrimination,'' J. Acoust. Soc. Am. (in revision).

Schlauch, R. S., Lanthier, N., and Neve, J. (**1997**). ''Forward-masked intensity discrimination: Duration effects and spectral effects,'' J. Acoust. Soc. Am. **102**, 461–467.

Schneider, B. A., and Parker, S. (**1987**). ''Intensity discrimination and loudness for tones in notched noise,'' Percept. Psychophys. **41**, 253–261.

Sidwell, A., and Summerfield, Q. (**1985**). ''The effect of enhanced spectral contrast on the internal representation of vowel-shaped noise,'' J. Acoust. Soc. Am. **78**, 495–506.

Smith, R. L. (**1979**). ''Adaptation, saturation, and physiological masking in single auditory-nerve fibers,'' J. Acoust. Soc. Am. **65**, 166–178.

Turner, C. W., Zeng, F.-G., Relkin, E. M., and Horwitz, A. R. (**1992**). ''Frequency discrimination in forward and backward masking,'' J. Acoust. Soc. Am. **92**, 3102–3108.

Viemeister, N. F. (**1972**). ''Intensity discrimination of pulsed sinusoids: The effects of filtered noise,'' J. Acoust. Soc. Am. **51**, 1265–1269.

Viemeister, N. F. (**1974**). ''Intensity discrimination of noise in the presence of band-reject noise,'' J. Acoust. Soc. Am. **56**, 1594–1600.

Zeng, F.-G., and Shannon, R. V. (**1995**). ''Possible origins of the nonmonotonic intensity discrimination function in forward masking,'' Hearing Res. **82**, 216–224.

Zeng, F.-G., and Turner, C. W. (**1991**). ''Binaural loudness matches in unilaterally impaired listeners,'' Q. J. Exp. Psych. **43A**, 565–583.

Zeng, F.-G., and Turner, C. W. (**1992**). ''Intensity discrimination in forward masking,'' J. Acoust. Soc. Am. **92**, 782–787.

Zeng, F.-G., Turner, C. W., and Relkin, E. M. (**1991**). ''Recovery from prior stimulation. II. Contribution to intensity discrimination,'' Hearing Res. **55**, 223–230.

Zeng, F.-G., Galvin, J. J., and Relkin, E. M. (**1996**). ''Relative contributions of two neural populations responses to intensity coding,'' J. Acoust. Soc. Am. **100**, 2719.

Zwicker, E. (**1970**). ''Masking and psychophysical excitation as consequences of the ear's frequency analysis,'' in *Frequency Analysis and Periodicity in Hearing*, edited by R. Plomp and G. F. Smoorenburg (Sijthoff, Leiden), pp. 376–396.

Zwicker, E., and Fastl, H. (**1990**). *Psychoacoustics—Facts and Models* (Springer-Verlag, Berlin).