Forward masking: Adaptation or integration?

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(Received 1 October 1999; revised 1 October 2000; accepted 30 October 2000)

The aim of this study was to attempt to distinguish between neural adaptation and persistence (or temporal integration) as possible explanations of forward masking. Thresholds were measured for a sinusoidal signal as a function of signal duration for conditions where the delay between the masker offset and the signal offset (the offset–offset interval) was fixed. The masker was a 200-ms broadband noise, presented at a spectrum level of 40 dB (*re*: 20 μPa), and the signal was a 4-kHz sinusoid, gated with 2-ms ramps. The offset–offset interval was fixed at various durations between 4 and 102 ms and signal thresholds were measured for a range of signal durations at each interval. A substantial decrease in thresholds was observed with increasing duration for signal durations up to about 20 ms. At short offset–offset intervals, the amount of temporal integration exceeded that normally found in quiet. The results were simulated using models of temporal integration (the temporal-window model) and adaptation. For both models, the inclusion of a peripheral nonlinearity, similar to that observed physiologically in studies of the basilar membrane, was essential in producing a good fit to the data. Both models were about equally successful in accounting for the present data. However, the temporal-window model provided a somewhat better account of similar data from a simultaneous-masking experiment, using the same parameters. This suggests that the linear, time-invariant properties of the temporal-window approach are appropriate for modeling forward masking. Overall the results confirm that forward masking can be described in terms of peripheral nonlinearity followed by linear temporal integration at higher levels in the auditory system. However, the difference in predictions between the adaptation and integration models is relatively small, meaning that influence of adaptation cannot be ruled out. © *2001 Acoustical Society of America.* [DOI: 10.1121/1.1336501]

PACS numbers: 43.66.Dc, 43.66.Mk, 43.66.Ba [RVS]

I. INTRODUCTION

Forward masking, where the threshold of a signal is elevated by a masker preceding it in time, has been the subject of intense study over a number of decades (e.g., de Maré, 1940; Lüscher and Zwislocki, 1947; Munson and Gardner, 1950; Zwislocki *et al.*, 1959; Plomp, 1964; Elliott, 1971; Widin and Viemeister, 1979; Jesteadt *et al.*, 1982; Moore and Glasberg, 1983; Nelson, 1991; Plack and Oxenham, 1998). Despite the continued interest in the phenomenon, and the many empirical facts known about it, the mechanisms underlying forward masking remain poorly understood and a matter of debate.

In situations where the masker is a brief impulse, Duifhuis (1973) has shown that peripheral frequency selectivity can play a role in producing forward (and backward) masking, because of the finite response times of the auditory filters. In such situations, the responses to the masker impulse and a brief signal may physically overlap in the auditory periphery, even if the acoustic stimuli do not, producing what is essentially simultaneous masking. However, subsequent work has indicated that for maskers longer than a single impulse, the role of peripheral interaction in forward masking is generally negligible, at least for signal frequencies of 1 kHz and above (Vogten, 1978; Gorga *et al.*, 1980; Carlyon, 1988).

Adaptation in the auditory nerve has been proposed as a candidate for the neural site of forward masking (Smith, 1977, 1979). Certainly, a number of aspects of auditory-nerve adaptation resemble psychophysical forward masking. For instance, the growth of adaptation with increasing stimulus level is nonlinear and eventually saturates, just as the growth of forward masking is generally nonlinear, with signal threshold often increasing only slowly as a function of masker level (Jesteadt *et al.*, 1982; Moore and Glasberg, 1983). Such resemblances have led many psychophysicists to refer to forward masking in terms of neural adaptation (Duifhuis, 1973; Kidd and Feth, 1981; Jesteadt *et al.*, 1982; Bacon, 1996; Nelson and Swain, 1996). However, quantitative studies of forward masking in the auditory nerve, using detection theoretic analysis techniques, have demonstrated much less masking in individual auditory-nerve fibers than is measured psychophysically (Relkin and Turner, 1988), as well as different dependencies on parameters such as signal duration and rise time (Turner *et al.*, 1994). Also, the fact that cochlear implant patients show forward masking over a similar time scale as normal-hearing listeners (Shannon, 1990) suggests that forward masking occurs at a higher stage of processing than the inner hair cells. No physiological studies using signal-detection methods have been carried out at centers higher than the auditory nerve. Thus it is possible that neural adaptation at higher levels of the auditory pathways mediates forward masking.

An alternative view of forward masking is that it is due to a continuation, or persistence, of neural activity, after the

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physical offset of the masker (Plomp, 1964; Penner, 1975; Zwicker, 1984; Moore *et al.*, 1988; Oxenham and Moore, 1994). The site of such masking is hypothesized to be higher than the auditory nerve, but no specific mechanisms have been proposed, other than that it could reflect stimulus integration in neurons with relatively long time constants.

Quantitative models of forward masking have generally been in the persistence category, with the exception of the model of Dau *et al.* (1996a,b), which uses feedback loops to produce an effect similar to adaptation, although the output of the model also shows persistence, due to a low-pass filter with a cutoff frequency of 8 Hz. In the model of Moore *et al.* (1988), after peripheral filtering, stimuli are squared (giving a quantity proportional to intensity) and then passed through a linear temporal integrator, which smooths the temporal representation of the stimuli such that the response to the masker overlaps with, and hence can mask, the response to the signal. The disadvantage of using a linear temporal integrator with a square-law nonlinearity, such as that proposed by Moore *et al.* (1988), is that many nonlinear aspects of forward masking, such as its growth with masker level, can only be predicted by assuming that the integrator changes shape with level (Plack and Moore, 1990).

More recently, it has been suggested that the nonlinear aspects of forward masking may be due to mechanical nonlinearities observed in the response of the basilar membrane (BM) to sound, and that once those nonlinearities are taken into account, forward masking can be treated as linear (Oxenham and Moore, 1995, 1997). This account relies on the finding that the response of the BM to tones at characteristic frequency (CF) is linear at very low levels, but becomes highly compressive at higher levels, with the transition occurring at sound levels of somewhere between 20 and 50 dB SPL (Rhode, 1971; Sellick *et al.*, 1982; Ruggero *et al.*, 1997). At very short masker-signal intervals, when the masker and signal are in the same level region, growth of masking should be nearly linear. As the delay between the masker and signal is increased, the growth of masking should become increasingly nonlinear as the masker level falls into the compressive region of the BM response, while the signal remains in the low-level, linear region. Further data and model predictions by Plack and Oxenham (1998) support the idea that the nonlinear growth of forward masking is due to BM nonlinearity rather than saturating neural adaptation.

Based on studies to date, a model with a BM-like compressive nonlinearity, followed by a linear sliding temporal integrator, or temporal window, provides a quantitative framework for describing the nonlinear growth of masking for different masker-signal delays (Plack and Oxenham, 1998); the effect of masker duration (Oxenham and Moore, 1994); and the effect of cochlear hearing impairment (Oxenham and Moore, 1997) in forward masking. However, as noted by Plack and Oxenham (1998), the fact that BM nonlinearity can account for many of the nonlinearities observed in forward masking does not rule out the possibility that forward masking is due to neural adaptation following BM nonlinearity. It could be, for instance, that the responsible adaptation behaves in a quasi-linear way, such that the amount of adaptation is approximately proportional to the excitation produced by the masker.

The aim of this study was to distinguish between two possible mechanisms, adaptation and temporal integration, which have both been hypothesized to underlie forward masking. In this attempt it is assumed that the integration mechanism is linear and time-invariant, as assumed in most models (Moore *et al.*, 1988; Oxenham and Moore, 1994). Adaptation, on the other hand, is by definition time-variant; that is, the response to a given stimulus depends on any previous stimulation.

In an adaptation-based explanation, it seems likely that the portion of the signal furthest from the masker is most important in determining threshold, and that portions of the signal closer in time to the masker should contribute less to detection. This is because the response to portions closer to the masker will be more adapted, and hence less detectable, than later portions of the signal. It follows, therefore, that thresholds in forward masking should be less dependent on signal duration than in simultaneous masking or in quiet, as long as the time interval between the forward masker offset and signal offset is kept constant.

The temporal window is hypothesized to be a peaked function with a shorter time constant for times after the peak than before, in order to account for the fact that backward masking decays much more rapidly than does forward masking. Because of this, the greatest signal output from the window is achieved when the peak of the window is near the offset of the signal. It is generally assumed that threshold is determined by the point in time at which the signal-to-masker ratio at the output of the temporal window is greatest, and that threshold corresponds to a fixed signal-to-masker ratio. Because an increase in signal duration results in a greater signal area under the temporal window at this point in time, the model predicts that signal thresholds will decrease as signal duration is increased, at least up to durations of 20 ms or so (Oxenham *et al.*, 1997). This is true whether or not a forward masker is present; because the window is linear, the presence of the masker has no effect on the response to the signal. Thus the temporal-window model predicts at least as much temporal integration in forward masking as in quiet, or in simultaneous masking. The prediction that adaptation should lead to less dependence on signal duration in forward masking, while an integration-based account should lead to at least as much integration as is observed in quiet, forms the basis of this study.

Zwislocki *et al.* (1959) found no effect of signal duration if the interval between masker and signal offsets was held constant, thus supporting the adaptation hypothesis. However, they used smoothly gated 1-kHz tones for both masker and signal. It is possible that the signal was perceived simply as a continuation of the masker at short gaps between the masker offset and the signal onset, thus confounding the effect of signal duration (Neff, 1986). This view is supported by another experiment in that study. Initially, Zwislocki *et al.* (1959) found a nonmonotonic relationship between signal threshold and *masker* duration. The relationship reverted to being monotonic when the masker was gated abruptly, providing a salient cue for the masker offset. Unfortunately, the experiment varying *signal* duration was not repeated with an abruptly gated masker. Elliott (1962) used a broadband noise forward masker and compared thresholds for 5- and 10-ms sinusoidal signals (gated with 1-ms ramps) at 2 kHz. She concluded that her results were consistent with Zwislocki *et al.*'s hypothesis that thresholds did not depend on signal duration. However, as only two short signal durations were tested, it is difficult to draw strong conclusions from her results.

More recent studies have suggested that signal duration may affect thresholds in forward masking, even when the offset–offset interval is held constant. Thornton (1972), using a 1170-Hz forward masker and a 1753-Hz signal, found that signal thresholds decreased with increasing duration for durations between 10 and 20 ms in roughly the same way as they did in quiet. However, the effect is small (less than 5 dB) and in the only figure of untransformed data (his Fig. 3), there appears to be a nonmonotonic relationship, with thresholds *increasing* again as the signal duration is increased from 30 to 250 ms. Fastl, using himself as the only observer, measured integration for a signal with a fixed offset–offset interval of 20 ms for a broadband masker (Fastl, 1976a), 10 ms for a critical-band masker (Fastl, 1976b), and 10 ms for a pure-tone masker (Fastl, 1979). In all these studies (Fig. 7 in all three papers), Fastl found a decrease in threshold with increasing signal duration, except in the case of the 4-kHz pure-tone masker when the signal was at the same frequency as the masker, which he also ascribed to a ''confusion'' effect. For the two noise maskers, the decrease in thresholds with increasing duration was similar to that observed in quiet. Finally, Gralla (1992) performed a similar study also using a 4-kHz signal and offset–offset times ranging from 1.5 to 100 ms. In broad agreement with Fastl's data, he found that thresholds with a broadband forward masker decreased with increasing signal duration for the first 10 ms, and then remained constant. Results with a tonal and critical-band masker showed nearly no effect, perhaps also due to confusion.

In summary, there seems to be disagreement in the literature regarding the effects of signal duration in forward masking, which makes it difficult to support either adaptation or integration theories. Also, none of the studies discussed above used a forced-choice measurement procedure, using instead variations of a Bekesy tracking method. The purpose of the present experiment was to study the effects of signal duration in forward masking using an adaptative forced-choice procedure with the aim of helping to distinguish between a theory of adaptation or a theory of linear temporal integration to account for forward masking.

II. TEMPORAL INTEGRATION IN FORWARD MASKING

A. Stimuli

A broadband Gaussian noise (0–7000 Hz) with a half-amplitude duration of 200 ms, gated with 2-ms raised-cosine ramps, and a spectrum level of 40 dB (*re*: 20 μPa) was used as a forward masker. The signal was a 4-kHz sinusoid, gated with 2-ms ramps. A broadband noise was used to avoid possible confusion effects. A relatively high signal frequency was chosen to allow the use of very brief signals (4-ms total duration) without the signal bandwidth exceeding the estimated bandwidth of the auditory filter at 4 kHz (Glasberg and Moore, 1990). Also, at such high frequencies, it is unlikely that peripheral interaction due to filter ringing limits performance. The masker-signal offset–offset interval was set to 4, 6, 9, 12, 22, 52, or 102 ms. At each of these intervals, thresholds were measured for the same range of signal durations, provided the masker and signal did not overlap in time. For example, for an offset–offset interval of 22 ms, thresholds were measured for total signal durations of 4, 6, 9, 12, and 22 ms; for an offset–offset interval of 4 ms, thresholds were only measured for a signal duration of 4 ms. When discussing the data, the signals are referred to by their half-amplitude durations, which were 2, 4, 7, 10, 20, 50, and 100 ms.

The masking noise was created at the beginning of each run by generating a 2-s circular buffer of Gaussian noise, performing a discrete Fourier transform, setting the components above 7 kHz to 0, and applying an inverse Fourier transform. A random starting point within the resulting noise buffer was selected for each presentation. Stimuli were generated digitally at a sampling rate of 32 kHz and were played out via the built-in 16-bit DAC and reconstruction filter of a Silicon Graphics workstation. Stimuli were then passed through a programmable attenuator (TDT PA4) and a headphone buffer (TDT HB6) before being presented to the left earpiece of a Beyer DT 990 headset.

B. Procedure

Thresholds were measured using a three-interval forced-choice method with a two-down one-up adaptive procedure that tracks the 70.7%-correct point of the psychometric function. Each interval contained the noise masker, and one interval, chosen at random, also contained the signal. The interstimulus interval, measured from the offset of one masker to the onset of the next, was 500 ms. Listeners were required to select the interval containing the signal. The signal level was initially adjusted in steps of 8 dB. After every two reversals, the step size was halved until the minimum step size of 2 dB was reached. The run was terminated after another eight reversals. Threshold was defined as the median level at the last eight reversals. For every listener, four such estimates were made for each condition, and the mean and standard deviation of the four estimates were recorded. Listeners were given at least two hours practice before data were recorded. Responses were made via a computer keyboard, and feedback was provided via a computer monitor, which was placed outside the listening booth and was visible through a booth window. Listeners were tested in a single-walled sound-attenuating booth, which was situated in a sound-attenuating room.

C. Subjects

Four normal-hearing listeners participated as subjects. S1 was the author, S2 and S3 were female and male univer-

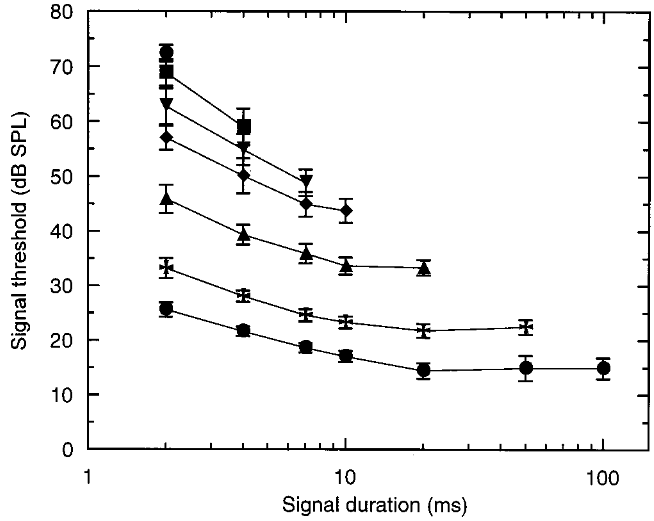

FIG. 1. Mean thresholds for a 4-kHz signal after a 40-dB spectrum level (*re*: 20 μPa) broadband forward masker, as a function of signal duration. The parameter is the time interval between the masker offset and the signal offset. These offset–offset intervals were (from top to bottom on the graph): 4, 6, 9, 12, 22, 52, and 102 ms. Error bars represent ± 1 standard error of the mean across the four listeners.

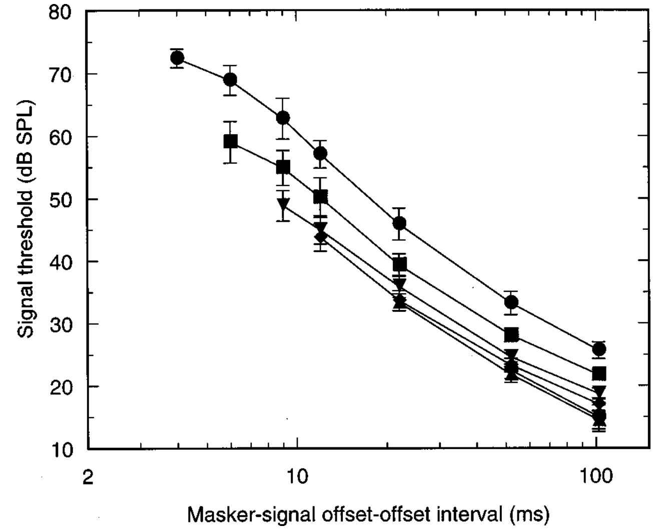

FIG. 2. Mean signal thresholds in forward masking, replotted from Fig. 1, as a function of masker-signal interval (measured from the masker offset to the signal offset). The parameter is signal duration. Durations were (from top to bottom on the graph): 2, 4, 7, 10, 20, 50, and 100 ms.

sity students, and S4 was a female university employee. S2 through S4 were paid for their participation. All had thresholds at octave frequencies between 250 and 8000 Hz of 15 dB HL or less. The ages of the listeners were 27, 19, 20, and 55 years for S1–S4, respectively.

D. Results

All four listeners showed a very similar pattern of results, and so only the mean data are shown in Fig. 1. Thresholds are plotted as a function of signal duration, with the masker-signal offset–offset interval as the parameter. Standard deviations across the four repetitions for each listener were generally less than 2.5, and always less than 5 dB. The error bars in Fig. 1 denote ± 1 standard error of the mean across the four listeners. All listeners showed considerable temporal integration for short offset–offset intervals. For instance, at an offset of 9 ms (downward-pointing triangles) mean thresholds decreased by nearly 14 dB as the signal duration increased from 2 to 7 ms. This is a *greater* change than would be expected for thresholds in quiet or in simultaneous masking, where a decrease of between 2.5 and 3 dB per doubling of duration is expected (e.g., Florentine *et al.*, 1988). At larger offset–offset intervals, the amount of temporal integration is less. Even so, for an offset–offset interval of 102 ms, the 11-dB decrease in mean thresholds as the signal duration is increased from 2 to 20 ms at least matches that normally found in quiet and in simultaneous masking. Little or no temporal integration was observed for signal durations greater than 20 ms.

Figure 2 depicts the mean data in a more conventional way, with thresholds plotted as a function of offset–offset interval, and signal duration as the parameter. The decay of forward masking is very similar to that observed in previous studies. However, in contrast to the studies of Zwislocki *et al.* (1959) and Elliott (1962), the data show a clear effect of signal duration for durations of 20 ms and less. The next section examines how well the results are quantitatively described by models of both adaptation and integration, with and without peripheral nonlinearity.

III. MODEL PREDICTIONS

A. Temporal-window model

The mean data from the experiment were fitted using the temporal-window model, as described in previous papers (Oxenham and Moore, 1994; Plack and Oxenham, 1998). Stimuli, including the noise maskers, were represented by envelopes which were flat during the steady-state periods, as it is assumed that the random fluctuations in the broadband noise do not play a decisive role in determining thresholds. The level of the noise was set at the expected level passing through an auditory filter centered at 4 kHz with an equivalent rectangular bandwidth (ERB) of 456 Hz, as derived by Glasberg and Moore (1990). The amplitude envelopes of the stimuli were then passed through a nonlinearity, designed to simulate the effect of BM compression. The compressive nonlinearity is described by the equations:

$$\begin{aligned} L_{\text{out}} &= 0.78 L_{\text{in}}, & L_{\text{in}} &< 35\ \text{dB SPL}, \\ L_{\text{out}} &= 0.16 L_{\text{in}} + 21.7, & L_{\text{in}} &\geqslant 35\ \text{dB SPL}. \end{aligned} \quad (1)$$

The slopes were determined by the psychophysical estimate of BM nonlinearity found by Oxenham and Plack (1997). The breakpoint of 35 dB is somewhat lower than that found in their study, but is the same as that used by Plack and Oxenham (1998). This breakpoint is also well within the range of physiological estimates, which range from 20 to 55 dB SPL (Murugasu and Russell, 1995; Ruggero *et al.*, 1997). The output of this stage is expressed in units of intensity (i.e., the values are squared). This is consistent both with psychophysical (Oxenham and Moore, 1995; van de Par and Kohlrausch, 1998) and physiological (Yates *et al.*, 1990) data.

TABLE I. Parameter values for the temporal-window model. Values from the three different fits are given, along with the sum of squared errors (SSQ). The total number of data points fitted was 29. Fit 1 was the original fit using the nonlinearity described by Eq. (1) and the window parameters from subject AO in Oxenham and Moore (1994). Fit 2 used the same nonlinearity as Fit 1, but allowed the window parameters to vary so as to provide the best fit (lowest sum of squared errors, SSQ). Fit 3 used a less compressive nonlinearity, with a slope of unity (in dB/dB coordinates) below 35 dB SPL and a slope of 0.25 above. The decision ratio was always allowed to vary to best fit the data.

	Parameters					
	T_{b1} (ms)	T_{b2} (ms)	w	T_a (ms)	Decision ratio	SSQ
Fit 1	4.0	29.0	0.0251	3.5	2.75	475.8
Fit 2	3.1	21.0	0.206	3.5	1.62	113.0
Fit 3	4.6	16.6	0.170	3.5	1.67	50.7

The stimuli were then passed through a sliding temporal integrator, or temporal window. The window comprises three exponential functions, one to describe backward masking (making it largely irrelevant for the present study), and two to describe the initial and later portions of forward masking. The window is described by the following equations:

$$W(t)=(1-w)\exp(t/T_{b1})+w\exp(t/T_{b2}), \quad t<0,$$
$$W(t)=\exp(-t/T_a), \quad t\geqslant 0, \tag{2}$$

where t is time relative to the peak of the window, T_{b1} and T_{b2} are the time constants describing the decay of forward masking, w is the weighting factor determining the relative contributions of these two time constants, and T_a is the time constant describing the decay of backward masking. The parameters of the window were set in advance to those derived for subject AO in the study by Oxenham and Moore (1994), and are given in the first line of Table I.[1] The decision device was based on the ratio of the output due to the masker and signal, and output due to the masker alone. The point in time at which this value is greatest is assumed to be the time at which the decision is made. The signal-to-masker ratio provided the only free parameter, and was assumed to remain constant for all conditions. A constant ''internal noise'' was added to simulate threshold in quiet (see Oxenham and Moore, 1994, for details). This was set so as to correctly predict the mean threshold in quiet (20.9 dB SPL) for the 2-ms (half-amplitude duration) tone for listeners S1–S3. (This threshold was not measured in S4.)

Results from these simulations are shown in the right panel of Fig. 3. The left panel replots the mean data from Fig. 1 for comparison. The overall fit is not good, with the sum of squared errors for the 29 data points of 476, giving an rms error of 4.05 dB. This is caused primarily by very poor predictions of one or two data points, such as the threshold for the 4-ms offset–offset interval. The poor fit is perhaps not surprising, given that the window was derived using a simple power-law nonlinearity (Oxenham and Moore, 1994), rather than the more complex nonlinearity used here. It is known that changes in the input nonlinearity change the effective window shape (Penner, 1978; Oxenham *et al.*, 1997), meaning that the old window was probably not appropriate for the current nonlinearity. Nevertheless, the model manages to capture the main trends of the data rather well. In particular, the model shows an increase in the slope of integration at shorter offset–offset intervals, as in the data. This increased integration at short offset–offset intervals in the model predictions can be explained as follows. At the longer intervals, the overall signal level is low, falling into the more linear region of the BM input–output function. At shorter intervals, the overall signal level is above 40 dB SPL and would therefore be expected to fall within the more compressive region of the BM input–output function (Oxenham and Plack, 1997). As greater compression leads to a steeper integration slope (Penner, 1978; Oxenham *et al.*, 1997), greater integration for the higher signal levels is expected.

The lack of temporal integration for signal durations greater than 20 ms is also reflected in the predictions of the temporal-window model. Oxenham *et al.* (1997) proposed that integration for signal durations up to between 10 and 20 ms may be governed by a short-term temporal integrator. For durations longer than that, temporal integration in quiet and in simultaneous masking may be due to a multiple-looks mechanism, whereby information from discrete samples is combined over time (Viemeister and Wakefield, 1991). Such multiple looks would not provide much advantage in a forward-masking situation, as the ''looks'' closer to the masker would be less detectable and would hence provide

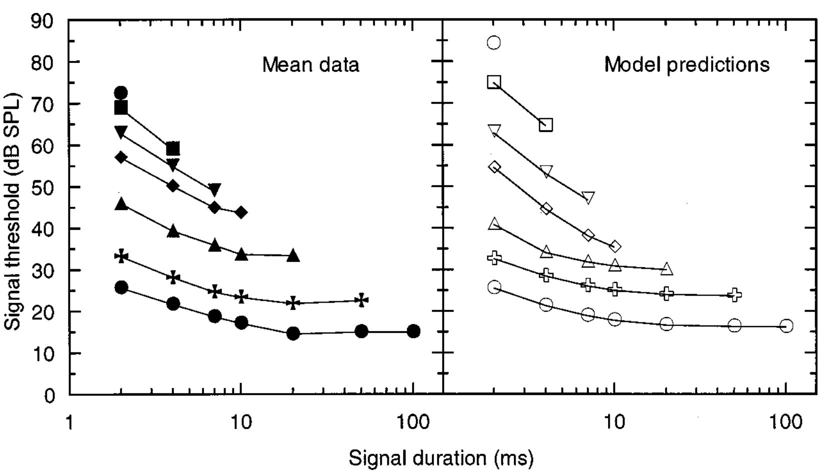

FIG. 3. Predictions of the temporal-window model (right panel) compared with the mean data (left panel). Thresholds are plotted as a function of signal duration, as in Fig. 1.

less information than looks further from the masker. Thus, temporal integration beyond 10 or 20 ms would not be expected.

The fact that the model captures the main trends of the data is encouraging, especially as all parameters except the signal-to-masker ratio were fixed in advance. However, as mentioned above, the overall fit is rather poor. This could be due to a nonoptimal choice of model parameters, or simply because it is not possible to accurately predict both the decay of forward masking and signal integration in forward masking using a simple integrator model. This is an important question: If the latter explanation is correct, it suggests that additional mechanisms, such as adaptation, may be required to provide a full account of forward masking.

To answer this question, the model was used to fit the data again, but this time certain parameters were either optimized using a minimization routine, or were fixed to different values. First, the nonlinearity remained the same [see Eq. (1)], but the three window parameters defining forward masking, T_{b1}, T_{b2}, and w, were allowed to vary so as to produce the best fit to the data (defined using a least-squares criterion). The best-fitting values, given in the second line of Table I, produced a considerably improved fit, with a total sum of squares of only 113, as opposed to 476.

Next, the nonlinearity was changed. Instead of using slopes of 0.78 and 0.16 for lower and higher signal levels, respectively, the values were changed to 1.0 and 0.25. These values are consistent with some previous studies (Oxenham and Moore, 1994; Oxenham *et al.*, 1997) and imply linear growth at low levels and compressive growth with a compression ratio of 4:1 (as opposed to 6:1) at levels above 35 dB SPL. Thus these values imply less compression overall, but are still within reasonable limits of what is known physiologically about BM nonlinearity. Again, the three window parameters were allowed to vary, and the resulting values are given in the third line of Table I. With these parameters, the overall fit was excellent, with a total sum of squares of only 50.7. These predictions are shown as curves along with the mean data in Fig. 4.

The additional modeling shows that it is possible to account accurately for both the decay of forward masking and temporal integration in forward masking using a simple linear integrator. As there is considerable interaction between the model parameters, it is not trivial to attach a meaning to the window changes necessary to provide a good fit to the data. It seems, however, that the data are best described by a somewhat less compressive nonlinearity than has been used in some previous studies.

It should be noted that the compressive nonlinearity within the model is essential in producing good fits to the data. This is demonstrated by the poor performance of a linear version of the model which integrates intensity, as described by Moore *et al.* (1988) and Plack and Moore (1990). With four free parameters (as with the nonlinear model), the best fit produced a sum of squared errors of 285—considerably worse than the nonlinear model. As expected from a linear model, the predicted amount of temporal integration was the same for all masker-signal offset intervals and for the signal in quiet. This is in contrast to the

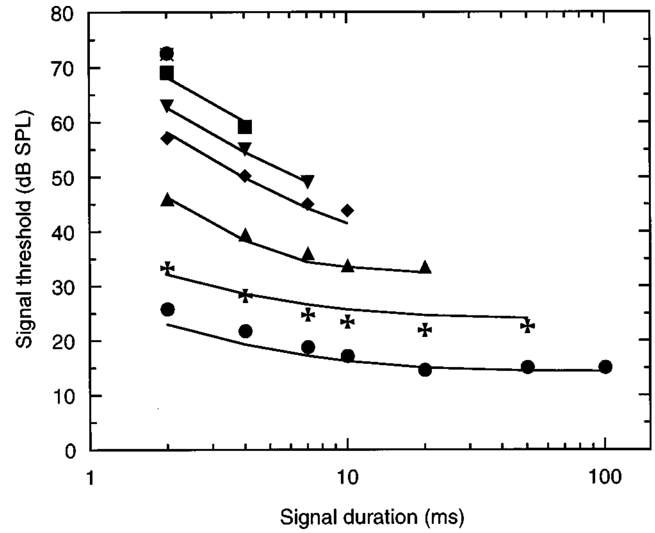

FIG. 4. Predictions of the modified temporal-window model (solid curves, and cross for the 4-ms offset condition) compared with the mean data (symbols). See text for model details. Thresholds are plotted as a function of signal duration, as in Fig. 1.

data, where more integration was observed at shorter masker-signal offset intervals. Also, the window shape necessary to predict a sufficiently rapid decay of forward masking was too narrow to predict the observed amount of temporal integration in any condition. For instance, the linear model predicted a decrease in threshold of 5.2 dB as the signal duration increased from 2 to 10 ms, while for the same increase in duration, the mean data show a decrease of 13.3 dB in the 12-ms offset–offset condition and 8.6 dB in the 102-ms condition. The present data therefore provide further evidence for the importance of including peripheral nonlinearity in models of temporal processing.

In summary, the results appear to be quantitatively consistent with the idea that forward masking is mediated by BM nonlinearity followed by linear temporal integration. However, as with all previous modeling studies (e.g., Plack and Oxenham, 1998), the success of the temporal-window approach does not rule out the possibility that an adaptation mechanism could account for the data equally well. The following section introduces a functional model of adaptation, to provide a quantitative comparison with the temporal-window model.

B. Adaptation model

In modeling adaptation, it is assumed that a signal is masked because the response of the auditory system to the signal is reduced to a level at or below threshold in quiet. Thus adaptation due to a forward masker is modeled as a gain function, which is lowest at the masker offset and increases as the time from the masker offset increases, such that the gain is unity (0 dB) at times of about 200 ms or greater. It is further assumed that the auditory system can integrate over the duration of the signal, with a rectangular window, and that the threshold for a given signal is determined by the integral of the signal intensity, modified by the continuously varying gain function. In this way, when no masker is present, the gain is always 0 dB and the model acts

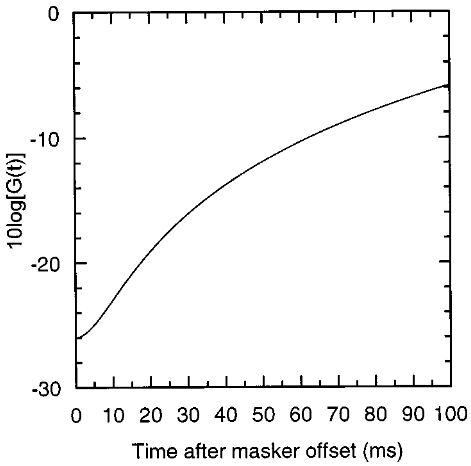

FIG. 5. Third-order polynomial function from Eq. (3), plotted as $10\log[G(t)]$, which was used to determine the instantaneous gain in the adaptation model.

as an energy detector at low levels, predicting thresholds in quiet as a function of duration reasonably well. Note that this model is in fact also a model of temporal integration. What distinguishes the two models is whether the masker is partly integrated with the signal (as in the temporal-window model) to produce masking, or whether (as in the adaptation model) it is assumed that the integration window can be optimally shaped and positioned by the auditory system so that no masker energy is integrated with the signal.

In this model, the stimuli were first passed through the same static nonlinearity that was used with the final, most successful, temporal-window model: for levels at and below 35 dB SPL the stimuli were passed linearly; for levels above 35 dB SPL the stimuli were compressed using a power-law nonlinearity with a slope of 0.25 in dB coordinates (i.e., 4:1 compression). As in the temporal-window model, the output of the nonlinearity was squared to provide units of intensity. Following this, the stimuli were multiplied by the gain function over the duration of the signal, to produce an ''adapted'' representation of the signal. At threshold, the integral of this adapted representation should be constant for all combinations of signal duration and masker-signal interval.

A number of mathematical functions were tried in attempting to describe the adaptation gain function. The most successful of these was a third-order polynomial. The values of the polynomial's four coefficients were fitted using a multidimensional minimization routine, incorporating all the mean data from the experiment. The best-fitting equation is given below, where $G(t)$ is the gain at time t in ms following masker offset:

$$G(t)=2.83\times10^{-8}t^3+2.29\times10^{-5}t^2+1.96\times10^{-5}t+2.5\times10^{-3}. \quad (3)$$

The threshold output was set by integrating the 2-ms signal at a level corresponding to threshold in quiet (20.9 dB SPL). Using this function, which is plotted in Fig. 5, the fit to the data was very good. The sum of squared errors was 68.7, which is comparable to the error of 50.7 from the best-fitting temporal window using the same number of free parameters. The pattern of predictions was also very similar to the data, predicting increasing amounts of integration at higher signal levels.

As with the temporal-window model, a linear version of the adaptation model, using a gain function derived from Plomp's (1964) exponential equation, was not successful in predicting the data, producing an overall sum of squared errors of 534.4. As with the linear temporal-window model, insufficient temporal integration was observed. However, whereas the linear temporal-window model predicted equal integration at all masker-signal offsets, the linear adaptation model predicted more integration at longer offset–offset intervals than at shorter intervals. This is contrary to the data, but is expected because the adaptation gain function becomes shallower (and so has less influence) at longer intervals when plotted as a function of linear time; at shorter offset intervals, the gain function changes more rapidly, leading to less integration being predicted.

In summary, an adaptation model was almost as successful at predicting the data as the temporal-window model. For both categories of model, the initial nonlinearity was crucial in producing good predictions. Thus, taken on their own, the data from the present study do not distinguish between integration and adaptation as mechanisms underlying forward masking.

C. Accounting for temporal integration in simultaneous masking with the temporal-window model and the adaptation model

The previous two sections showed that both integration and adaptation models could account reasonably well for the data from the present study, given sufficient free parameters. At this point it is worth considering whether the two mechanisms could ever be distinguished, or whether they are in some way mathematically equivalent. In the adaptation model, a rectangular integration window was used. At levels above 35 dB SPL, the 4:1 compression of the nonlinearity would result in an integration slope four times steeper than at low levels for a long integration window (Penner, 1978), which is much more than actually measured. This ''over-integration'' is offset by the effects of adaptation, which attenuate early portions of the signal in much the same way that a temporal window would. In this way, the effect of adaptation in forward masking can be thought of as a temporal weighting function and a trade can be established between the recovery from adaptation (zero in the case of the temporal-window model) and the attenuation due to the temporal weighting function (zero in the case of the rectangular-window adaptation model).

This apparent equivalence of adaptation and integration only holds in the presence of a forward masker. In the absence of recovery from adaptation, the two models become different, with the temporal-window model retaining the same weighting function and the adaptation model changing its effective weighting function (to become rectangular in the present model). To illustrate this point, data were taken from a study of temporal integration in simultaneous masking (Oxenham *et al.*, 1997). The signal was a 6-kHz sinusoid, gated with 1-ms ramps and the masker was a broadband Gaussian noise at a spectrum level of 20 dB (*re*: 20 μPa).

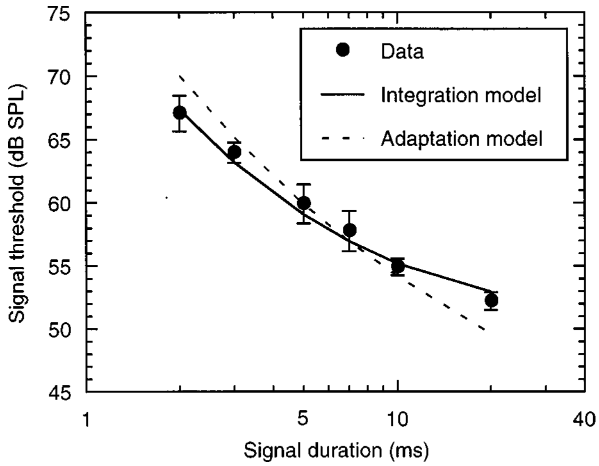

FIG. 6. Signal integration in the presence of a simultaneous masker, taken from Oxenham *et al.* (1997) (circles) together with the predictions from the temporal-window model (solid curves) and the adaptation model (dashed curves).

This masker level was chosen here as the threshold levels most closely match the levels found for short masker-signal offset intervals in the present study. Data, representing the mean of four normal-hearing listeners, are shown in Fig. 6 for signal durations from 2 to 20 ms; see Oxenham *et al.* (1997) for further details. Both the temporal-window and the adaptation models were used to simulate the data. For the adaptation model, it was assumed that recovery from adaptation plays no role in simultaneous masking, and so only the rectangular weighting function (20-ms duration) was used. The window shapes and the nonlinearity were kept as they were for the forward-masking data—the only free parameter was the threshold signal-to-masker ratio. The predictions of the temporal-window model and the adaptation model are shown as a solid curve and dashed curve, respectively.

It can be seen that the temporal-window model provides a better description of the simultaneous-masking data than does the adaptation model, which predicts too much integration. The difference in thresholds between the 2-ms and 20-ms signal is 14.8 dB, compared with 14.4 dB predicted by the temporal-window model and 20.4 dB predicted by the adaptation model. Thus the adaptation model overestimates the amount of temporal integration between 2 and 20 ms by almost 6 dB. This suggests that, while both models can provide a reasonable account of signal integration in forward masking, the temporal-window model produces predictions that are more consistent with both simultaneous and forward masking. In other words, the assumption of time invariance, inherent in the temporal-window approach, seems to be justified.

The support for the temporal-window approach relies on the assumption that the integration window shape remains the same for both simultaneous and nonsimultaneous masking. If one is prepared to allow the window shape to vary between these two conditions, then the adaptation model could be altered to bring it into line with the simultaneous-masking data also. At present it appears more parsimonious to assume that the window shape remains constant.

D. Why ignore adaptation?

The emphasis so far has been on distinguishing between integration (or persistence) and adaptation on an either/or basis. Clearly, it is not currently possible to rule out some complex interaction between both mechanisms. Also, given that adaptation is clearly observable at the level of the auditory nerve, it may seem perverse to ignore it completely. On the other hand, it may be that adaptation acts somewhat like an automatic gain control, which equally affects the response to stimuli *and* the spontaneous rate, or noise floor. If this is so, the net effect of adaptation on forward masking may approach zero. Some support for this view can be found in the work of Relkin and Turner (1988). They argued that, because spontaneous neural firing, as well as the response to the signal, is reduced by a forward masker, the physiological measure of forward masking should not simply be the reduction in the response to the signal, but rather the discriminability of the response to the signal from the response to no signal. When they did this, they found many auditory nerve fibers that exhibited little or no forward masking. These arguments and findings can be interpreted as support for an approach that ignores the effects of neural adaptation in the periphery.

E. Limitations of the models

While the temporal-window model has proved useful, especially in its ability to elucidate the role of peripheral compression, there are many aspects of it which are unsatisfactory. For instance, the decision device uses only one instant in time, rather than combining information over time (Oxenham and Moore, 1994); it ignores statistical fluctuations, taking into account only average power; and it cannot make use of any fine-structure cues. The window itself provides a reasonable description of forward masking, decrement detection (Oxenham and Moore, 1994), and short-term signal integration (Oxenham *et al.*, 1997), but it is not capable of describing modulation detection (Dau *et al.*, 1997) or of capturing the asymmetry between increment and decrement detection (Oxenham, 1997). Perhaps it could be viewed as the low-pass filter in a bank of modulation filters (Dau *et al.*, 1997).

Unlike the model proposed by Dau *et al.* (1996a,1997), no set of parameters have so far been proposed which can provide a reasonable fit to a wide variety of data. Indeed, the often *ad hoc* alteration of window shape for specific data sets (Alcántara *et al.*, 1996; Carlyon and Datta, 1997), including the ones presented here, suggests that no such set may be possible. Nevertheless, the simplicity of the model, in terms of both its assumptions and implementation, make it a useful tool for testing other hypotheses, such as the one addressed in the present study. While the data presented here and elsewhere support the idea of linear temporal integration following peripheral nonlinearity, many other peripheral and central factors, which are not currently captured by the temporal-window model, may also play a role.

Another inconsistency between the temporal-window model predictions and the data is that the model does not predict elevated signal thresholds at the onset of a long masker, relative to thresholds in the temporal center. This effect is known as overshoot (Zwicker, 1965). Interestingly, the effect requires a relatively wide-band or off-frequency masker with a narrow-band, high-frequency signal. This suggests that the effect will never be captured satisfactorily with a single-channel model, at least with a linear filter. In contrast, the temporal-window model predicts ''undershoot,'' i.e., that thresholds at the onset of a masker will be somewhat lower than thresholds in the temporal center. It is possible that the mechanism responsible for overshoot produces an effect that is sufficiently large to counteract the undershoot that would otherwise be observed. However, providing a quantitative account of overshoot will be challenging, as individual differences can be very large (Bacon and Liu, 2000).

The adaptation model presented here is simply an *ad hoc* construction designed to test the feasibility of an adaptation mechanism in principle. It is therefore unlikely that it would be useful in its current form as a more general model of auditory processing.

Alterations in either model may change the predictions in many ways. The apparently poorer fits of the adaptation model to the simultaneous-masking data might change if different assumptions about the influence of, for instance, noise variability were made. While the present results lean in favor of the temporal-window model, further work will be necessary to provide a definitive answer to the question of whether integration or adaptation is more responsible for forward masking.

IV. SUMMARY

Temporal integration in forward masking was studied as a way to try to distinguish between explanations of forward masking in terms of adaptation and integration. Signal thresholds in the presence of a broadband forward masker were measured as a function of signal duration, with the time interval between the masker offset and the signal offset (offset–offset interval) held constant at a value between 4 and 102 ms.

The experiment showed that substantial temporal integration was observed for signal durations between 2 and 20 ms. The amount of temporal integration varied with offset–offset interval: at the shorter offset–offset intervals, the amount of temporal integration exceeded that normally found in quiet, while at longer offset–offset intervals, where the signal level fell below about 40 dB SPL, the amount of integration matched that found in quiet. No further improvements in threshold were found for signal durations longer than 20 ms.

The data were used to test models of temporal integration and adaptation. For both models, the inclusion of peripheral nonlinearity, resembling the input–output function of the basilar membrane, was essential in predicting the data. Using such a nonlinearity, both models provided similarly good fits to the data. However, the temporal-integration model provided a better fit to data from simultaneous masking with the same parameters. If a constant window shape is assumed for both forward and simultaneous masking, the results favor the view that forward masking is better described as a persistence in neural activity than as neural adaptation. However, the weight of evidence is at present still not overwhelming.

ACKNOWLEDGMENTS

This work was supported mainly by NIH/NIDCD Grant No. R01 DC 03909. The data were collected while the author was a Wellcome Trust Research Fellow (Grant No. 0044215/Z/95/Z) at the Institute for Perception Research (IPO), Eindhoven, The Netherlands. I thank Neal Viemeister for helpful exchanges on the modeling of adaptation. Comments by Chris Plack and two anonymous reviewers resulted in a substantial improvement of this paper.

[1]An error in Table I of Oxenham and Moore (1994) gives the value of 10 log(w) for the AO exponential, instead of 20 log(w); all other entries in that table are correct. This incorrect value was also used in the study of Plack and Oxenham (1998), although that paper actually cited the corrected value. The correct value, which was used here, is −32 and not −16 dB, or 0.025 in linear units.

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