The effect of basilar-membrane nonlinearity on the shapes of masking period patterns in normal and impaired hearing[a)]

Magdalena Wojtczak,[b)] Anna C. Schroder, Ying-Yee Kong, and David A. Nelson
Clinical Psychoacoustics Laboratory, University of Minnesota, 420 Delaware Street SE, Minneapolis, Minnesota 55455

(Received 29 August 2000; revised 28 November 2000; accepted 23 January 2001)

Masking period patterns (MPPs) were measured in listeners with normal and impaired hearing using amplitude-modulated tonal maskers and short tonal probes. The frequency of the masker was either the same as the frequency of the probe (on-frequency masking) or was one octave below the frequency of the probe (off-frequency masking). In experiment 1, MPPs were measured for listeners with normal hearing using different masker levels. Carrier frequencies of 3 and 6 kHz were used for the masker. The probe had a frequency of 6 kHz. For all masker levels, the off-frequency MPPs exhibited deeper and longer valleys compared with the on-frequency MPPs. Hearing-impaired listeners were tested in experiment 2. For some hearing-impaired subjects, masker frequencies of 1.5 kHz and 3 kHz were paired with a probe frequency of 3 kHz. MPPs measured for listeners with hearing loss had similar shapes for on- and off-frequency maskers. It was hypothesized that the shapes of MPPs reflect nonlinear processing at the level of the basilar membrane in normal hearing and more linear processing in impaired hearing. A model assuming different cochlear gains for normal versus impaired hearing and similar parameters of the temporal integrator for both groups of listeners successfully predicted the MPPs.
[DOI: 10.1121/1.1356702]

PACS numbers: 43.66.Ba, 43.66.Dc, 43.66.Mk, 43.66.Sr [SPB]

I. INTRODUCTION

Masking produced by stimuli with fluctuating envelopes has been shown to depend on the rate of fluctuations, the depth of fluctuations, and on the relative frequencies of the masker and the signal (e.g., Zwicker, 1976a, b; Zwicker and Schorn, 1982; Nelson and Swain, 1996; Bacon *et al.*, 1997). Different experimental paradigms have been used to study various aspects of masking by these stimuli. Zwicker (1976a, b, 1986) measured masking period patterns (MPPs) in order to assess temporal resolution in auditory processing and to relate it to the understanding of speech. An MPP is obtained when detection threshold for a short stimulus, or probe, is measured as a function of the temporal position of the probe within a modulated masker. Zwicker and Schorn (1982) suggested that there is no need to ''track'' the whole modulation cycle to assess temporal limitations of envelope processing. They postulated that temporal resolution could be described based on the difference between the masked threshold observed with the probe presented at a peak of a modulated masker and that observed with the probe placed in a valley. Their data showed that this difference decreased with increasing modulation rate of the masker suggesting limited temporal resolution of auditory processing.

It is questionable whether MPPs or simply the difference between thresholds measured at a peak and in a valley of a modulated masker provide information about temporal processing that is not confounded by other factors. Zwicker (1976c) measured MPPs using tonal maskers and probes having either the same or different frequencies. These two masking conditions will be referred to as on-frequency masking (masker frequency equals probe frequency) and off-frequency masking (masker frequency below probe frequency) throughout this paper. Although Zwicker's data were most likely affected by energy splatter produced by the short probe, due to the relatively low frequencies used in this study, they clearly suggest that the shapes of MPPs depend on the relative frequencies of the masker and the probe. In particular, his data show that the dynamic range of MPPs is substantially larger for off-frequency masking than it is for probe frequencies near the masker frequency. Such a result suggests that temporal resolution of fluctuating envelopes is better within the upper accessory excitation produced by the masker (the place above that corresponding to the masker frequency), than it is in the region of the main excitation (the place corresponding to the masker frequency). A similar result was observed by Nelson and Swain (1996) who used probes that did not produce detectable splatter. The probe in their study spanned one cycle of the 100%-modulated masker (starting and ending at zero amplitude) and was temporally positioned so that the peak of the probe coincided either with a peak or with a valley of the masker. Nelson and Swain found that the difference between the thresholds measured with the probe at the peak and in the valley was relatively large in the off-frequency masking condition and was much smaller in the on-frequency masking condition. From the masked thresholds measured at the peak and in the valley for different masker levels, Nelson and Swain constructed

---

[a)]Portions of these data were presented at the 138th meeting of the Acoustical Society of America [M. Wojtczak, A. C. Schroder, Y.-Y. Kong, and D. A. Nelson, J. Acoust. Soc. Am. **106**, 2147(A) (1999)] and the 139th meeting of the Acoustical Society of America [M. Wojtczak, A. C. Schroder, and D. A. Nelson, J. Acoust. Soc. Am. **107**, 2881(A) (2001)].
[b)]Electronic mail: wojtc00l@tc.umn.edu

growth-of-masking functions for each masker-probe combination. For the off-frequency case, the rate of masking growth was faster than for the on-frequency conditions. This was true both at the peak and in the valley, though the difference between the slopes observed in the valley was much smaller than the difference observed at the peak. The steeper growth of masking observed with an off-frequency masker is in agreement with the larger dynamic range of the MPP produced by such maskers (Zwicker, 1976c).

The greater peak-valley difference measured with off-frequency maskers was originally explained in terms of nonlinear growth of simultaneous masking occurring in the region of a peak. It was suggested that the nonlinear growth of masking was mediated by nonlinear neural responses and suppression (Javel *et al.*, 1983; Delgutte, 1990a, b). However, recent physiological and psychophysical studies shed new light onto the observed differences in the rate of masking growth. Ruggero (1992) and Ruggero *et al.* (1997) measured basilar-membrane (BM) responses to tonal stimulation in the chinchilla cochlea. Their data show that a characteristic-frequency (CF) tone produces a BM response that grows in a compressive manner with the tone's intensity. In contrast, a below-CF tone produces a response that grows linearly with intensity. Nonlinear responses of the BM were described earlier by Rhode (1971), Sellick *et al.* (1982), and Robles *et al.* (1986), but their data were obtained using a much less accurate technique, and thus prevented construction of a detailed BM input–output function. The compressive growth of response is believed to reflect the operation of the so-called active mechanism in the cochlea, which was first discovered by Kemp (1978). In a healthy cochlea, this mechanism applies a level-dependent gain to the BM response resulting in strong amplification of the softest stimuli and progressively less amplification of increasingly intense stimuli. As a result of this level-dependent gain, a function exhibiting compressive response growth is observed at the output of the cochlea. When there is damage to the cochlea, to outer hair cells in particular, the gain is reduced and can even be completely eliminated. The reduced gain results in a linearization of BM-response growth (Ruggero and Rich, 1991; Ruggero *et al.*, 1993, 1995, 1996).

The description of the BM mechanical response triggered a series of psychophysical experiments designed to test the consequences of the nonlinear BM behavior. Oxenham and Plack (1997) used a forward-masking paradigm to measure growth of masking produced by an on- and off-frequency masker in listeners with normal and impaired hearing in the presence of a high-pass noise. The growth-of-masking function (described by Oxenham and Plack as the masker level required to just mask the probe, plotted as a function of the probe level) observed in normal-hearing listeners with the off-frequency masker had a substantially shallower slope than the function observed for on-frequency masking. This is in agreement with physiological data, which demonstrate that the BM response to below-CF tones grows faster than the BM response to CF tones (e.g., Ruggero *et al.*, 1997). A different result was observed for the hearing-impaired listeners tested by Oxenham and Plack. For those listeners, the slopes of the masking-growth functions measured with on- and off-frequency maskers were similar. This effect presumably reflects the lack of the active process in those listeners. Based on their data, Oxenham and Plack estimated the rate of response growth for the probe in normal hearing. They accomplished this by computing a ratio between the slopes measured with the off- and on-frequency maskers. This ratio turned out to be very similar to the slope of the function describing BM-response growth in the study by Ruggero *et al.* (1997), supporting the idea that the nonlinear growth of masking observed psychophysically reflects nonlinear response growth at the BM. Further support for the connection between the nonlinear BM behavior and psychophysically observed differences in growth of masking produced by on- and off-frequency maskers was provided by the studies of Nelson and Schroder (1996, 1997), Gregan *et al.* (1998), Hicks and Bacon (1999a, b), and Moore *et al.* (1999).

In the present study, MPPs were measured using on- and off-frequency maskers. The study was primarily motivated by the finding that for maskers with fluctuating envelopes, temporal resolution of the envelopes is better in the upper accessory excitation produced by the masker than it is in the region of the main excitation. The goal of the study was to demonstrate that the seemingly better temporal resolution exhibited for off-frequency maskers reflects nonlinear BM behavior. It is generally believed that temporal processing takes place at a higher stage of the auditory system, whereas the compressive transformation of the stimulus occurs at the level of the BM. It is hypothesized that the differences observed in the measurement of on- and off-frequency MPPs reflect BM nonlinearity rather than an actual difference in temporal processing. In experiment 1, normal-hearing listeners were tested using different masker levels. The MPPs were measured in great detail to establish differences in the shapes of the masking patterns, as measured with on-frequency versus off-frequency maskers (masker frequency an octave below the probe frequency). A model was used to predict the shapes of the measured MPPs. While the model assumed different rates of growth of the response to stimulation by on- and off-frequency maskers at the probe-frequency place, it assumed that the same temporal integrator was operating on the internal representation of the input stimulus in the two masking conditions. In experiment 2, MPPs were measured in listeners with hearing loss of cochlear origin. This was done in order to test whether the differences in the shapes of the on- and off-frequency MPPs are much smaller or practically nonexistent in the case of significant hearing loss, where BM response is more linear.

There is another important aspect to this study. An MPP reflects a combination of simultaneous and nonsimultaneous (forward and backward) masking. The model presented here provides satisfactory predictions of the effects of this combined masking. Although additivity of masking has been modeled in past studies (e.g., Robinson and Pollack, 1973; Penner, 1980; Penner and Shiffrin, 1980; Lutfi, 1983; Moore *et al.*, 1988; Plack and Moore, 1990; Oxenham and Moore, 1994, 1995), to our knowledge none of the models allowed the prediction of masked thresholds in the case where the masker and the signal differed in frequency and overlapped in time. The present study proposes a way to deal with such a complex masking situation.

II. EXPERIMENT 1

To establish differences in the shapes of MPPs observed with on- and off-frequency maskers in normal-hearing listeners, detection threshold for a short probe was measured as a function of the temporal position of the probe within one period of a modulated masker. The experiment was similar to that described by Zwicker (1976c), but higher frequencies and a longer probe duration were used to avoid detection of energy splatter in channels tuned to frequencies different from the probe frequency.

A. Subjects

MPPs were measured in four listeners with normal hearing, but not every subject was available for testing in each condition. Absolute thresholds in these listeners conformed to ANSI standards (1996) for normal hearing at all audiometric frequencies. All subjects had previous experience in psychoacoustic tasks. Subject S1 was the third author and subject S2 was the first author. The other two subjects were paid for their services.

B. Conditions and stimuli

MPPs were measured using a short tonal probe presented at different times during one envelope cycle of a longer-duration sinusoidally amplitude-modulated masker. The probe was gated on for 8 ms, which included a 4-ms steady-state portion and 2-ms raised-cosine ramps. A probe frequency of 6 kHz was used to avoid detection of splatter outside the critical band, due to the relatively short rise and decay times. The masker had a total duration of 512 ms and was 100% modulated at a 3.91-Hz rate, resulting in two full 256-ms modulation cycles during masker presentation. The modulating tone was a cosine starting at the 180-deg phase, thus the masker started and ended at zero amplitude and comprised two envelope peaks and one centered valley, as shown in Fig. 1.

At the beginning of each session, thresholds in quiet were measured separately for the modulated masker and for the probe. Subsequently, masked thresholds for the probe were measured in the presence of the masker with the probe presented at different modulator phases between the two peaks in the masker envelope. Two masker frequencies were used in the experiment: a 3-kHz masker was used to measure off-frequency MPPs and a 6-kHz masker was used to measure on-frequency MPPs. The probe always started with a phase of 90 deg relative to the masker phase at the probe's onset. On- and off-frequency MPPs were measured at masker levels of 65, 75, 85, and 90 dB SPL.

The stimuli were generated digitally on a computer and played out through separate channels of the Tucker-Davis Technologies (TDT) digital-to-analog converter (DD1) at a sampling rate of 50 kHz. The masker and probe were low-pass filtered at 20 kHz (TDT FT6-2) to prevent aliasing and routed to separate attenuators (TDT PA4s). After attenuation, the stimuli were added electrically (TDT SM3) and passed (via a TDT HB6) to a TDH-49 earphone for monaural presentation.

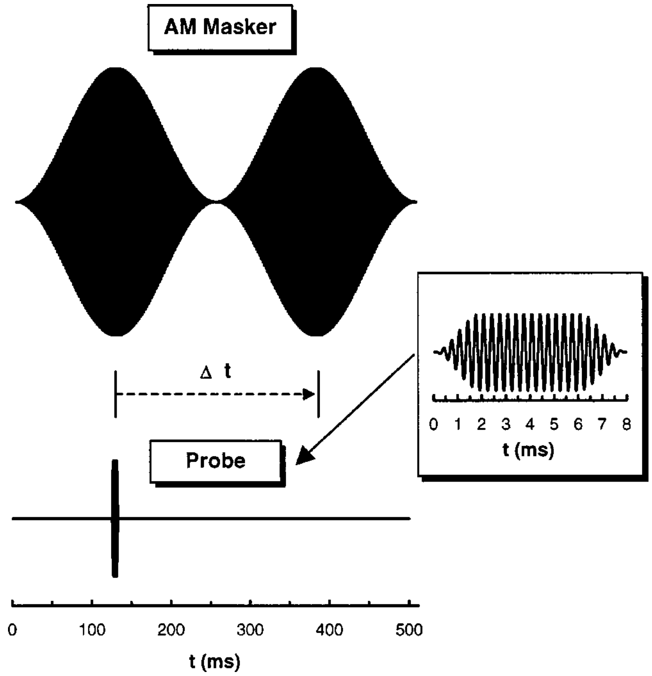

FIG. 1. Schematic illustration of the stimuli used to measure MPPs. A modulated masker is shown in the top section and the probe is shown at the bottom (also magnified in the insert). Time interval Δt marks the cycle of masker envelope, within which masked thresholds for the probe were measured.

C. Procedure

All thresholds were measured using a three-interval forced-choice procedure. The three observation intervals were marked by lights and were separated from one another by 250 ms of silence. For the thresholds measured in quiet, the signal appeared randomly in one of the observation intervals while the other two were silent. When the MPPs were measured, the signal interval contained the masker and the probe, while the other two intervals contained the masker alone. At the beginning of each track, the signal was presented at a highly detectable level. Initially, the signal level was decreased by 8 dB after each correct response and increased by the same amount after each incorrect response until four reversals were obtained. The next two reversals were also obtained using a 1-up/1-down paradigm, but the step size was reduced to 2 dB. This was done in order to quickly reach the range of levels around threshold. Subsequently, another six reversals were obtained using 2-dB steps and a 2-down, 1-up technique, which estimates the 70.7% point on the psychometric function (Levitt, 1971). The threshold was computed as the mean of the last six reversals. After each trial, up to 4 s were allowed for the subject's response. If no response was registered during this period, the trial was repeated with the signal presented at the same level in a randomly selected interval. Feedback indicating the correct interval was provided after each response. Final data points were computed based on at least three threshold esti-

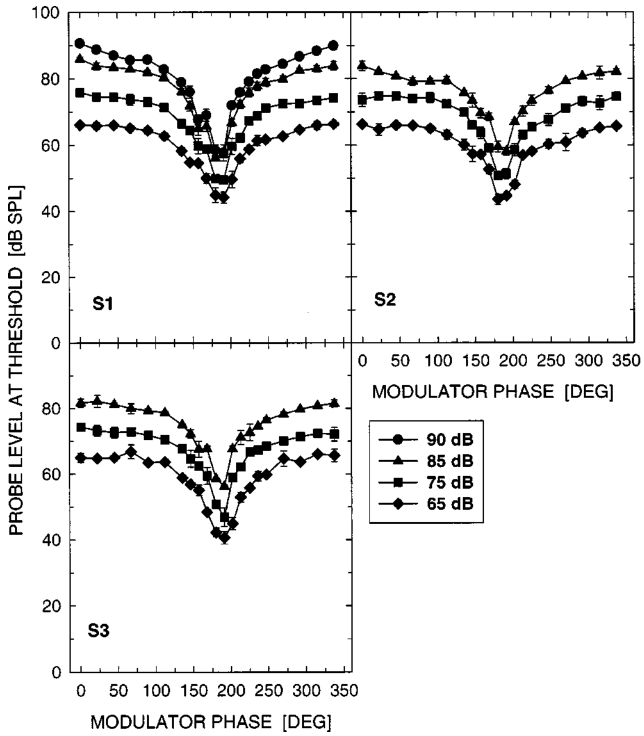

FIG. 2. Individual MPPs measured with a 6-kHz masker and a 6-kHz probe (on-frequency masking) in listeners with normal hearing. Different symbols indicate data obtained at different masker levels. Each panel shows data for a different listener.

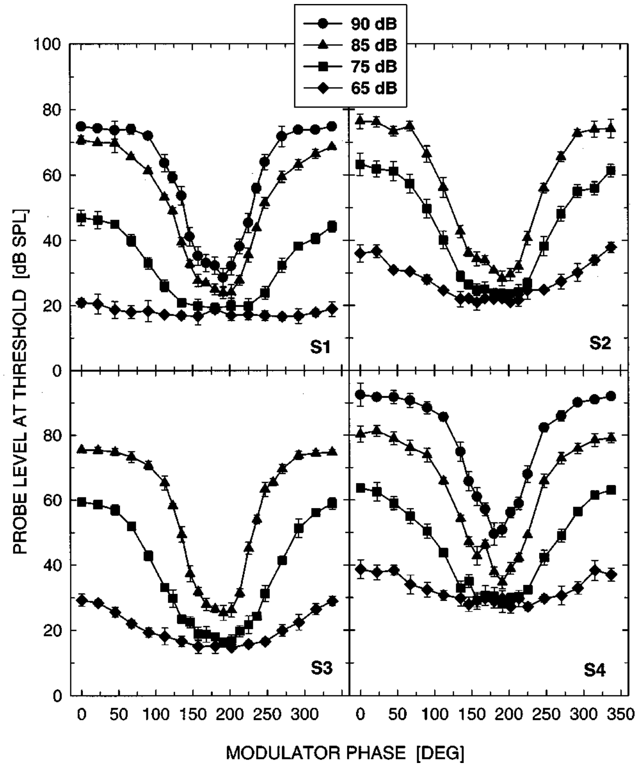

FIG. 3. Individual MPPs measured with a 3-kHz masker and a 6-kHz probe (off-frequency masking) in listeners with normal hearing. Different symbols indicate data obtained at different masker levels. Each panel shows data for a different listener.

mates. More threshold estimates were obtained when the standard deviation for the averaged threshold was larger than 3 dB. It took 35–45 min to obtain an MPP with a single threshold estimate for each temporal position of the probe within the modulation cycle of the masker. Two such masking patterns were typically obtained during one experimental session and the listeners were given a 10-min break between the two runs.

III. RESULTS AND DISCUSSION

Individual masked thresholds measured with the on-frequency masker are shown in Fig. 2. They are plotted as a function of the modulator phase within one modulation cycle of the masker, assuming that the cycle of interest begins at the phase corresponding to the first peak of the masker (0 deg) and ends at the phase corresponding to the second peak of the masker [(360 deg) see Fig. 1]. Separate panels show data obtained from three normal-hearing listeners. Different symbols represent MPPs observed for different masker levels, noted within the insert. These on-frequency MPPs have very short, sharp valleys at all masker levels used in this experiment. The average peak-valley differences were 23 dB, 25.5 dB, 26 dB, and 32.9 dB for masker levels of 65, 75, 85, and 90 dB, respectively. The observed increase in peak-valley difference with increasing masker level reflects slower growth of masking in the valley compared with growth of masking at the peak. This is consistent with the notion that thresholds measured at the peak of a modulated masker are governed by simultaneous masking whereas thresholds measured in a valley are governed mainly by forward masking from the preceding peak. It has been shown that the growth-of-masking function measured in forward masking has a slope that is less than one (Jesteadt *et al.*, 1982; Moore and Glasberg, 1983) and the growth-of-masking slope for simultaneous masking is close to one (Hawkins and Stevens, 1950; Viemeister, 1972). Gregan *et al.* (1998) specifically compared growth-of-masking functions measured at a peak and in a valley of a sinusoidally-modulated masker with growth-of-masking functions measured in simultaneous and forward masking using an unmodulated masker. Their data strongly support the idea that the threshold measured in the valley of a modulated masker reflects forward masking by the preceding peak, whereas the threshold measured at a peak results from simultaneous masking. It has been demonstrated that nonlinear growth of forward masking may be attributed to the nonlinear growth of BM response (Oxenham and Moore, 1995; Plack and Oxenham, 1998). There is evidence based on physiological study that compression on the BM is fast acting, i.e., stimuli presented immediately one after another are compressed independently (Yates, 1995). When the probe is presented during the valley of a modulated masker, the amount of compression applied to the probe most likely differs from the amount of compression applied to the masker during its peak. In effect, nonlinear growth of masking is observed in the valley.

Figure 3 shows MPPs obtained for the off-frequency masker. The peak-valley differences are substantially larger than those observed with the on-frequency masker, except when the threshold in the valley is limited by absolute threshold for the probe (e.g., at the 65 and 75 dB masker levels). For masker levels of 85 and 90 dB SPL, the average peak-valley differences were 47.7 dB and 44.6 dB, respectively. This result is in agreement with earlier reports that, for a given masker frequency, the peak-valley difference is especially large when the masker frequency is much lower than the signal frequency (Egan and Hake, 1950; Mott and Feth, 1986; Nelson and Swain, 1996; Gregan *et al.*, 1998). Gregan *et al.* (1998) demonstrated that the larger peak-valley difference observed with an off-frequency masker compared to that difference measured with an on-frequency masker is determined by the relative frequencies of the masker and the signal rather than the frequency of the signal itself.

Studies that were confined to the measurements of masked thresholds at a peak and in a valley of a fluctuating masker do not provide exhaustive information about the effects of relative masker and signal frequencies on MPPs. In particular, they do not show that MPPs measured with an off-frequency masker have valleys that are not only deeper but also much longer than those observed with an on-frequency masker. As a result, there are substantial differences in the shapes of MPPs measured with on- and off-frequency maskers, as shown in Figs. 2 and 3. These differences could be explained in terms of nonlinear BM behavior. When a sinusoidally varying envelope is subjected to a compressive transformation, the envelope peaks of the compressed masker become broader and the valleys become narrower. However, a short on-frequency probe added to the masker during its presentation would be subjected to the same compression as the portion of the masker that coincides with the probe. Therefore, if the temporal processing of the auditory system had unlimited temporal resolution, the shape of MPPs measured in the on-frequency case would precisely reflect the shape of the original uncompressed masker envelope. That is because any given change in masker amplitude would require a proportional change in probe amplitude to reach the threshold (assuming a constant detection criterion for threshold).

A different situation would be observed with an off-frequency sinusoidally amplitude-modulated masker, whose carrier frequency is well below the probe frequency. Such a masker would produce a linear response at the probe-frequency place, whereas the response to the probe would grow in a compressive way. When moving along a cycle of the masker envelope, any change in the instantaneous masker amplitude would require a much greater change in the probe amplitude to reach the criterion for threshold. The change in the probe amplitude would have to be large enough to overcome the compression. Thus under the assumptions of unlimited temporal resolution and a constant detection criterion for threshold, MPPs with narrower peaks and extended valleys would be observed in the off-frequency masking situations. As demonstrated by results of numerous masking and gap detection tasks, auditory processing appears to have a limited temporal resolution. Assuming the same limited resolution of temporal processing in on- and off-frequency masking situation, more extended valleys should still be expected for the off-frequency MPPs due to the nonlinear BM response.

Sluggishness of auditory temporal processing has often been modeled by applying a temporal integrator (Robinson and Pollack, 1973; Viemeister, 1979; Penner and Shiffrin, 1980; Moore *et al.*, 1988; Plack and Moore, 1990; Oxenham and Moore, 1994), which is assumed to be a linear device. At least to a first approximation, the parameters of the temporal integrator are independent of the frequencies of the stimuli and are also independent of their levels.[1] Therefore, the narrow valleys observed with the on-frequency masker in Fig. 2, and the much longer valleys observed with the off-frequency masker in Fig. 3, most likely reflect the combined effects of the BM nonlinearity *and* the integration due to a limited temporal resolution.

IV. EXPERIMENT 2

Studies of masking using on- and off-frequency maskers in hearing-impaired listeners have consistently demonstrated that the amount of off-frequency masking grows more gradually with masker level than it does in listeners with normal hearing (Nelson and Bilger, 1974; Smits and Duifhuis, 1982; Stelmachowicz *et al.*, 1987; Buus and Florentine, 1989; Murnane and Turner, 1991; Nelson and Schroder, 1996, 1997; Oxenham and Plack, 1997). This is consistent with changes observed in the BM mechanical response of a damaged cochlea. Damage to outer hair cells results in a reduced sensitivity to incoming sounds and a more linear growth of response once the stimuli are presented at levels above their detection thresholds (Ruggero and Rich, 1990, 1991; Ruggero *et al.*, 1993, 1996). As a result, in more severely damaged cochleae, BM responses to CF tones and below-CF tones grow at a similar rate. Oxenham and Plack (1997) measured growth-of-masking functions in hearing-impaired listeners and found that the slopes were similar when the functions were measured with on- and off-frequency maskers, and that they were also similar to the slopes observed in listeners with normal hearing for the on-frequency masking condition. All those results indicate that, in hearing-impaired listeners with a sufficient amount of hearing loss, masking measured with an on-frequency masker grows in a similar way to masking measured with an off-frequency masker. In the discussion of the results obtained from normal-hearing listeners in the present study, it was hypothesized that the different shapes of MPPs observed with the on- and off-frequency maskers result from different rates of masking growth. If our reasoning was correct, then for listeners with cochlear hearing loss, similar MPP shapes should be observed in the two masking conditions. Experiment 2 was designed to test this hypothesis.

A. Subjects

Four listeners with sensorineural hearing loss participated in the study. Their absolute thresholds, expressed in dB SPL, are presented by open symbols in Fig. 4. They are plotted along with thresholds for normal hearing represented by the solid curve (ANSI, 1996). Two listeners (S5, S6) had relatively flat hearing losses across all audiometric frequencies. Listener S7 had normal thresholds for the two lowest frequencies, 125 Hz and 250 Hz, and hearing losses at all higher frequencies. The fourth listener (S8) had a high-frequency hearing loss with thresholds that were within the

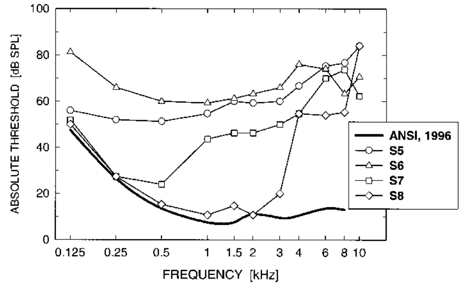

FIG. 4. Absolute thresholds (expressed in dB SPL) measured with 200-ms tones for four listeners with sensorineural hearing loss. The solid line shows the normal threshold curve based on ANSI (1996).

normal range up to about 3 kHz. All four listeners had earlier experience with psychoacoustic tasks and were given practice on the present task until their performance became stable.

B. Stimuli and procedure

MPPs were measured using on- and off-frequency maskers. The duration and gating of the stimuli used to test listeners with impaired hearing were the same as those used in experiment 1, in which only listeners with normal hearing were tested. However, it was not possible to use the same levels of the masker and the same frequencies of the masker and probe in both experiments. To produce a sufficient amount of masking in hearing-impaired listeners, a level of 95 dB SPL was used for the on- and off-frequency maskers. Three out of four listeners (S5, S6, and S7) exhibited substantial hearing loss at a frequency of 6 kHz. Limitations of our equipment prevented us from using probe levels high enough to measure masked thresholds around the peaks of the modulated masker at that frequency for the on-frequency masking condition. Therefore for listeners S5 and S7, a 3-kHz tone was used for the probe and for the carrier of the on-frequency masker. A 1.5-kHz tone was then used as the carrier for the off-frequency masker. Listener S6 was not available for testing with a masker frequency of 1.5 kHz. For this listener, the on-frequency MPP was measured using a 3-kHz probe and the off-frequency MPP was measured using a 6-kHz probe. Only listener S8 was tested using a 6-kHz tone for the probe and the carrier of the on-frequency masker and a 3-kHz tone for the carrier of the off-frequency masker. Similar to experiment 1, a modulation rate of 3.91 Hz was used to measure the MPPs. Because of the reduced dynamic range of hearing in the hearing-impaired listeners, only one masker level was tested. The procedure used to measure MPPs in the hearing-impaired listeners was the same as that used in experiment 1.

V. RESULTS AND DISCUSSION

MPPs measured in the four listeners with cochlear hearing loss are plotted in Fig. 5. The left column shows MPPs obtained with an on-frequency masker and the right column shows MPPs obtained with an off-frequency masker. Data for individual subjects are presented in separate rows of panels.

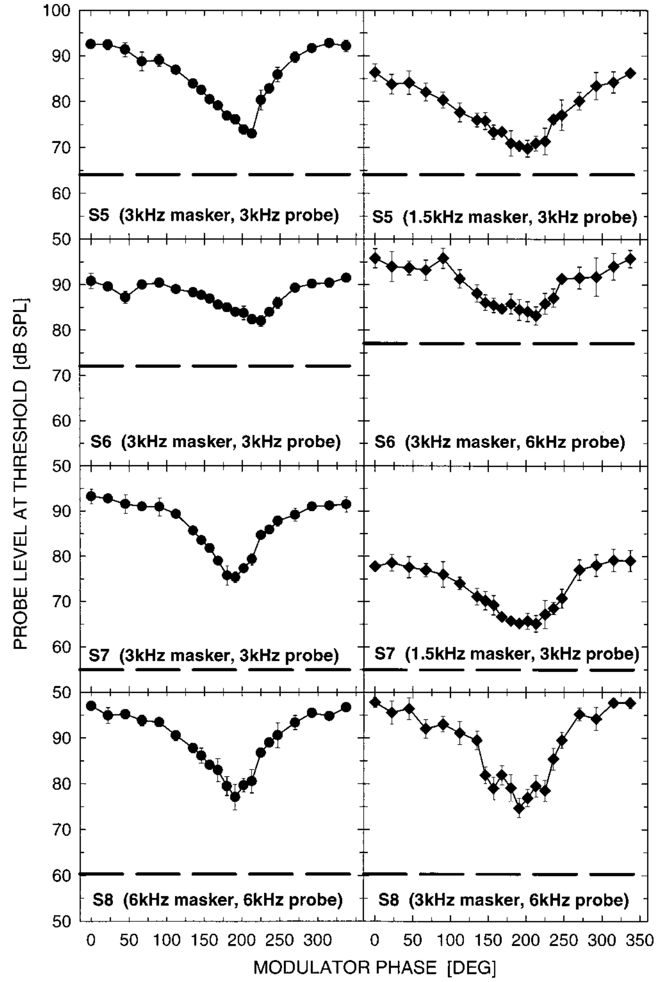

FIG. 5. Individual MPPs for hearing-impaired listeners. The left column of panels shows MPPs measured with an on-frequency masker, and the right column shows MPPs for an off-frequency masker. Masker and probe frequencies are shown in each panel. The dashed lines represent absolute threshold for the probe.

In general, the MPPs measured with the on-frequency masker (left column of panels) are similar in shape across hearing-impaired listeners. They exhibit V-shaped forms and they cover a much smaller range of probe levels compared to the normal-hearing data (see Fig. 2). The peak-valley differences in the MPPs of the hearing-impaired listeners were much smaller than the peak-valley differences observed at any masker level for the normal-hearing listeners. It might be argued that, in hearing-impaired listeners, the reduced dynamic range of the on-frequency MPP results from elevated absolute thresholds for the probe, which might limit performance in the valley. That does not appear to be the case, since the absolute thresholds, as shown by the dashed lines in each panel, were still well below the minimum of the MPP for each listener. For listener S6, different probe frequencies were used in the on- versus off-frequency masking conditions, thus the different thresholds for the probe in quiet in the right and left columns. As will be discussed later, the reduced peak-valley differences seen in the MPPs of hearing-impaired subjects reflect reduced or absent compression.

The off-frequency masking results in the right column of Fig. 5 differ substantially from those observed with the off-frequency masker in normal-hearing listeners (see Fig. 3). In particular, they do not exhibit deep extended valleys. Instead, they have valleys that are more similar to those observed for the on-frequency masker (left column of panels in Fig. 5). This result would be expected assuming that, for normal-hearing listeners, the difference in the MPP shapes for on- versus off-frequency maskers is due to the different rates of growth of BM response to stimulation by those maskers at the probe-frequency place. Similar MPP shapes observed for the hearing-impaired listeners presumably reflect similar rates of growth of BM responses for on- and off-frequency maskers. It is worth noting that the MPPs measured for listeners S7 and S8 with the off-frequency masker exhibit slightly different patterns. They appear to have more bowl-shaped valleys, similar to those observed with the off-frequency masker in normal hearing, but they are much shallower. This result might suggest that there is some residual compression in those two listeners. This seems likely given that the absolute threshold for the probe, for listener S7 at 3 kHz and that for listener S8 at 6 kHz were lower than the thresholds observed at 3 kHz for listener S5, and at 6 kHz for listener S6 (even though the difference between absolute thresholds for S8 at 6 kHz and S5 at 3 kHz was only about 4 dB).

The differences observed between the MPPs for the two groups of listeners may partly result from the fact that the listeners with normal hearing were tested using a 6-kHz probe, whereas some listeners with impaired hearing were tested using a 3-kHz probe. For the listeners with normal hearing, a high probe frequency was used to prevent detection of spectral splatter. For the listeners with hearing loss, the effect of energy splatter on the data was probably quite small. It has been shown that auditory filters are often broader than normal in regions of cochlear hearing loss (e.g., Glasberg and Moore, 1986). Furthermore, because of the elevated absolute thresholds, most of the splattered energy was not detectable to the listeners tested with the 3-kHz probe. Another factor that could potentially lead to differences between MPP shapes observed for the 3- and 6-kHz probes is the dependence of the amount of compression on stimulus frequency. Although the amount of compression appears to be frequency dependent, it has been shown that for frequencies above 1 kHz, the changes in estimates of compression across frequency appear to be relatively small (Bacon *et al.*, 1999; Plack and Oxenham, 2000; Glasberg and Moore, 2000).[2]

The MPPs for the hearing-impaired listeners were measured using a masker level that was higher than the levels used to test subjects with normal hearing. Data of Oxenham and Plack (1997) and Gregan *et al.* (1998) provide evidence that at high levels of stimulation, a more linear growth of BM response is observed in normal hearing. Thus the higher level of testing could be responsible for some of the differences between the data obtained from listeners with normal and impaired hearing.

An interesting aspect observed in the data presented in Fig. 5 is that, for the listeners with the largest amount of hearing loss (S5, S6), there was a substantial shift of the minimum of the MPP away from 180 deg and toward larger modulation phases. For listener S5 the minima occurred at a phase of 213 and 202 deg, and for listener S6 the minima occurred at 225 and 213 deg, for the on- and off-frequency maskers, respectively. This shift of the minimum was much smaller in listeners S7 and S8, whose hearing loss at the probe frequency was a little milder and whose data, gathered with the off-frequency maskers, suggested that some compression might be preserved in their auditory systems.

VI. DESCRIPTION OF THE MODEL

The data shown above appear to support the idea that the difference in the shapes of MPPs observed for on- versus off-frequency maskers is due to a different BM-response growth at the probe-frequency place for the two masking conditions. Existing models that have been used to make predictions about the effect of combined forward and backward masking have not considered the case where the stimuli (the masker and the probe) were overlapping in time and had different frequencies. This case must be taken into consideration to make predictions about the shape of an off-frequency MPP. Therefore, the present study adapts an existing model to make it usable for predicting the MPPs measured in our experiments. The main frame of the model has been used in the past to account for different aspects of temporal processing (e.g., Viemeister, 1979; Buus and Florentine, 1985; Moore *et al.*, 1988; Plack and Moore, 1990; Oxenham and Moore, 1994). The models used in those studies involved some or all of the following stages of processing: peripheral filtering, half-wave rectification, compression, a temporal integrator, and a decision device.

Because highly distorted waveforms are not observed in basal regions of the BM in response to tonal stimulation (Ruggero *et al.*, 1997), in the model, compression was applied to the envelopes of the waveforms rather than to the waveforms themselves. Therefore, half-wave rectification was replaced by computation of the absolute value of the analytic signal. This operation led to extraction of the input signal's envelope. Each point of the envelope was then subjected to compression corresponding to the instantaneous level.

The model assumes that, when the carrier frequency f_m of the modulated masker and the probe frequency f_p are equal ($f_m = f_p$), the two stimuli are subjected to the same compression as described by compression exponent α. We will denote the envelope of waveform x by $\{x\}$. Following the finding of Ruggero (1992) and Ruggero *et al.* (1997), it can be assumed that the BM response R, to the simultaneous stimulation by the masker x_m and the probe x_p, is proportional to the compressed amplitude of the sum of the two stimuli:

$$R_{m+p} = a \cdot \{x_m + x_p\}^{\alpha}, \tag{1}$$

where a is a proportionality constant. The response to the masker alone can be represented by

$$R_m = a \cdot \{x_m\}^{\alpha}. \tag{2}$$

Because the probe used to measure the MPPs was very short, it was assumed that for each position of the probe during the modulated masker, the temporal integrator $W(t)$ was centered at the temporal center of the probe t_c. The integrator was assumed to be operating on a squared representation of the input stimulus. This square-law nonlinearity has been applied in past studies that used a temporal window (e.g., Oxenham *et al.*, 1997; Plack and Oxenham, 1998) because it correctly predicts additivity of masking in the case of hearing loss (Oxenham and Moore, 1995).[3] The squared representation of the stimulus was then corrupted by internal noise before it was input to the temporal integrator. Limiting the integration time to the duration of the masker, the output of the temporal integrator for the masker and the probe combined can be described by

$$y_{m+p}(t_c)=a\cdot\int_0^{T_m}[\{x_m(\tau)+x_p(\tau)\}^{2\alpha}+N_{\mathrm{INT}}]\cdot W(\tau-t_c)\,d\tau. \tag{3}$$

The output of the temporal integrator for the masker alone would be

$$y_m(t_c)=a\cdot\int_0^{T_m}[\{x_m(\tau)\}^{2\alpha}+N_{\mathrm{INT}}]\cdot W(\tau-t_c)\,d\tau, \tag{4}$$

where T_m represents the total duration of the masker, and N_{INT} represents an additive internal noise, the purpose of which is to account for absolute threshold.

For the detection of the probe, the ratio of the output of the temporal window for the masker and probe presented together and the output of the temporal window for the masker alone has to reach some constant criterion denoted by *K*. Thus the masked threshold of the probe is obtained when

$$\frac{y_{m+p}(t_c)}{y_m(t_c)}=K. \tag{5}$$

The situation becomes more complicated when the frequency of the masker is lower than the frequency of the probe ($f_m<f_p$). In this case, the rate of response growth at the probe-frequency place is different for the masker than it is for the probe. Similar to the on-frequency masking condition, when the two stimuli overlap in time, the BM response is not simply the sum of the responses produced by the masker and the probe when each is presented alone. The present model takes into consideration the fact that in the case of simultaneous masking the BM response results from a nonlinearly combined effect of the masker and the probe. At the same time it assumes, based on physiological and psychophysical studies mentioned earlier, that the response to the masker at the probe-frequency place grows at a different rate than does the response to the probe. We assume that the BM response to the masker at the probe-frequency place (R_{mp}) grows at a rate described by a compression exponent denoted by β. In this case

$$R_{mp}=b\cdot\{x_m\}^{\beta}, \tag{6}$$

where b is a proportionality constant for the masker representation at the probe-frequency place. When the frequency of the masker is an octave lower than the frequency of the probe (as was the case in the present study), the masker produces a linear response at the probe-frequency place and the exponent β can be assumed equal to one. However, for

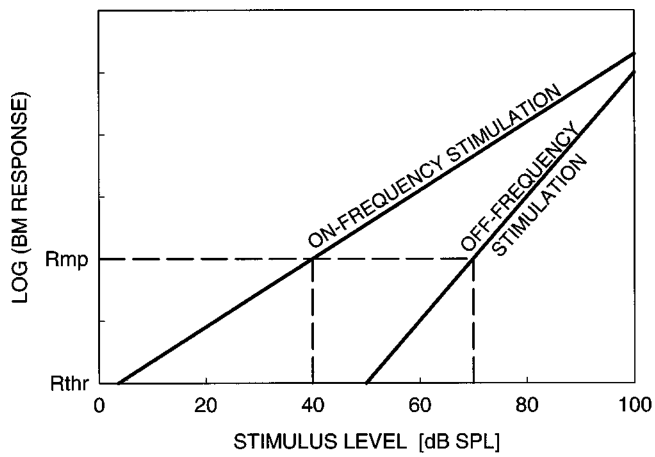

FIG. 6. Illustration of BM-response growth for on- and off-frequency stimulation, presented in a log–log coordinate system. The rate of response growth is slower for the on-frequency stimulus due to compressive BM nonlinearity, and based on Eq. (7) is described by α. The rate of response growth for the off-frequency stimulus is faster (close or equal to one), but the stimulus does not produce any response until its level reaches the threshold value. Based on Eq. (6) the slope of the steeper line is represented by β. Equation (8) is derived under the assumption that the two stimuli produce the same response R_{mp}.

greater generalization, we will keep the exponent β in the following equations. This exponent becomes smaller as the masker frequency approaches the probe frequency, finally reaching the value of the compression exponent applied to the probe when the two stimuli have the same frequency.

The model further assumes that the same response (R_{mp}) could be produced by a signal x_s whose frequency (f_s) is equal to the frequency of the probe ($f_s=f_p$), as long as the amplitude of that signal is appropriately adjusted. This is schematically illustrated in Fig. 6. Such a signal would be compressed according to the same BM input–output function as the probe. Therefore, analogous to Eq. (1), the response to such a signal could be expressed as

$$R_{mp}=a\cdot\{x_s\}^{\alpha}. \tag{7}$$

For each magnitude of the response to the masker, we can find the amplitude of the on-frequency signal by expressing it in terms of the amplitude of the masker based on Eqs. (6) and (7):

$$\{x_s\}=\left(\frac{b}{a}\right)^{1/\alpha}\cdot\{x_m\}^{\beta/\alpha}. \tag{8}$$

If signal x_s is always chosen so that it produces the same response as the masker, it can be used to compute the combined response to the masker and the probe at the probe-frequency place. Such a signal can be thought of as the representation of the masker at the probe-frequency place. The signal can be added directly to the probe and it has to produce the same growth-of-response function as the probe. Similar to the on-frequency case, an intensity-like (squared) representation was input to the temporal integrator. Thus the output of the temporal integrator for the masker and the probe presented together is described by this formula, which is similar to Eq. (3):[4]

$$y_{m+p}(t_c)=a\int_0^{T_m}[\{C^{1/\alpha}\cdot x_m(\tau)^{\beta/\alpha}+x_p(\tau)\}^{2\alpha}+N_{\mathrm{INT}}]\cdot W(\tau-t_c)d\tau, \tag{9}$$

where $C=b/a$, and represents attenuation of the masker by the auditory filter centered at the probe frequency. The output of the temporal integrator for the masker alone at the probe-frequency place would be

$$y_m(t_c)=a\int_0^{T_m}[\{C^{1/\alpha}x_m(\tau)^{\beta/\alpha}\}^{2\alpha}+N_{\mathrm{INT}}]\cdot W(\tau-t_c)d\tau. \tag{10}$$

The masked threshold for the probe is obtained when the criterion K described by Eq. (5) is fulfilled. The constant a does not need to be known because it appears in the numerator and the denominator of the ratio describing the criterion in the on- and off-frequency masking case, and thus will cancel out. The approach applied in the present study to the case where the masker frequency is lower than the signal frequency is similar to the approach used by Goldstein (1990), which is depicted by the diagram in Fig. 1 of his paper.

Several types of temporal integrator have been proposed in the past, but the most frequently used have been an exponential temporal window and a ROEX (rounded exponential) temporal window (Moore *et al.*, 1988; Plack and Moore, 1990; Oxenham and Moore, 1994; Moore *et al.*, 1996; Plack and Oxenham, 1998). For the model described here, a ROEX-shaped window was chosen as the temporal integrator. Following Moore *et al.* (1988), it was assumed that each side of the temporal window is described by two exponential functions added together: one representing the central part of the window and the other representing the skirt of the window. Thus each side of the temporal integrator was described by

$$W(t)=(1-w)\cdot\left(1+\frac{2t}{T_p}\right)\cdot\exp\left(-\frac{2t}{T_p}\right)+w\cdot\left(1+\frac{2t}{T_s}\right)\cdot\exp\left(-\frac{2t}{T_s}\right),$$

where time t is measured relative to the center of the window, w is a weighting function describing the relative contributions of the steeper (central part) and shallower (the skirt) exponential functions, T_p is the time constant determining the sharpness of the central part of the window, and T_s is the time constant determining the sharpness of the skirt. It was also assumed that the temporal window is asymmetric with the longer time constants describing the side preceding the center of the temporal window and the shorter time constants describing the side following the center. The ratio of the time constants describing both sides of the center of the window was assumed to be the same as the ratio of the time constants describing the skirts. This assumption reduced the number of the parameters of the ROEX-shaped integrator to four.

The compression exponent α was computed based on the gain function described by a formula proposed by Glasberg and Moore (2000). The function is based on the assumption that in a normal auditory system, strong gain is applied by the cochlear amplifier to very faint stimuli, and that the gain decreases as stimulus level increases. The shape of the gain function depends on the maximum gain, which is applied to the softest sounds. The maximum gain, in turn, depends on the functional status of the outer hair cells. When there is some damage to outer hair cells, the maximum gain decreases so that faint stimuli are amplified less and therefore are rendered inaudible. Consequently, absolute threshold increases and the BM response becomes more linear. The function proposed by Glasberg and Moore is given by the following formula

$$\mathrm{Gain}=-0.1\cdot L+A+B\cdot(1-1/(1+\exp(0.05\cdot(50-L)))), \tag{11}$$

where L is the input level in dB SPL. A and B are defined as

$$A=-0.0894\cdot G_{\max}+10.894,\quad B=1.1789\cdot G_{\max}-11.789,$$

where $G_{\max}$ represents the maximum gain.

The left panel of Fig. 7 shows a set of the gain functions plotted against the input level for different values of the maximum gain. The intercept with the ordinate for each curve represents the maximum gain. The right panel of Fig. 7 shows the BM input–output functions based on the gain functions computed for the corresponding maximum gain. The functions resemble the BM input–output functions measured by Robles *et al.* (1986), Ruggero (1992), and Ruggero *et al.* (1997). They clearly show that as the maximum gain decreases, the threshold is shifted toward higher levels and the BM input–output function becomes more linear. The figure also shows that at high levels, the outputs corresponding to the larger maximum gains and the output corresponding to the maximum gain of zero converge (an effect observed in psychophysical study as loudness recruitment).

Compression exponents α were computed based on the gain function using the following formula

$$\alpha=(L+\mathrm{Gain}-G_{\max})/L. \tag{12}$$

The resulting compression exponent is plotted in Fig. 8 as a function of the input level for different values of the maximum gain.

It has to be noted that the compression exponent observed with the largest maximum gain of 60 dB does not reach a value lower than 0.34, even though the shallowest slope of the BM-response growth was only 0.17 for the 60-dB maximum gain.[5] As the maximum gain decreases, the compression exponent increases in the mid-to high-level region reaching a value of one (linear response) for the maximum gain of zero.

To obtain predictions for the MPPs, the instantaneous level L corresponding to each point of the stimulus envelope was computed. Based on the instantaneous level, the exponent α was obtained for each point of the envelope using Eq. (12). This quasi-instantaneous compression (point-by-point envelope compression) was equivalent to the level-dependent nearly instantaneous gain and thus it did not distort the compressed waveforms. For the off-frequency masker, the exponent β was set to be equal to one assuming

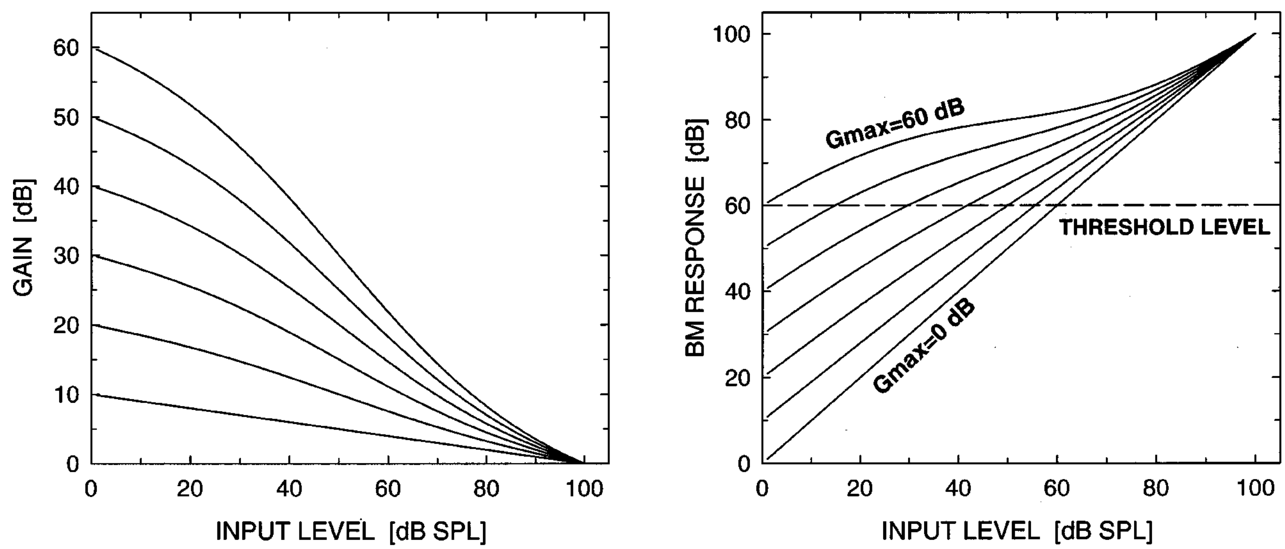

FIG. 7. Cochlear gain in dB (left panel) and BM response (right panel) plotted as a function of stimulus level. Different curves were obtained for different values of maximum gain using a formula proposed by Glasberg and Moore (2000). In the left panel, the maximum gain corresponds to the intercept of each curve with the *y*-axis. In the right panel, the maximum gain of 60 dB corresponds to the most compressive function and the maximum gain of 0 dB corresponds to the straight line with a slope of one. The dashed line in the right panel shows the level of the BM response that produces threshold sensation (detection threshold).

a linear response to the masker. This assumption is reasonable, since the frequency of the masker was one octave lower than the frequency of the probe.

VII. PREDICTIONS BY THE MODEL

Predictions for the measured MPPs were obtained using the model described above. Each point for the model predictions was obtained by iteratively adjusting the amplitude of the probe, x_p, until the absolute value of the difference between a fixed criterion (estimated in pilot computations) and the value of K computed from Eq. (5) reached the minimum. The parameter C in Eq. (10) was originally estimated to be equal to 0.0022 based on the rate at which attenuation by the ROEX-shaped auditory filter changes with masker level (Moore and Glasberg, 1987a). However, this parameter had to be adjusted slightly for each individual listener to produce a good fit. The adjustments were justifiable since the auditory filters derived by Moore and Glasberg are based on data averaged across the normal-hearing listeners used in their study. In studies measuring auditory filters, the inter-subject variability has often been reported to be quite high. That was likely to be the reason why the adjustments of the parameter representing attenuation of the masker by the filter tuned to the probe frequency were necessary in our computations for individual listeners. In the present model, values of C between 0.002 and 0.006 were used, depending on the listener.

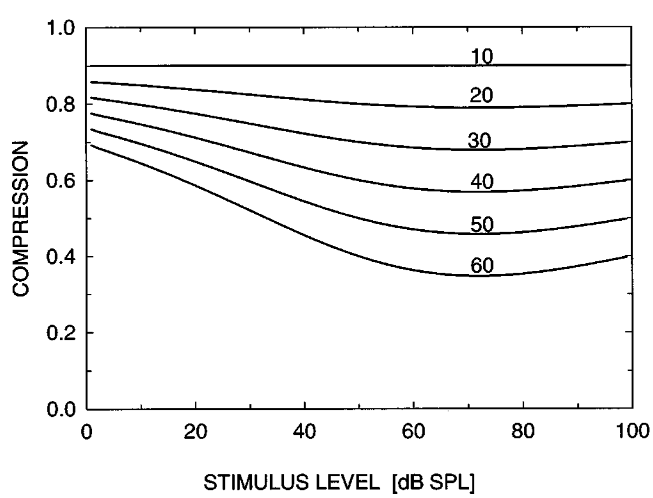

FIG. 8. Compression exponents plotted as a function of stimulus level. The functions were computed based on Eq. (12) using different values of maximum gain (shown on top of the respective curves).

For each listener, only one MPP (for the highest level of the on-frequency masker) was simulated using four free parameters. The free parameters were the following parameters of the ROEX-shaped temporal window: weight w, the time constant describing the central part of the temporal window before the center (T_p), the time constant describing the skirt before the center (T_s), and a ratio of the time constant T_p (or T_s) to the corresponding time constant describing the side after the center of the temporal window (denoted by Asym in Table I). These four parameters were changed iteratively, during a computation of the MPP, until the squared deviations between the predicted and the measured thresholds, summed across the modulation cycle of the masker envelope, produced a minimal value. Once the parameters of the temporal window producing the best prediction for that selected case were established, they were used in computation of all the other MPPs for the listener.

The predicted MPPs observed with the on-frequency masker in listeners with normal hearing are shown by solid lines in Fig. 9. The symbols represent the data replotted from Fig. 2. Separate panels show the data and the predictions for individual listeners. In each panel, different symbols represent the data obtained for different masker levels.

Overall, there is good agreement between the data and the predictions. For the on-frequency masker the model pro-

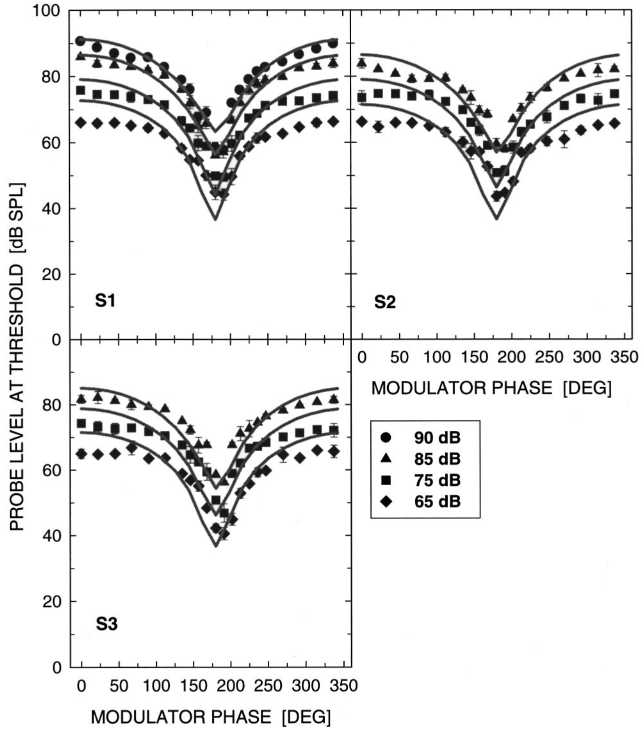

FIG. 9. On-frequency MPPs for normal-hearing listeners, replotted from Fig. 2 (symbols) along with predictions by the model (solid lines).

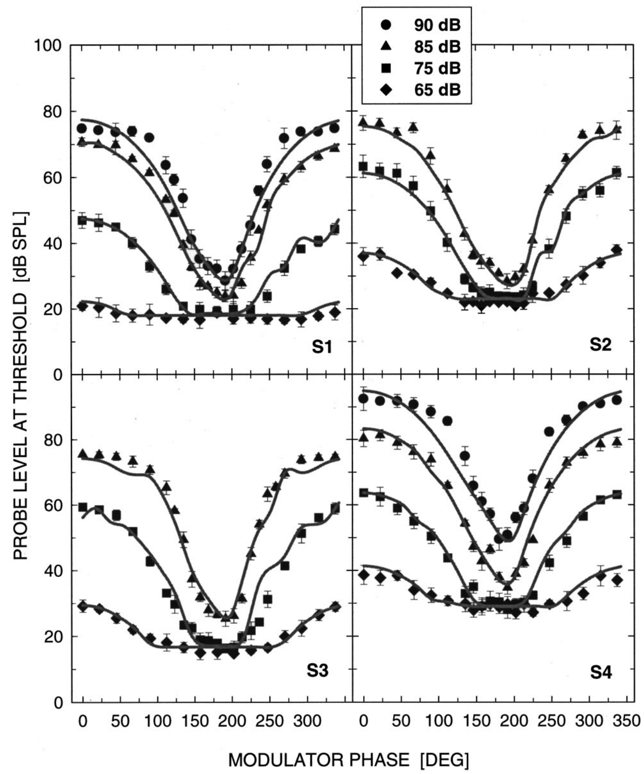

FIG. 10. Off-frequency MPPs for normal-hearing listeners, replotted from Fig. 3 (symbols) along with predictions by the model (solid lines).

duces MPPs with sharp narrow valleys. However, in many cases the model overpredicts the measured thresholds near the peaks of the modulated masker by about 2–8 dB. It also sometimes underpredicts the thresholds in the region of the valley.

One possible reason for the discrepancy between the predictions and the data may be related to the gain function used for the computation of compression exponents. The function was derived based on both physiological and psychophysical data and represents some average shape for a given maximum gain in the auditory system. In the model, the compression exponent could only vary according to the strictly defined function based on that ''average'' gain function. This might have contributed to the error in the predictions produced for each individual listener.

Figure 10 shows the predictions and the data observed for the off-frequency masker in listeners with normal hearing. The model correctly predicts the longer and deeper valleys observed in the data. The predictions for the off-frequency masking condition are more accurate than those produced for the on-frequency masker. The solid lines fall very close to the data for each condition and each listener.[6]

Because of a relatively small dynamic range of hearing at the probe frequency, the hearing-impaired listeners were tested using only one masker level for the on- and off-frequency masking conditions. For each listener, the MPP for the on-frequency masker was computed using the four parameters of the temporal window as free parameters of the simulation. The values of those parameters producing the best predictions ''on-frequency'' were then used to compute the MPP observed with the off-frequency masker. The compression exponent α was computed for each point of the on-frequency masker envelope and each point of the envelope of the probe and masker combined. It was done using Eq. (12) for the value of maximum gain selected based on pilot computations. For the off-frequency masker, the compression exponent β was set equal to one. Figure 11 shows the predictions (solid lines) and the data (symbols) for the hearing-impaired listeners. The left column presents the results for the on-frequency masker and the right column presents the results for the off-frequency masker. For all four listeners, the predictions fall reasonably close to the data.

It should be noted that for the hearing-impaired listeners, the model produces a minimum of the MPP that is shifted away from the 180-deg phase toward larger phases, in agreement with what is observed in the data. Within the model, this shift results from combined effects of the temporal-window asymmetry and reduced maximum gain. The shift is not produced by the model when the maximum gain is large or when both sides of the temporal window are described by the same time constants.

Table I contains the parameters resulting from the computations of the MPPs. The maximum gain producing the predictions for listeners with normal hearing presented in Figs. 9 and 10 had to be set to values larger than 40 dB. For two out of four listeners with hearing loss, the maximum gain of 0 dB produced the best predictions. This presumably suggests that there is no compressive nonlinearity in the auditory systems of those hearing-impaired listeners in the region corresponding to the probe frequency. For listeners S7 and S8, the maximum gains of 15 and 8 dB were used to produce the predictions. A maximum gain greater than 0 dB

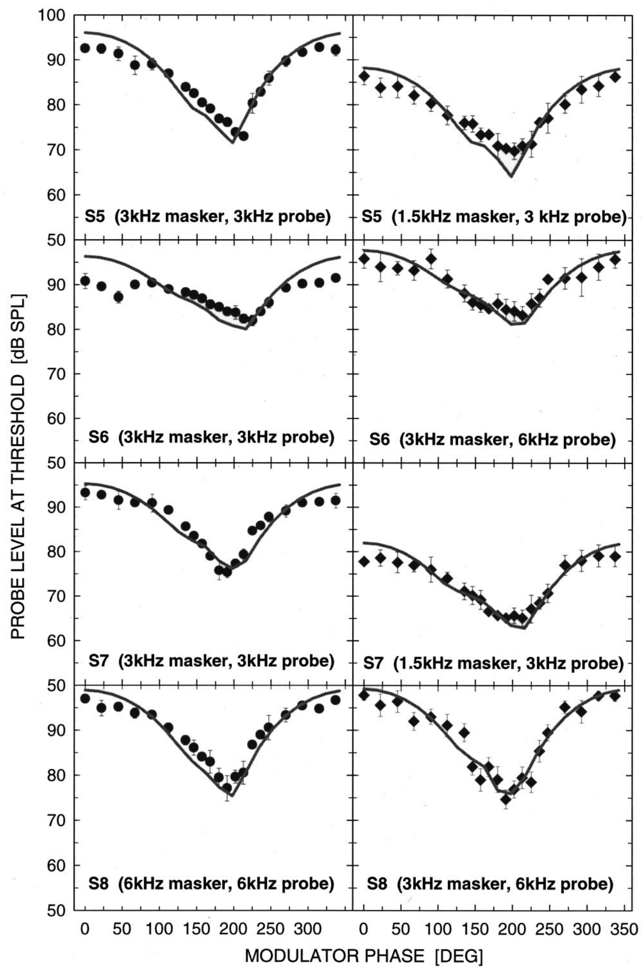

FIG. 11. MPPs measured in hearing-impaired listeners, replotted from Fig. 5 (symbols) along with predictions by the model (solid lines). The data and the predictions for the on- and off-frequency maskers are shown in the left and right column of panels, respectively.

suggests some residual compression in those listeners' auditory systems at the probe frequency.

The parameters of the temporal window resulting from the simulations were similar across all listeners. In all cases, the differences between values of any given parameter across the listeners (with normal and impaired hearing) were not greater than those differences seen across the individual normal-hearing listeners in studies by Moore *et al.* (1988), Plack and Moore (1990), and Oxenham and Moore (1994). Therefore, the results of the present simulations appear to indicate that the temporal integrator in the hearing-impaired subjects participating in our study does not differ from the temporal integrator operating in the listeners with normal hearing. Consequently, it can be concluded that the shallower MPPs observed in the hearing-impaired listeners with the on-frequency masker (shown in Fig. 5) result from reduced or absent compression (due to dysfunction of the active mechanism and possibly due to the higher level of masker presentation) rather than reduced temporal resolution.

TABLE I. The maximum gain and the four parameters of the ROEX-shaped temporal window that produced the predictions shown in Figs. 9–11.

Subject	G_{max} [dB]	W	Asym	T_p [ms]	T_s [ms]
S1	48	0.09	1.5	2.0	36
S2	47	0.09	1.7	2.0	38
S3	45	0.09	1.6	2.0	34
S4	42	0.07	1.5	2.0	30
S5	0	0.06	1.7	2.0	25
S6	0	0.09	1.9	1.2	34
S7	15	0.09	1.8	2.5	37
S8	8	0.09	1.7	2.0	27

VIII. GENERAL DISCUSSION AND CONCLUSIONS

The purpose of the present study was to account for the differences in the shapes of MPPs measured with a masker whose frequency is the same as the frequency of the probe and MPPs measured with a masker whose frequency is much lower than the frequency of the probe. In experiment 1, MPPs were measured in detail over one modulation cycle of the masker in listeners with normal hearing. It was found that when the frequency of the masker is well below the frequency of the probe, MPPs exhibit deep and extended valleys. In contrast, the valleys of MPPs measured with the on-frequency masker are sharp and narrow, and the dynamic range of those patterns is not as large as the dynamic range observed for off-frequency masking. The results are consistent with the often-reported release from masking within the upper accessory excitation observed with fluctuating maskers. It has been shown that masked thresholds, measured using a tonal probe and a masker much lower in frequency than the probe, are substantially reduced when the masker is a narrowband noise compared with the case where the masker was a pure tone of equal intensity (Buus, 1985; Mott and Feth, 1986; Moore and Glasberg, 1987b; Nelson and Schroder, 1996). To explain the difference in the amount of masking, it has been suggested that when an off-frequency masker with a fluctuating envelope is used, listeners can detect the probe by ''listening in the valleys'' of the masker envelope. This explanation seems plausible, since the valleys in the internal representation of an off-frequency masker at the probe-frequency place appear to be longer compared with those in the internal representation of the on-frequency masker, due to nonlinear BM behavior. Results of the present study indicate that listeners with normal hearing can take advantage of those longer and deeper valleys.

In listeners with hearing loss of cochlear origin, the discussed differences in the shape of MPPs are much smaller or are not observed, depending on the degree of hearing loss at the test frequency. The MPPs are very shallow and tend to have V-shaped valleys when measured with both on- and off-frequency maskers. This was shown in experiment 2. The results are consistent with the data of Nelson and Schroder (1996), who demonstrated that the release from masking within the upper accessory excitation occurring in normal hearing for temporally fluctuating maskers is markedly reduced and sometimes absent in the regions of high-frequency hearing loss. Very shallow MPPs indicate more difficulty in detecting the probe.

A model consisting of peripheral filtering, envelope extraction, compression, a temporal window operating on an intensity-like representation, and a decision device was used to demonstrate that the data can be accounted for by assuming that an off-frequency masker produces a linear response at the probe-frequency place while the probe produces a compressed response. For the on-frequency masking case, the masker and the probe were compressed according to the same compression function. In the computation of the response to the masker and the probe, the model assumed that the internal representations of the two stimuli are combined in a nonlinear manner, i.e., the combined response is not a simple sum of the responses produced by the masker and the probe in their separate presentations. The model correctly predicted the different shapes of the MPPs observed with on- and off-frequency maskers and produced predictions that fall reasonably close to the data.

Results of the simulations indicate that good predictions for hearing-impaired listeners are obtained when the maximum gain in Eq. (11) is set to a value equal or slightly higher than zero, depending on the amount of hearing loss at the probe frequency. As expected, for listeners with normal hearing, much higher values of maximum gain had to be used, as shown in Table I. The four parameters of the temporal window were similar across all listeners used in the study. The obtained time constants describing the central part of the temporal window before its center (T_p) were slightly shorter than those reported by Moore *et al.* (1988), Plack and Moore (1990), and Oxenham and Moore (1994). The time constants describing the skirt (T_s) were comparable to those reported in their study. Computations of equivalent rectangular durations (ERD) produced values between 6.9 and 7.2 ms for the normal-hearing listeners and values between 5.5 and 7.7 ms for the hearing-impaired listeners. Those values are similar to the ERDs reported by Plack and Moore (1990) for high stimulus frequencies. The important finding seems to be that the time constants did not differ across listeners in our study, whether their hearing was normal or impaired. This suggests that the shallower MPPs observed in the hearing-impaired listeners do not result from reduced temporal resolution. Instead, reduced or absent compression appears to be responsible for the impaired processing of temporal envelopes. Oxenham and Moore (1997) suggested, based on their forward-masking data, that the temporal integrator in listeners with impaired hearing may not differ from that in normal hearing. The difference occurs in the processing at more peripheral stages. The processing is linear (or nearly linear) in impaired hearing and it is compressive in normal hearing. Results of the present simulations provide support for their findings.

The difference between patterns of masking produced by off-frequency maskers with fluctuating envelopes in listeners with normal hearing versus those in listeners with impaired hearing may have consequences for the recognition of target speech in the presence of a competing talker. The results presented in this work appear to imply that when speech is presented at a clearly audible level, to listeners with normal hearing and to listeners with cochlear hearing loss, normal-hearing subjects should be much better at detecting and recognizing short high-frequency consonants of the target talker immediately following or preceding lower-frequency vowels uttered by a competing talker. That is because the masker (the low-frequency vowel) will produce a linear response at the signal-frequency place (corresponding to the higher-frequency content of a consonant) in both groups of listeners, but only listeners with normal hearing can take advantage of deeper valleys in the masking pattern when the vowel is fading off. Hearing-impaired listeners would be expected to perform much worse under such listening conditions. Furthermore, our results argue that the worse performance of hearing-impaired listeners should be observed despite apparently normal temporal processing in their auditory system.

In the present paper, the differences in the shapes of MPPs measured with on- and off-frequency maskers and also the differences observed between MPPs measured in listeners with normal and impaired hearing were all attributed to BM compressive nonlinearity. However, another property of nonlinear cochlear mechanics might have played a role. Delgutte (1990a, b) demonstrated that for maskers well below the signal frequency, two masking mechanisms are operating. One of them is related to spread of excitation produced by a masker, and the other is based on suppression of the activity evoked in response to the probe by a simultaneous lower-frequency masker. Sizeable suppression was also shown by psychophysical data of Oxenham and Plack (1998). In our study, suppression could have affected the shapes of MPPs measured with the off-frequency masker in listeners with normal hearing. It is possible that it affected thresholds in the regions of each peak of the modulated masker where simultaneous masking prevails. In the valley, where the masked thresholds are governed by forward masking by the preceding peak, suppression should play little or no role (Arthur *et al.*, 1971). Suppression presumably did not affect the data from the hearing-impaired listeners. It has been demonstrated that suppression is reduced or eliminated as a result of damage to outer hair cells (Schmiedt *et al.*, 1980; Dallos *et al.*, 1980; Hicks and Bacon, 1999b). While the presented model provides satisfactory predictions without accounting for the effects of suppression, a more realistic model of the auditory periphery needs to take this nonlinear process into consideration.

The main conclusions from the present study may be summarized as follows:

(1) MPPs measured with on-frequency maskers in listeners with normal hearing exhibit sharp narrow valleys. For maskers much lower in frequency than the probe, MPPs have deeper and longer valleys. This difference in the shapes of MPPs observed for on- versus off-frequency maskers most probably results from different rates of masking growth in the two masking conditions. Different rates of masking growth are, in turn, the consequence of different BM-response growth rates produced by on- and off-frequency maskers at the probe-frequency place.
(2) The on- and off-frequency MPPs were more similar for hearing-impaired listeners than they were for listeners with normal hearing. This reflects similar rates of BM-response growth produced by the two types of masker in an impaired auditory system.
(3) The shapes of MPPs in listeners with normal hearing can be predicted by a model assuming compressive transfor-

mation of the probe and the on-frequency masker, and a linear BM response to the off-frequency masker at the probe-frequency place. The shapes of MPPs in listeners with impaired hearing can be predicted using the same model under the assumption that the response to the probe and the on-frequency masker grows at the same or a similar rate as the response to the off-frequency masker, which is assumed to grow linearly.

(4) Best predictions by a model assuming linear or nearly linear BM behavior in the case of hearing loss, and nonlinear BM behavior in the case of normal hearing, are obtained when similar parameters of the temporal integrator are used for both normal-hearing and hearing-impaired listeners. This suggests that the apparent poorer temporal processing of envelopes observed in impaired hearing results from reduced or absent compression rather than from a reduced efficacy of the temporal processing mechanism. This result supports a similar observation made by Oxenham and Moore (1997) based on their forward-masking data.

ACKNOWLEDGMENTS

This work was supported by Grant No. R01-DC00149 from NIDCD. It was also supported in part by the Lion's 5M International Hearing Foundation. We also thank Sid Bacon and the reviewers, Andrew Oxenham and Van Summers, for their helpful and constructive comments.

[1]Plack and Moore (1990) used different frequencies and different levels of the stimulus to estimate the parameters of their rounded-exponential-shaped temporal window. Their results suggested that the sharpness of the temporal window increases most when the stimulus frequency changes from 300 Hz to 900 Hz, but only a slight further increase is observed when the frequency increases up to 8100 Hz. It has to be noted that Plack and Moore did not apply compression to the stimulus intensity in their derivation of the parameters of the temporal window. That might have affected their estimates. As temporal integration is believed to be a central process, it seems reasonable to assume that the shape of the integrator does not depend on stimulus frequency or level. However, as the output of the temporal window would be affected by the combined effect of compression and temporal integration, the ''apparent'' temporal resolution might be better at higher frequencies and at moderate levels (where BM response is most compressive).

[2]Data collected using some of the normal-hearing listeners participating in the present study, for masker frequencies of 500 Hz and 1200 Hz paired with a probe frequency of 1200 Hz and for masker frequencies of 1200 Hz and 2400 Hz paired with a probe frequency of 2400 Hz, showed a similar difference in the shapes of MPPs measured with an on- and off-frequency masker as the difference observed in this study for the normal-hearing listeners tested at higher frequencies. Those data are not presented here because they were affected by splatter. However, they provide additional evidence that the similar MPPs observed with on- and off-frequency maskers for the hearing-impaired listeners, tested with a probe frequency of 3 kHz do not result from the effect of frequency on the amount of compression.

[3]The temporal window must be integrating information encoded as some aspect of neural activity. Yates *et al.* (1990) found that, once BM compression is factored out, the auditory-nerve response appears to grow in proportion to stimulus intensity rather than stimulus amplitude. This finding is in agreement with additivity-of-masking data (Oxenham and Moore, 1995). In listeners with cochlear hearing loss, two equally intense maskers produce a 3-dB rather than 6-dB increase in threshold relative to the threshold observed when only one of the maskers is present. Assuming that the BM response is linear (or nearly linear) in the case of cochlear damage, this result suggests linear additivity of the auditory response with respect to intensity rather than with respect to amplitude. Psychophysical data of Oxenham and Plack (1997) suggest that, in normal hearing, the nonlinear BM response is preserved at higher stages of the auditory processing. Based on their results it is assumed in our model that the squared BM response is essentially unaltered by further neural processing. Therefore, only a stochastic process (internal noise) is added to the squared BM output before the stimulus representation is input to the temporal integrator. This assumption allows greater simplification of the model; however, one needs to be aware that it may not be entirely correct.

[4]In Eq. (9), the internal representation of the masker at the probe-frequency place was computed by raising the masker envelope (the modulator) to the power of β/α and then multiplying it by the carrier of the masker. Subsequently, such a ''transformed'' masker multiplied by the constant $C^{1/\alpha}$ was added to the probe, and the envelope of the obtained waveform was extracted. Extracting the envelope of the masker representation and adding it to the envelope of the probe would not be equivalent to adding the stimuli first and extracting the envelope of the resulting stimulus, and thus it would lead to a different (incorrect) result. Physical stimuli add before they reach the ear and undergo the processing at the basilar membrane and at higher stages of the auditory system, which involves envelope extraction.

[5]In a healthy auditory system, gain applied by the cochlear amplifier to an input stimulus decreases progressively with increasing stimulus level. The rate at which gain changes is not constant across levels. The greatest decrease is observed at medium levels leading to the shallowest slope of the growth-of-response function in this range (see Fig. 7). As a result of this level-dependent gain, a compressive function is observed at the output of the cochlear amplifier. To compute the output level for each given input level, the input level needs to be multiplied by the compression exponent corresponding to that level. This compression exponent is *not* equivalent to the rate at which the response grows at the output of the cochlear amplifier. Because gain decreases at a slower rate for low input levels than it does for medium levels, the compression exponents for levels corresponding to the shallowest part of the output function have to be *larger* than the slope for this range of levels. The slope of the growth-of-response function would be equivalent to the compression exponent only if gain decreased at a constant rate across levels, which is not the case for a healthy cochlea. Therefore, it is not justifiable to expect that models applying compression, such as the ones used by Oxenham and Moore (1994) and in the present work, should produce compression exponents equal to the slope of the BM input-output function.

[6]The wiggles in the predicted MPPs are an artifact of the iteration procedure. The model itself does not produce such nonmonotonicities since the BM input–output function is monotonic and the temporal window is linear.

ANSI (**1996**). ANSI S3.6-1996, ''Specifications for audiometers'' (ANSI, New York).

Arthur, R. M., Pfeiffer, R. R., and Suga, N. (**1971**). ''Properties of 'two-tone inhibition' in primary auditory neurons,'' J. Physiol. (London) **212**, 593–609.

Bacon, S. P., Boden, L. N., Lee, J., and Repovsch, J. L. (**1999**). ''Growth of simultaneous masking for $f_m < f_s$: Effects of overall frequency and level,'' J. Acoust. Soc. Am. **106**, 341–350.

Bacon, S. P., Lee, J., Peterson, D. N., and Rainey, D. (**1997**). ''Masking by modulated and unmodulated noise: Effects of bandwidth, modulation rate, signal frequency, and masker level,'' J. Acoust. Soc. Am. **101**, 1600–1610.

Buus, S. (**1985**). ''Masking release caused by envelope fluctuations,'' J. Acoust. Soc. Am. **78**, 1958–1965.

Buus, S., and Florentine, M. (**1985**). ''Gap detection in normal and impaired listeners: The effect of level and frequency,'' in *Time Resolution in Auditory Systems*, edited by A. Michelsen (Springer-Verlag, New York), pp. 159–179.

Buus, S. and Florentine, M. (**1989**). ''Simulated hearing loss as a baseline for the assessment of auditory function in cochlearly impaired listeners,'' in *Proceedings of the Fifteenth Annual Bioengineering Conference*, edited by S. Buus (IEEE, Piscataway, NJ).

Dallos, P., Harris, D. M., Relkin, E., and Cheatham, M. A. (**1980**). ''Two-tone suppression and intermodulation distortion in the cochlea: Effect of outer hair cell lesions,'' in *Psychophysical, and Behavioral Studies in Hearing*, edited by G. van den Brink and F. A. Bilsen (Delft U. P., The Netherlands), pp. 242–249.

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

Delgutte, B. (**1990b**). ''Two-tone rate suppression in auditory-nerve fibers: Dependence on suppression frequency and level,'' Hear. Res. **49**, 225–246.

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

Glasberg, B. R., and Moore, B. C. J. (**1986**). ''Auditory filter shapes in subjects with unilateral and bilateral cochlear impairments,'' J. Acoust. Soc. Am. **79**, 1020–1033.

Glasberg, B. R., and Moore, B. C. J. (**2000**). ''Frequency selectivity as a function of level and frequency measured with uniformly exciting notched noise,'' J. Acoust. Soc. Am. **108**, 2318–2328.

Goldstein, J. L. (**1990**). ''Modeling rapid waveform compression on the basilar membrane as multiple-bandpass-nonlinearity filtering,'' Hear. Res. **49**, 39–60.

Gregan, M. J., Bacon, S. P., and Lee, J. (**1998**). ''Masking by sinusoidally amplitude-modulated tonal maskers,'' J. Acoust. Soc. Am. **103**, 1012–1021.

Hawkins, J. E., and Stevens, S. S. (**1950**). ''The masking of pure tones and of speech by white noise,'' J. Acoust. Soc. Am. **22**, 6–13.

Hicks, M. L., and Bacon, S. P. (**1999a**). ''Psychophysical measures of auditory nonlinearities as a function of frequency in individuals with normal hearing,'' J. Acoust. Soc. Am. **105**, 326–338.

Hicks, M. L., and Bacon, S. P. (**1999b**). ''Effects of aspirin on psychophysical measures of frequency selectivity, two-tone suppression, and growth of masking,'' J. Acoust. Soc. Am. **106**, 1436–1451.

Javel, E., McGee, J., Walsh, E., Farley, G., and Gorga, M. (**1983**). ''Suppression of auditory nerve responses. II. Suppression threshold and growth, iso-suppression contours,'' J. Acoust. Soc. Am. **74**, 801–813.

Jesteadt, W., Bacon, S. P., and Lehman, J. R. (**1982**). ''Forward masking as a function of frequency, masker level, and signal delay,'' J. Acoust. Soc. Am. **71**, 950–962.

Kemp, D. T. (**1978**). ''Stimulated acoustic emissions from within the human auditory system,'' J. Acoust. Soc. Am. **64**, 1386–1391.

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

Lutfi, R. A. (**1983**). ''Additivity of simultaneous masking,'' J. Acoust. Soc. Am. **73**, 262–267.

Moore, B. C. J., and Glasberg, B. R. (**1983**). ''Growth of forward masking for sinusoidal and noise maskers as a function of signal delay: Implications for suppression in noise,'' J. Acoust. Soc. Am. **73**, 1249–1259.

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

Moore, B. C. J., and Glasberg, B. R. (**1987b**). ''Factors affecting thresholds for sinusoidal signals in narrow-band maskers with fluctuating envelopes,'' J. Acoust. Soc. Am. **82**, 69–79.

Moore, B. C. J., Glasberg, B. R., Plack, C. J., and Biswas, A. K. (**1988**). ''The shape of the ear's temporal window,'' J. Acoust. Soc. Am. **83**, 1102–1116.

Moore, B. C. J., Peters, R. W., and Glasberg, B. R. (**1996**). ''Detection of decrements and increments in sinusoids at high overall levels,'' J. Acoust. Soc. Am. **99**, 3669–3677.

Moore, B. C. J., Vickers, D. A., Plack, C. J., and Oxenham, A. J. (**1999**). ''Inter-relationship between different psychoacoustic measures assumed to be related to the cochlear active mechanism,'' J. Acoust. Soc. Am. **106**, 2761–2778.

Mott, J. B., and Feth, L. L. (**1986**). ''Effects of the temporal properties of a masker upon simultaneous-masking patterns,'' in *Auditory Frequency Selectivity*, edited by B. C. J. Moore and R. D. Patterson (Plenum, New York), pp. 381–386.

Murnane, O., and Turner, C. W. (**1991**). ''Growth of masking in sensorineural hearing loss,'' Audiology **30**, 275–285.

Nelson, D. A., and Bilger, R. C. (**1974**). ''Pure-tone octave masking in listeners with sensorineural hearing loss,'' J. Speech Hear. Res. **17**, 252–269.

Nelson, D. A., and Schroder, A. C. (**1996**). ''Release from upward spread of masking in regions of high-frequency hearing loss,'' J. Acoust. Soc. Am. **100**, 2266–2277.

Nelson, D. A., and Schroder, A. C. (**1997**). ''Linearized response growth inferred from growth-of-masking slopes in ears with cochlear hearing loss,'' J. Acoust. Soc. Am. **101**, 2186–2201.

Nelson, D. A., and Swain, A. C. (**1996**). ''Temporal resolution within the upper accessory excitation of a masker,'' Acoustica **82**, 328–334.

Oxenham, A. J., and Moore, B. C. J. (**1994**). ''Modeling of additivity of nonsimultaneous masking,'' Hear. Res. **80**, 105–118.

Oxenham, A. J., and Moore, B. C. J. (**1995**). ''Additivity of masking in normally hearing and hearing-impaired subjects,'' J. Acoust. Soc. Am. **98**, 1921–1934.

Oxenham, A. J., and Moore, B. C. J. (**1997**). ''Modeling the effects of peripheral nonlinearity in listeners with normal and impaired hearing,'' in *Modeling Sensorineural Hearing Loss*, edited by W. Jesteadt (Erlbaum, Hillsdale, NJ), pp. 273–288.

Oxenham, A. J., Moore, B. C. J., and Vickers, D. A. (**1997**). ''Short-term temporal integration: Evidence of the influence of peripheral compression,'' J. Acoust. Soc. Am. **101**, 3676–3687.

Oxenham, A. J., and Plack, C. J. (**1997**). ''A behavioral measure of basilar-membrane nonlinearity in listeners with normal and impaired hearing,'' J. Acoust. Soc. Am. **101**, 3666–3675.

Oxenham, A. J., and Plack, C. J. (**1998**). ''Suppression and the upward spread of masking,'' J. Acoust. Soc. Am. **104**, 3500–3510.

Penner, M. J. (**1980**). ''The coding of intensity and the interaction of forward and backward masking,'' J. Acoust. Soc. Am. **67**, 608–6616.

Penner, M. J., and Shiffrin, R. M. (**1980**). ''Nonlinearities in the coding of intensity within the context of a temporal summation model,'' J. Acoust. Soc. Am. **67**, 617–627.

Plack, C. J., and Moore, B. C. J. (**1990**). ''Temporal window shape as a function of frequency and level,'' J. Acoust. Soc. Am. **87**, 2178–2187.

Plack, C. J., and Oxenham, A. J. (**1998**). ''Basilar-membrane nonlinearity and the growth of forward masking,'' J. Acoust. Soc. Am. **103**, 1598–1608.

Plack, C. J., and Oxenham, A. J. (**2000**). ''Basilar-membrane nonlinearity estimated by pulsation threshold,'' J. Acoust. Soc. Am. **107**, 501–507.

Rhode, W. S. (**1971**). ''Observations of the vibration of the basilar membrane in squirrel monkeys using the Mössbauer technique,'' J. Acoust. Soc. Am. **49**, 1218–1231.

Robinson, C. E., and Pollack, I. (**1973**). ''Interaction between forward and backward masking: a measure of the integrating period of the auditory system,'' J. Acoust. Soc. Am. **53**, 1313–1316.

Robles, L., Ruggero, M. A., and Rich, N. C. (**1986**). ''Basilar membrane mechanics at the base of the chinchilla cochlea. I. Input–output functions, tuning curves, and phase responses,'' J. Acoust. Soc. Am. **80**, 1364–1374.

Ruggero, M. A. (**1992**). ''Responses to sound of the basilar membrane of the mammalian cochlea,'' Curr. Opin. Neurobiol. **2**, 449–456.

Ruggero, M. A., and Rich, N. C. (**1990**). ''Systemic injection of furosemide alters the mechanical response to sound of the basilar membrane,'' in *The Mechanics and Biophysics of Hearing*, edited by P. Dallos, C. D. Geisler, J. W. Matthews, M. A. Ruggero, and C. R. Steele (Springer Verlag, Berlin), pp. 314–321.

Ruggero, M. A., and Rich, N. C. (**1991**). ''Furosemide alters organ of Corti mechanics: Evidence for feedback of outer hair cells upon the basilar membrane,'' J. Neurosci. **11**, 1057–1067.

Ruggero, M. A., Rich, N. C., and Recio, A. (**1993**). ''Alteration of basilar membrane responses to sound by acoustic overstimulation,'' in *Biophysics of Hair Cell Sensory Systems*, edited by H. Duifhuis, J. W. Horst, P. v. Dijk, and S. M. v. Netten (World Scientific, Singapore), pp. 258–265.

Ruggero, M. A., Rich, N. C., Robles, L., and Recio, A. (**1995**). ''The effects of acoustic overstimulation, other cochlear injury and death on basilar membrane responses to sound,'' in *Effects of Noise on Hearing: Vth International Symposium*, edited by R. J. Salvi, A. Axelsson, D. Henderson, and R. Hamernik (Thieme Medical, Stockholm).

Ruggero, M. A., Rich, N. C., Robles, L., and Recio, A. (**1996**). ''The effects of acoustic trauma, other cochlear injury and death on basilar-membrane responses to sound,'' in *Proceedings of the Vth International Symposium on the Effects of Noise on Hearing*, edited by A. Axelsson, H. Borchgrevink, D. Henderson, R. P. Hamernik, and R. Salvi (Thieme Medical, Stuttgart), pp. 258–264.

Ruggero, M. A., Rich, N. C., Recio, A., Narayan, S. S., and Robles, L. (**1997**). ''Basilar-membrane responses to tones at the base of the chinchilla cochlea,'' J. Acoust. Soc. Am. **101**, 2151–2163.

Schmiedt, R. A., Zwislocki, J. J., and Hamernik, R. P. (**1980**). ''Effects of hair cell lesions on responses of cochlear nerve fibers. I. Lesions, tuning curves, two-tone inhibition, and responses to trapezoidal-wave patterns,'' J. Neurophysiol. **43**, 1367–1389.

Sellick, P. M., Patuzzi, R., and Johnstone, B. M. (**1982**). ''Measurement of basilar membrane motion in the guinea pig using the Mössbauer technique,'' J. Acoust. Soc. Am. **72**, 131–141.

Smits, J. T. S., and Duifhuis, H. (**1982**). ''Masking and partial masking in

listeners with a high frequency hearing loss,'' Audiology **21**, 310–324.
Stelmachowicz, P., Lewis, D. E., Larson, L., and Jesteadt, W. (**1987**). ''Growth of masking as a measure of response growth in hearing-impaired listeners,'' J. Acoust. Soc. Am. **81**, 1881–1887.
Viemeister, N. F. (**1972**). ''Intensity discrimination of pulsed sinusoids: The effects of filtered noise,'' J. Acoust. Soc. Am. **51**, 1256–1269.
Viemeister, N. F. (**1979**). ''Temporal modulation transfer functions based upon modulation thresholds,'' J. Acoust. Soc. Am. **66**, 1364–1380.
Yates, G. K. (**1990**). ''Basilar membrane nonlinearity and its influence on auditory nerve rate-intensity functions,'' Hear. Res. **50**, 145–162.
Yates, G. K. (**1995**). ''Cochlear structure and function,'' in *Hearing*, edited by B. C. J. Moore (Academic, San Diego, CA), pp. 41–73.
Yates, G. K., Winter, I. M., and Robertson, D. (**1990**). ''Basilar membrane nonlinearity determines auditory nerve rate-intensity functions and cochlear dynamic range,'' Hear. Res. **45**, 203–220.
Zwicker, E. (**1976a**). ''Psychoacoustic equivalent of period histograms,'' J. Acoust. Soc. Am. **59**, 166–175.
Zwicker, E. (**1976b**). ''Masking-period patterns of harmonic complex tones,'' J. Acoust. Soc. Am. **60**, 429–439.
Zwicker, E. (**1976c**). ''Mithörschwellen-Periodenmuster amplitudenmodulierter Töne (Masking-period patterns of amplitude modulated pure tones),'' Acoustica **36**, 113–120.
Zwicker, E. (**1986**). ''Das Zeitauflösungsvermögen des Gehörs—Eine zweckmäßige Meßmethode im Hinblick auf die Sprachverständlichkeit,'' Audiol. Acoustics **25**, 170–184.
Zwicker, E., and Schorn, K. (**1982**). ''Temporal resolution in hard-of-hearing patients,'' Audiology **21**, 474–492.