ELSEVIER

Hearing Research 150 (2000) 258–266

HEARING RESEARCH

www.elsevier.com/locate/heares

Effects of masker frequency and duration in forward masking: further evidence for the influence of peripheral nonlinearity

Andrew J. Oxenham [a,*], Christopher J. Plack [b]

[a] Research Laboratory of Electronics, Rm. 36-763, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[b] Department of Psychology, University of Essex, Wivenhoe Park, Colchester CO4 3SQ, UK

Received 21 March 2000; accepted 28 August 2000

Abstract

Forward masking has often been thought of in terms of neural adaptation, with nonlinearities in the growth and decay of forward masking being accounted for by the nonlinearities inherent in adaptation. In contrast, this study presents further evidence for the hypothesis that forward masking can be described as a linear process, once peripheral, mechanical nonlinearities are taken into account. The first experiment compares the growth of masking for on- and off-frequency maskers. Signal thresholds were measured as a function of masker level for three masker-signal intervals of 0, 10, and 30 ms. The brief 4-kHz sinusoidal signal was masked by a 200-ms sinusoidal forward masker which had a frequency of either 2.4 kHz (off-frequency) or 4 kHz (on-frequency). As in previous studies, for the on-frequency condition, the slope of the function relating signal threshold to masker level became shallower as the delay between the masker and signal was increased. In contrast, the slopes for the off-frequency condition were independent of masker-signal delay and had a value of around unity, indicating linear growth of masking for all masker-signal delays. In the second experiment, a broadband Gaussian noise forward masker was used to mask a brief 6-kHz sinusoidal signal. The spectrum level of the masker was either 0 or 40 dB (re: 20 μPa). The gap between the masker and signal was either 0 or 20 ms. Signal thresholds were measured for masker durations from 5 to 200 ms. The effect of masker duration was found to depend more on signal level than on gap duration or masker level. Overall, the results support the idea that forward masking can be modeled as a linear process, preceded by a static nonlinearity resembling that found on the basilar membrane.

Key words: Forward masking; Cochlear nonlinearity; Temporal processing

1. Introduction

Forward masking, where the masker precedes the signal in time, has long been regarded as a measure of temporal resolution, or how well the auditory system is able to follow rapid changes in level (Plomp, 1964). However, the underlying mechanisms of forward masking remain poorly understood. In particular, the many nonlinear effects, such as the dependence of forward masking on masker level and masker duration, have proved challenging to explain quantitatively. Qualitative similarities between adaptation, as measured in the auditory nerve, and forward masking have led some researchers to suggest a link between the two phenomena (e.g. Smith, 1977). However, evidence from auditory nerve masking studies (Relkin and Turner, 1988) and behavioral cochlear implant studies (Shannon, 1990) suggests that adaptation at the level of the sensory hair cells and synapses cannot account for forward masking.

Recently, a theory has emerged in which it is postulated that the many nonlinear aspects of forward masking can be accounted for by the mechanical nonlinearities observed at the level of the basilar membrane (BM), and that all subsequent processing can be treated as linear and time invariant (Oxenham and Moore, 1995, 1997; Moore and Oxenham, 1998; Plack and Oxenham, 1998). In other words, forward masking can be modeled using a linear sliding temporal integrator (or temporal window) preceded by a static nonli-

* Corresponding author. Tel.: +1 (617) 253-5995; Fax: +1 (617) 258-7003; E-mail: oxenham@mit.edu

0378-5955/00/$ – see front matter
PII: S0378-5955(00)00206-9

nearity. This is surprising, given the complexity of the auditory system following cochlear processing, and the highly nonlinear interactions found in forward masking. On the other hand, if shown to be generally applicable, the assumption of linearity would make modeling efforts far more tractable than would be the case if nonlinearities at each stage of processing were shown to have significant effects.

As explained below, this theory can account quantitatively for the effects of masker-signal interval on the growth of forward masking for an on-frequency masker (Plack and Oxenham, 1998). Furthermore, the more linear growth of forward masking with masker level and the shallower decay of forward masking with increasing masker-signal delay observed in hearing-impaired listeners (Kidd et al., 1984; Nelson and Freyman, 1987) can be explained in terms of a loss or reduction of BM nonlinearity (Oxenham and Moore, 1997). An alternative model of forward masking is provided by Dau et al. (1996a,b). In their model, which can successfully account for a wide range of psychoacoustic data from both simultaneous and nonsimultaneous masking, forward masking is modeled as an interaction between nonlinear adaptation and persistence, which are a consequence of five feedback loops, each having a different time constant, and a final lowpass filter, which has an effect similar to that of the temporal window. Peripheral compression is not explicitly included, meaning that some of the effects ascribed to peripheral nonlinearity are probably not well accounted for in that model. The purpose of this study was to provide further experimental tests of the hypothesis that nonlinearities in forward masking can be fully accounted for by known peripheral nonlinearities.

The first test involves the growth of masking in the presence of a masker with a frequency well below the signal frequency. The response of a point along the BM to stimuli well below its characteristic frequency (CF) is linear at all levels (Ruggero et al., 1997). If, as postulated, the effect of masker-signal gap on the growth of on-frequency forward masking is due to changes in the local slope of the BM input–output function with level, then the effect should be different for maskers well below the signal frequency. Specifically, if the signal thresholds occupy the same range of levels in all conditions, the slope of the growth of masking function using a low-frequency masker should be independent of masker-signal interval. This difference between on- and off-frequency maskers is illustrated in Fig. 1. A schematic diagram of the BM input–output function is shown for a tone at CF (Fig. 1a) and a tone well below CF (Fig. 1b). It is assumed that threshold corresponds to a fixed signal-to-masker ratio, measured as BM response, for a given masker-signal delay.

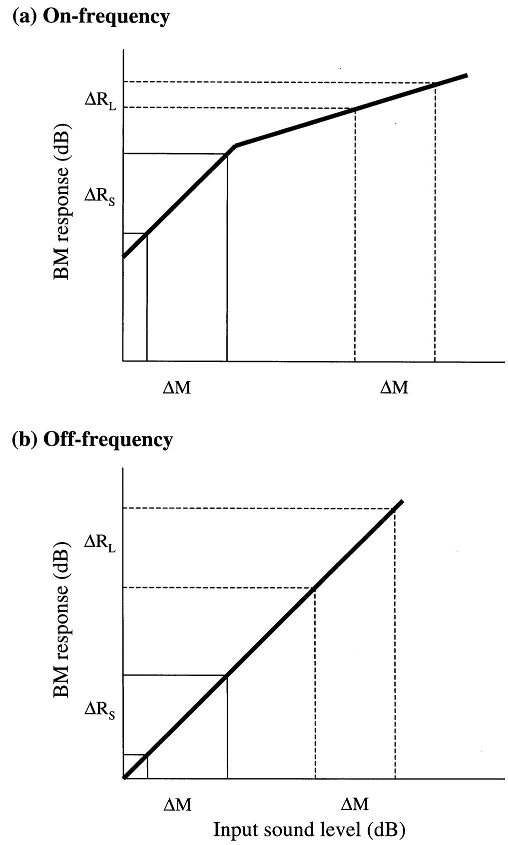

Fig. 1. Schematic diagram of the response of the BM to a masking tone at CF (a) and a tone well below CF (b). For the on-frequency tone, the change in response for a given change in stimulus level will depend on the initial stimulus level. For the off-frequency tone, the change in response is independent of the initial level.

Consider first a low-level signal masked by an on-frequency forward masker. When the masker-signal interval is short, the level of the masker will fall in the more linear, low-level region of the BM input–output function. A given increase in masker level, ΔM, will produce a similar increase in BM response, ΔR_S. If the masker-signal delay is increased, the masker level necessary to mask the signal will increase and will now fall in the compressive region of the BM input–output function. In this case, the same increase in masker level, ΔM, will produce a smaller increase in BM response (ΔR_L). This results in a shallower growth of masking function for the longer masker-signal interval. Plack and Oxenham (1998) have shown that this model can account quantitatively for the effects of masker-signal interval on the growth of on-frequency masking.

Consider next a low-level signal masked by a forward masker much lower in frequency than the signal. In this case, the response of the BM to the masker is linear at all levels, as shown schematically by the heavy line in

Fig. 1b. When the masker-signal interval is increased from short to long, the masker level also increases but, in contrast to the on-frequency condition, the change in response due to a given change in masker level is not dependent on the overall masker level, i.e. $\Delta R_L = \Delta R_S$. It follows that the slope of the growth of forward masking function should be independent of masker-signal interval.

This prediction is somewhat counterintuitive: the growth of forward masking is generally known to be highly dependent on the gap between the masker and signal, at least for on-frequency and broadband maskers (e.g. Kidd and Feth, 1981; Jesteadt et al., 1982; Moore and Glasberg, 1983). The prediction of parallel growth of masking functions for an off-frequency forward masker with different masker-signal intervals has not been directly tested before. Kidd and Feth (1981) show data from one listener using masker and signal frequencies of 1 and 2, respectively (their figure 5). The signal had 10-ms ramps and no steady-state portion. They found roughly parallel slopes for the growth of masking functions with masker-signal intervals of 5, 10, 20, and 40 ms. Although this supports the predictions based on BM nonlinearity, the data are from only one listener, which limits the strength of conclusions that can be drawn. Data from Oxenham and Plack (1997) are also consistent with the model predictions: thresholds were measured for 4- and 14-ms signals (total duration) at 6 kHz in the presence of a 3-kHz forward masker. The slopes of the two growth of masking functions were very similar for all three listeners. Again, however, data from two conditions, with a difference of only 10 ms, do not provide a rigorous test of the prediction that the slope of the growth of masking function for forward masking should be totally independent of masker-signal delay if the masker is well below the signal in frequency. The first experiment in this paper provides a systematic study of on- and off-frequency forward masking with the aim of supporting or disproving the hypothesis that nonlinearities in the growth of forward masking are primarily due to BM nonlinearity.

The second test involves the effect of masker duration on forward masking. It has been shown by Oxenham and Moore (1994) that the increase in signal threshold with increasing masker duration (e.g. Penner, 1974; Kidd and Feth, 1982; Zwicker, 1984) can be accounted for in the context of the temporal window model (Moore et al., 1988; Plack and Moore, 1990). In this model, forward masking is thought to reflect the smoothing effects of a sliding temporal integrator, or temporal window, such that the signal is masked by a persistence of activity due to the masker at the output of the integrator. The inclusion of a compressive nonlinearity in the model allows the short time constant (ca. 10 ms) necessary to account for the decay of forward masking to also account for the longer term effect of masker duration, over durations up to about 100 ms (Penner, 1978; Oxenham and Moore, 1994). In the model, the size of the effect of masker duration is determined almost solely by the signal level, rather than the masker level or frequency, or the gap between masker and signal, for the following reasons: (1) a given increase in masker duration will lead to the same proportional increase in the output of the temporal window regardless of the masker level or masker frequency, making the predicted amount of integration independent of these parameters. (2) The amount by which the signal level will need to be increased to match that increase depends on the compression applied to the signal. Hence, the predicted effect of masker duration depends on whether the signal level at threshold is within a more linear or more compressive region of the model's input nonlinearity (simulating the BM response). (3) If the temporal window was modeled as a single decaying exponential, the slope of the window's attenuation (in dB per unit time) would be constant. A given increase in masker duration would therefore always produce the same proportional increase in the window output regardless of the masker's temporal position relative to the window peak. Thus, the predicted amount of integration would be independent of the gap between the masker and signal. In the present model, the decay of masking is modeled by the sum of two exponentials, meaning that predictions are not strictly independent of the masker-signal gap. However, for most gaps and masker durations, the second, longer, time constant dominates the effect of masker duration, making predictions effectively independent of gap duration.

No study has specifically attempted to separate the effects of signal level from the effects of masker level and/or masker-signal interval. However, Kidd et al. (1984) found a much reduced effect of forward masker duration for listeners with hearing impairment. This finding can be understood in terms of hearing impairment reflecting a reduction of cochlear nonlinearity. Reduced compression is predicted to lead to a reduced effect of masker duration on forward masking. The second experiment described in this paper measures forward masking as a function of masker duration for two masker levels (0 and 40 dB spectrum level) and two masker-signal intervals (0 and 20 ms). The purpose of the second experiment was to collect data that would provide a rigorous test of the prediction of the temporal window model, specifically that the effect of masker duration is determined mainly by the level of the signal at masked threshold.

2. Growth of forward masking for on-frequency and off-frequency maskers

2.1. Stimuli

The signal was a 4-kHz sinusoid, gated on and off with 5-ms raised-cosine ramps and no steady-state portion (10-ms total duration). The masker was gated on and off with 2-ms ramps and had a total duration of 200 ms. The masker frequency was either 4 kHz (on-frequency condition) or 2.4 kHz (off-frequency condition). The gap between the masker offset and the signal onset was 0, 10, or 30 ms, measured at the 0-V points of the electrical envelope. For each of these six conditions (two masker frequencies and three signal delays), signal thresholds were measured for a number of masker levels, spaced 5 or 10 dB apart. The exact range of masker levels was chosen for each listener individually, based on pilot data, so that all conditions produced roughly the same range of signal levels at threshold.

The stimuli were generated digitally at a sampling rate of 50 kHz, played out via a 16-bit digital to analog converter (TDT DA1), and lowpass-filtered at 20 kHz (TDT FT5). The masker and signal were generated and converted separately, and were passed through programmable attenuators (TDT PA4) before being combined (TDT SM3) and presented via a headphone amplifier (TDT HB6) to one earpiece of a Sony MDR-V6 headset.

2.2. Procedure

Thresholds were measured using a two-interval, two-alternative forced-choice method with a three-down one-up adaptive procedure that tracks the 79.4%-correct point of the psychometric function. Each run consisted of three independent, interleaved tracks. Each trial, selected randomly from one of the three tracks, consisted of two intervals both containing the masker, and separated by an interstimulus interval of 400 ms. The signal occurred in one of the two intervals, selected at random, and listeners were required to select the signal interval. The signal level was initially adjusted in steps of 5 dB. In each track, after three reversals the step size was reduced to 2 dB. Each track was terminated after a total of five reversals, and the threshold was defined as the mean of the levels at the last two reversals. The threshold for each run was the mean of the three thresholds, comprising a total of six reversals. If the standard error of the three tracks was greater than 3 dB, the run was discarded and the run was repeated at a later time. For every listener, at least three such threshold estimates were made for each condition. If the standard deviation of the three threshold estimates was greater than 3 dB, a fourth threshold estimate was made. The mean and standard deviation of the three or four estimates are reported here. Listeners were tested in 2-h sessions, including short breaks. Responses were made and correct-answer feedback given via a response box. Listeners were tested individually in a double-walled sound-attenuating booth.

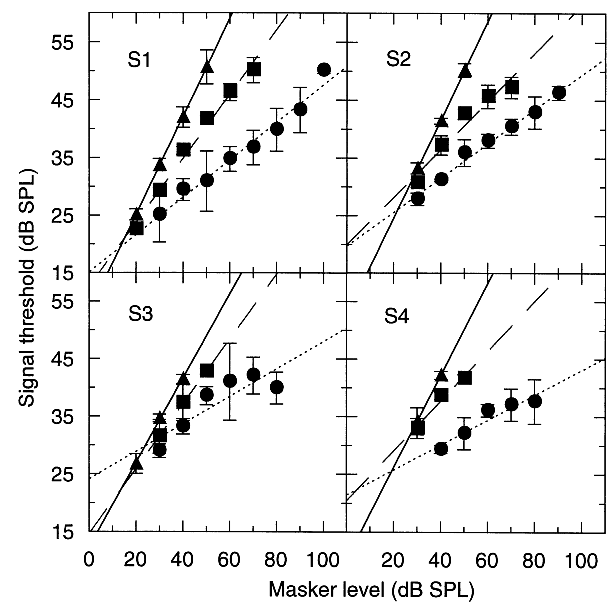

Fig. 2. Signal thresholds as a function of masker level for an on-frequency 4-kHz forward masker. Data from four listeners are presented separately in the four panels. Different values of the masker-signal intervals are denoted by the different symbols. The triangles, squares, and circles represent 0-, 10-, and 30-ms masker-signal intervals, respectively. The error bars denote ±1 S.D. of the mean.

2.3. Listeners

The four listeners all had audiometric thresholds of 15 dB HL or less at octave frequencies between 250 and 8000 Hz. The three females and one male (S3) were college students and were paid for their participation. The ages of S1–S4 were 21, 22, 23, and 44, respectively. All listeners were given about 4 h training on the task (including the collection of pilot data) before data were recorded. The threshold for the signal in quiet was also measured for each listener, using the same procedure as in the main experiment. Thresholds for the 5-ms (half-amplitude duration) signal in quiet were 16.2, 21.9, 20.3, and 22 dB SPL for S1–S4, respectively.

2.4. Results and discussion

Individual data are plotted in Fig. 2 for the on-frequency conditions and in Fig. 3 for the off-frequency conditions, with signal level at threshold plotted as a function of masker level. The triangles, squares, and circles represent data for the masker-signal intervals

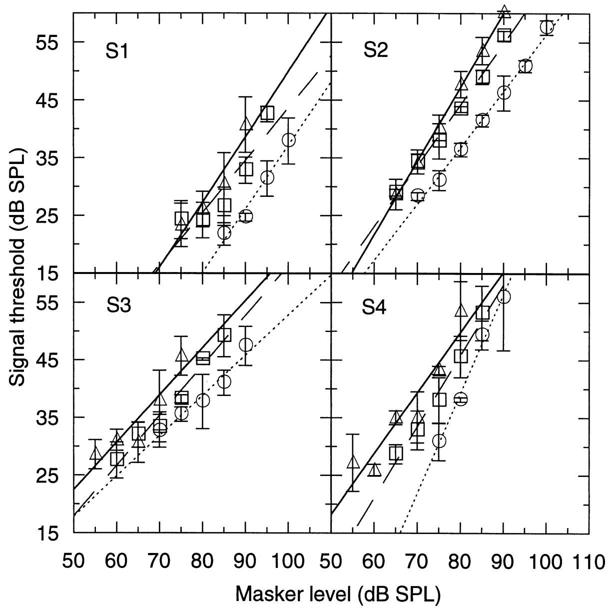

Fig. 3. Signal thresholds as a function of masker level for an off-frequency forward masker. The masker frequency was 2.4 kHz and the signal frequency was 4 kHz. Data are shown from the same four listeners as in Fig. 1. The triangles, squares, and circles represent 0-, 10-, and 30-ms masker-signal intervals, respectively.

of 0, 10, and 30 ms, respectively. Linear regression lines fitted to the data are also shown with solid, dashed and dotted lines for the 0-, 10-, and 30-ms intervals, respectively. The masker levels in both conditions were chosen such that signal thresholds would span a range from 5 dB above threshold in quiet to about 50 dB SPL, or lower if it was not possible to achieve a threshold of 50 dB SPL using a masker level of 100 dB SPL. It was important for testing the hypothesis that the range of signal levels for the three masker-signal intervals in each condition was comparable. Therefore, for each listener, signal thresholds less than 5 dB above threshold in quiet were excluded, as were thresholds which exceeded the maximum thresholds at any of the other masker-signal intervals by more than 5 dB.

The pattern of results from the on-frequency conditions (Fig. 2) is consistent with many previous studies (e.g. Jesteadt et al., 1982; Moore and Glasberg, 1983): the growth of masking is generally nonlinear and becomes increasingly shallow at longer masker-signal intervals. Slopes of the growth of masking functions, pooled across listeners and estimated by linear regression, are 0.82, 0.5, and 0.29 for the 0-, 10-, and 30-ms masker-signal intervals, respectively. The data from the off-frequency conditions (Fig. 3) show a very different pattern. As with the on-frequency data, thresholds generally decrease with increasing masker-signal delay for a given masker level. However, the growth of masking at a given masker-signal interval is steeper than in the on-frequency conditions, and overall there is little or no change in slope with increasing masker-signal interval. While there is a slight trend for the slopes to become steeper with increasing masker-signal interval for listeners S2 and S3, the opposite is true for S4. Pooled across listeners, the slopes of the growth of masking functions are 1.1, 1.0, and 1.0 for the 0-, 10-, and 30-ms masker-signal intervals, respectively.

The results from the off-frequency masking condition show that increasing the masker-signal delay does not automatically result in a shallower growth of masking function. Overall, the results are in line with the predictions outlined in Section 1, and can be explained in terms of known features of BM nonlinearity. For the on-frequency condition, the level differences between the masker and the signal at threshold change across the three masker-signal intervals. These level differences result in the masker and signal falling in different level regions of the BM input–output function. As shown by Plack and Oxenham (1998), these differences can be used to quantitatively predict the change in growth of masking slope with increasing masker-signal delay. For the off-frequency condition, the masker is more than half an octave below the signal frequency, and is therefore believed to be processed linearly at all levels at the place along the BM with a CF corresponding to the signal frequency (Ruggero, 1992). In this case, so long as the range of signal levels remains constant (as in this experiment), the relationship between the response to the masker and the response to the signal will not be altered by changing the masker-signal interval. Thus, the results support the idea that forward masking can be modeled as a linear process, once BM nonlinearity is taken into account.

One unexpected aspect of the data is that the linear growth of masking seems to continue up to signal levels of 50 dB SPL or more. Previous behavioral estimates of the level at which the BM response becomes highly compressive have ranged from around 30 to 45 dB SPL (Oxenham and Plack, 1997; Plack and Oxenham, 1998, 2000). It was therefore expected that the masking function would become steeper at the highest signal levels tested here. It is possible that 'off-frequency listening' resulted in the continuation of the linear growth of masking at higher levels (Plack and Oxenham, 2000): the signal may have been most detectable at places along the BM tuned higher than the signal frequency itself. The response to the signal at such places is expected to be more linear, producing a more linear growth of masking function. Whether such mechanisms can quantitatively account for the data remains to be seen, pending the development of realistic functional models of cochlear macromechanics for use in psychoacoustic models.

3. Effects of masker duration as a function of masker level and masker-signal interval

A number of studies have shown that thresholds in forward masking are dependent on masker duration (Penner, 1974; Kidd and Feth, 1982; Kidd et al., 1984; Zwicker, 1984; Carlyon, 1988). As discussed in Section 1, according to the theory of forward masking nonlinearity based on BM nonlinearity, the dependence of thresholds on masker duration should be determined by the range of signal levels at threshold. This is because any increase in the window output due to an increase in masker duration has to be matched by an increase in signal level. Only the compression applied to the signal determines what this increase will be; the masker level, or masker frequency, should not play any role in the amount of observed integration. A broadband masker was used to avoid possible 'confusion' effects that can sometimes affect tone-on-tone forward masking (Neff, 1986).

3.1. Stimuli

The signal was a 6-kHz sinusoid, gated on and off with 5-ms raised-cosine ramps and no steady-state portion (10-ms total duration). The masker was a wideband Gaussian noise gated on and off with 2-ms ramps. Steady-state duration was either 5, 10, 30, or 200 ms. The masker spectrum level was either 0 or 40 dB. The gap between the masker offset and the signal onset was 0 or 20 ms, measured at the 0-V points of the electrical envelope.

The stimuli were generated digitally at a sampling rate of 32 kHz on a Silicon Graphics workstation, and played out via the in-built 16-bit digital to analog converter. Stimuli were presented to the right earpiece of a Sennheiser HD 580 headset, connected directly to the headphone output on the computer.

3.2. Procedure

Thresholds were measured using a two-interval, two-alternative forced-choice method with a two-down one-up adaptive procedure that tracks the 70.7%-correct point of the psychometric function. The signal occurred in one of the two intervals, selected at random, and listeners were required to select the signal interval. The signal level was initially adjusted in steps of 4 dB. After four reversals, the step size was reduced to 2 dB. Each track was terminated after a total of 16 reversals, and the threshold was defined as the mean of the signal levels at the last 12 reversals. For every listener, four such threshold estimates were made for each condition. Listeners were tested in 2-h sessions, including short breaks. Responses were made and correct-answer feedback was given via a response box. Listeners were tested individually in a double-walled sound-attenuating booth.

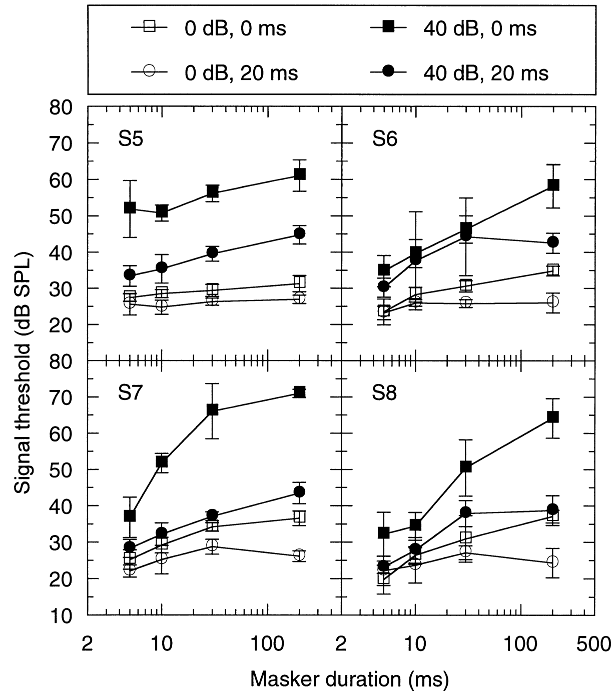

Fig. 4. Signal thresholds in forward masking as a function of masker duration. The parameters are masker spectrum level (filled symbols: 40 dB; open symbols: 0 dB) and masker-signal interval (squares: 0 ms; circles: 20 ms). The error bars denote ±1 S.D. of the mean.

3.3. Listeners

The four listeners all had audiometric thresholds of 15 dB HL or less at octave frequencies between 250 and 8000 Hz. The four females were college students and were paid for their participation. All listeners were given at least 4 h training on the task before data were recorded. The threshold for the signal in quiet was also measured for each listener, using the same procedure as in the main experiment. Thresholds for the signal in quiet were 17.4, 18.4, 12.9, and 10.3 dB SPL for S5–S8, respectively.

3.4. Results and discussion

The individual results are shown in Fig. 4. Signal level at threshold is plotted as a function of masker duration. The parameters are masker level and masker-signal interval. Each panel represents the data from a different listener. Conditions with the 0-dB spectrum level masker are shown with open symbols, while conditions with the 40-dB spectrum level masker are shown with filled symbols. Squares and circles represent

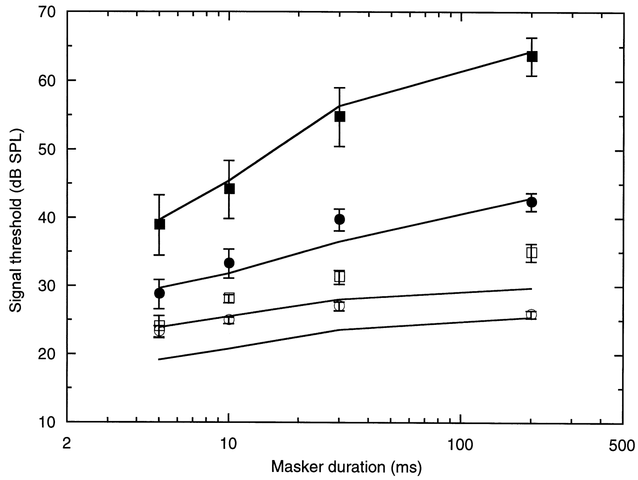

Fig. 5. Mean data from Fig. 4. The filled and open symbols represent masker spectrum levels of 40 and 0 dB, respectively. The squares and circles represent masker-signal intervals of 0 and 20 ms, respectively. Error bars denote ±1 S.E.M. across listeners. The solid curves represent the predictions of the temporal window model. See text for details.

the 0-ms and 20-ms masker-signal intervals, respectively. The error bars represent ±1 standard deviation from the mean across the four repetitions. While the trends of the data are similar across listeners, there are some substantial individual differences in threshold values, especially for the 40-dB, 0-ms condition. For all but one listener, thresholds in the 40-dB, 0-ms condition show a much greater dependence on masker duration than in any of the other three conditions. The exception (S5) shows approximately equal dependence for both 40-dB conditions. Otherwise, the basic trends are represented well by the mean data, shown in Fig. 5. The symbols have the same meaning as in Fig. 4, but the error bars represent ±1 standard error of the mean across listeners. The solid curves are predictions of the temporal window model, discussed below. Overall, the dependence of thresholds on masker duration is very similar for the 40-dB, 20-ms condition and the 0-dB, 0-ms condition. There is a trend for the 0-dB, 20-ms condition to show least dependence on masker duration.

It is clear from the data that neither masker level nor masker-signal interval alone determine the dependence of thresholds on masker duration. Overall, it seems that the range of signal levels at threshold is important in determining the amount of integration. Thus, the similar signal thresholds in the 0-dB, 0-ms and the 40-dB, 20-ms conditions could explain why the functions run approximately parallel to each other. While this appears to be a parsimonious explanation, it cannot account for why the effect of masker duration for the 0-dB, 20-ms condition seems to be less than that for the 0-dB, 0-ms condition, as the two produce identical signal thresholds for the 5-ms masker, but then diverge for longer masker durations. It is possible that the approach to absolute threshold can account for this discrepancy – the lowest thresholds may be determined more by absolute threshold than by the masker energy. Note, however, that the lowest mean thresholds are still at least 8 dB above the threshold for the signal in quiet. For the individual data, all masked thresholds were at least 5 dB above threshold in quiet. Thus, it seems unlikely that the lack of an effect of masker duration in the 0-dB, 20-ms condition is solely due to the approach of absolute threshold.

To study this question more quantitatively, the conditions in this experiment were simulated using the temporal window model, the details of which are described elsewhere (Oxenham and Moore, 1994; Plack and Oxenham, 1998). Briefly, stimuli are bandpass-filtered to represent peripheral filtering, and subject to a static nonlinearity representing the nonlinear compression of the BM. The stimuli are then rectified and passed through a sliding temporal integrator, or temporal window. The decision criterion is based on the ratio of the window output due to the masker and signal together to the output due to the masker alone. The point in time at which this internal signal-to-masker ratio is maximum is used for the decision. The parameters for the model are the nonlinearity used to simulate the effect of the BM, the time constants defining the window shape, and the signal-to-masker ratio defining the threshold criterion. All parameters except the threshold signal-to-noise ratio were defined in advance, based on the studies of Oxenham and Moore (1994) and Oxenham and Plack (1997), as described by Plack and Oxenham (1998). The nonlinearity was defined by the following equations:

$$L_{out} = 0.78L_{in} \qquad L_{in} < 35 \text{ dB SPL}$$
$$L_{out} = 0.16L_{in} + 21.7 \qquad L_{in} \geq 35 \text{ dB SPL}$$

where L_{in} and L_{out} are the input and output levels (in dB), respectively. The resulting amplitudes were squared before being passed through the temporal window, to produce an intensity-like quantity. The weighting function, $W(t)$, for the temporal window was defined by a double exponential function to describe times before the window peak and a single exponential for times after the peak:

$$W(t) = (1-w)\exp(t/Tb_1) + w\exp(t/Tb_2) \qquad t < 0$$
$$W(t) = \exp(-t/Ta) \qquad t \geq 0$$

where t is time relative to the window peak in ms, and the parameter values are $Tb_1 = 4$; $Tb_2 = 29$, $w = 0.16$; and $Ta = 3.5$. These are the values that are given for the data of subject AO in Oxenham and Moore (1994) and were also used by Plack and Oxenham (1998)[1]. The signal-to-masker ratio at threshold was the only free parameter. The best-fitting value corresponded to a signal-to-masker ratio at the output of the window of 2.67 dB.

The predictions of the model are shown as solid curves in Fig. 5. It can be seen that the model captures some of the main trends of the data, in particular the much greater integration observed in the 40-dB, 0-ms condition. This is because the signal level is reasonably high in this condition and therefore falls within the more compressive region of the model's nonlinearity. However, in contrast to the data, the model does not predict a difference in the slope for the two 0-dB masker conditions. Fitting the window parameters specifically to this data set resulted in a modest improvement in the overall sum of squared errors from 109 to 90, but the model was still not able to capture the difference in slopes between the two 0-dB masker conditions. As the effects of absolute threshold are included in this model, the failure of these predictions confirms the suggestion above, that the approach to absolute threshold also cannot account for the empirically obtained slope difference, at least in the context of this model.

4. Summary

In the first experiment, the growth of forward masking was measured using an on-frequency masker and a masker well below the signal frequency for masker-signal intervals of 0, 10, and 30 ms. As in previous studies, the growth of masking for the on-frequency masker was generally nonlinear and became increasingly shallow with increasing masker-signal interval. In contrast, for the off-frequency masker, the slopes of the growth of masking functions were independent of masker-signal interval and were close to unity. These results can be understood if it is assumed that BM nonlinearities are responsible for the nonlinearities observed in forward masking, and that subsequent processing, including the mechanisms responsible for the decay of forward masking, behaves as if linear, with respect to intensity.

In the second experiment, the effect of masker duration on forward masking was studied for two masker levels (0- and 40-dB spectrum level) and two masker-signal intervals (0 and 20 ms). The dependence of threshold on masker duration was greatest for the 40-dB, 0-ms condition, was approximately the same for the 40-dB, 20-ms and 0-dB, 0-ms conditions, and was least for the 0-dB, 0-ms condition. Thus, the dependence of threshold on masker duration was determined by neither the masker level nor the masker-signal interval alone. The results were reasonably well predicted by the temporal window model, which incorporates the effects of BM nonlinearity, although some discrepancies remained.

As with the study of Plack and Oxenham (1998), the results do not rule out the possibility that neural adaptation is responsible for forward masking. However, they place some constraints on the nature of such adaptation. In particular, the amount of adaptation should grow approximately linearly with (compressed) masker level and should recover with a time constant that is independent of adaptor level. In this way, the adaptation would be functionally very similar to the linear sliding temporal integrator used in the temporal window model. Note that explanations based on either adaptation or temporal integration are not mutually exclusive. As with excitation and suppression in simultaneous masking (Delgutte, 1990), it is possible that both neural adaptation and persistence play a role in determining thresholds in forward masking. As yet, it has not been possible to distinguish between adaptation and integration as explanations for forward masking, although it should be noted that other temporal resolution phenomena such as gap detection, decrement detection, and backward masking, are consistent with the temporal window framework (Oxenham and Moore, 1994; Peters et al., 1995), but are not readily explained by an adaptive mechanism alone.

Acknowledgements

The first author is supported by NIH/NIDCD Grant R01 DC 03909. The collaboration was facilitated by a Wellcome Trust Research Collaboration Grant. Experiment 1 was performed with the assistance of Jocelyn Hendrickson while the first author was at the Institute for Hearing, Speech, and Language, Northeastern University, Boston, MA, USA. Walt Jesteadt and Brian

[1] An error in table 1 of Oxenham and Moore (1994) gave AO's value for 20 log(w) as −16 dB, instead of the correct value of −32 (all other values in that table are correct). This error was compounded in the study of Plack and Oxenham (1998), where the value of −32 dB (0.025) was reported but −16 was used in the simulations. The 'incorrect' value of −16 has since been found to actually give better predictions for the data of Plack and Oxenham (1998) and for the present data. In fact, it would have been surprising if windows derived by Oxenham and Moore (1994) had provided good fits with the present model. This is because the nonlinearity is different from that used in the Oxenham and Moore (1994) study: a change in the nonlinearity results in an effective change in window shape (Oxenham et al., 1997), making a window fitted using a simple power-law nonlinearity (as in Oxenham and Moore, 1994) inappropriate for the more complex nonlinearity used here. We decided to use the same window here as was used by Plack and Oxenham (1998), because they also used the more complex nonlinearity, making the model used here identical to that used by Plack and Oxenham (1998).

Moore provided helpful comments on an earlier version of this paper.

References

Carlyon, R.P., 1988. The development and decline of forward masking. Hear. Res. 32, 65–80.

Dau, T., Püschel, D., Kohlrausch, A., 1996a. A quantitative model of the 'effective' signal processing in the auditory system. I. Model structure. J. Acoust. Soc. Am. 99, 3615–3622.

Dau, T., Püschel, D., Kohlrausch, A., 1996b. A quantitative model of the 'effective' signal processing in the auditory system. II. Simulations and measurements. J. Acoust. Soc. Am. 99, 3623–3631.

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

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

Kidd, G., Feth, L.L., 1981. Patterns of residual masking. Hear. Res. 5, 49–67.

Kidd, G., Feth, L.L., 1982. Effects of masker duration in pure-tone forward masking. J. Acoust. Soc. Am. 72, 1384–1386.

Kidd, G., Mason, C.R., Feth, L.L., 1984. Temporal integration of forward masking in listeners having sensorineural hearing loss. J. Acoust. Soc. Am. 75, 937–944.

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

Moore, B.C.J., Oxenham, A.J., 1998. Psychoacoustic consequences of compression in the peripheral auditory system. Psychol. Rev. 105, 108–124.

Neff, D.L., 1986. Confusion effects with sinusoidal and narrowband-noise forward maskers. J. Acoust. Soc. Am. 79, 1519–1529.

Nelson, D.A., Freyman, R.L., 1987. Temporal resolution in sensorineural hearing-impaired listeners. J. Acoust. Soc. Am. 81, 709–720.

Oxenham, A.J., Moore, B.C.J., 1994. Modeling the additivity of nonsimultaneous masking. Hear. Res. 80, 105–118.

Oxenham, A.J., 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 normal and impaired hearing. In: Jesteadt, W. (Ed.), Modeling Sensorineural Hearing Loss. Erlbaum, Hillsdale, NJ, pp. 273–288.

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

Oxenham, A.J., 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.

Penner, M.J., 1974. Effect of masker duration and masker level on forward and backward masking. J. Acoust. Soc. Am. 56, 179–182.

Penner, M.J., 1978. A power law transformation resulting in a class of short-term integrators that produce time-intensity trades for noise bursts. J. Acoust. Soc. Am. 63, 195–201.

Peters, R.W., Moore, B.C.J., Glasberg, B.R., 1995. Effects of level and frequency on the detection of decrements and increments in sinusoids. J. Acoust. Soc. Am. 97, 3791–3799.

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

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

Plomp, R., 1964. The rate of decay of auditory sensation. J. Acoust. Soc. Am. 36, 277–282.

Relkin, E.M., Turner, C.W., 1988. A reexamination of forward masking in the auditory nerve. J. Acoust. Soc. Am. 84, 584–591.

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

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

Shannon, R.V., 1990. Forward masking in patients with cochlear implants. J. Acoust. Soc. Am. 88, 741–744.

Smith, R.L., 1977. Short-term adaptation in single auditory nerve fibers: Some poststimulatory effects. J. Neurophysiol. 40, 1098–1112.

Zwicker, E., 1984. Dependence of post-masking on masker duration and its relation to temporal effects in loudness. J. Acoust. Soc. Am. 75, 219–223.