Broadened forward-masked tuning curves from intense masking tones: Delay-time and probe-level manipulations

David A. Nelson and Richard L. Freyman[a]
Hearing Research Laboratory, University of Minnesota, 2630 University Avenue S.E., Minneapolis, Minnesota 55414

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Forward-masked psychophysical tuning curves were obtained from normal-hearing listeners under two conditions: lengthened delay time between masker and probe, and increased probe level. Both conditions required higher-level masking tones and both conditions resulted in broader tuning curves. Comparisons were made of tuning curves obtained with different probe-level and delay-time combinations that were chosen to require equivalent masker levels at the probe frequency. Nearly identical tuning-curve shapes were obtained when masker level at the probe frequency was the same. The results are predicted by a two-process model, consisting of a nonlinear filter followed by an exponential decay. Tuning-curve shapes in forward masking appear to be largely dependent upon the masker level (filter output level) at which one attempts to measure them.

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INTRODUCTION

Previous investigations of forward-masked psychophysical tuning curves (PTCs) have reported changes in the shapes of those curves for different delay times between masking tone and probe tone. As delay time was lengthened, Small and Busse (1980) and Kidd and Feth (1981) obtained more broadly tuned PTCs. In addition, more intense masking tones were required to achieve the same amount of masking at longer delay times. Those results are qualitatively similar to the broadening in tuning-curve shape that results from raising probe level (Widin and Viemeister, 1979; Nelson, 1980; Green *et al.*, 1981). Both conditions, lengthened delay time and increased probe level, require higher masker levels.

One explanation of why tuning curves broaden with increasing probe level involves the broadening of excitation patterns that occurs with higher-level masking tones (Zwicker, 1970; Verschuure, 1978). Simply stated, the more intense masking tones, which are necessary to mask higher-level probe tones, have broader excitation patterns that translate directly into broader tuning curves (Zwicker, 1974). It may be that masker level *per se* is the primary determinant of tuning-curve shapes, regardless of whether increased probe level or lengthened delay time leads to a higher masker level.

The present experiments were originally designed to examine changes in PTCs that occur with different delay times between masker and probe. Psychophysical forward-masked tuning curves were obtained from the same normal hearing listeners under two delay-time conditions and at three probe levels. As we examined the results, it soon became apparent that changes in delay time and probe level had similar effects on the tuning curve. To determine whether or not the two conditions produced the same changes in the shape of forward-masked tuning curves, an additional experiment obtained PTCs for two combinations of probe level and delay time, where each combination was chosen to require the same masker level near the probe frequency. A descriptive model of forward masking, which attributes changes in tuning-curve shapes to changes in excitation patterns, was developed to account for the most dramatic changes in tuning-curve shapes that occur with either delay-time or probe-level manipulations.

I. METHOD

Listeners were three normal-hearing young adults who had extensive practice in forward-masking experiments before data collection began. Masking tones were 200 msec in duration, probe tones were 20 msec (time during which waveforms were above 90% of peak amplitude). If specified as "half-power" durations, the masker and probe durations would be 205 and 25 msec, respectively. Both were gated with 10-msec linear rise and decay times between 10% and 90% of peak amplitude. Temporal separations between masker offset and probe onset were either 2 or 40 msec, measured from 10% of peak amplitude during the masker offset to 10% of peak amplitude during probe onset. When specified as the time between masker offset and probe offset, as we prefer, the two delay times were 42 and 80 msec. Masker-level thresholds were obtained with a four-alternative forced-choice adaptive procedure that estimated the masker level at which a listener would detect the probe tone on 71% of the trials. All thresholds reported here are the average of three or more threshold determinations for each condition, where each threshold determination was the average of the last six out of nine turnarounds in the tracking procedure. Complete tuning curves for two different delay times (42 and 80 msec) were obtained at three different probe levels, each separated by 5 dB. The probe frequency was 1000 Hz.

II. RESULTS

Forward-masked tuning curves for different masker-probe delay times at three probe levels are shown in Figs. 1–3. Each figure contains the results for a different listener.

[a] The second author is currently in the Department of Communication Disorders at the University of Massachusetts, Amherst, MA 01003.

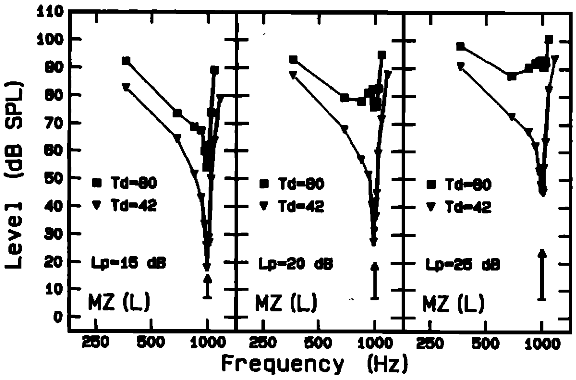

FIG. 1. Comparisons of forward-masked tuning curves obtained with 42- or 80-msec delay times (*Td*) between masker and probe, for different probe levels, in one normal-hearing subject (MZ). Pairs of tuning curves are shown for each probe level; the upper curve of each pair (squares) is for an 80-msec delay time, the lower curve (inverted triangles) is for a 42-msec delay time. Probe level (*Lp*) and probe frequency (*Fp*) is indicated by an upward pointing arrow beneath each pair of tuning curves. The base of the arrow indicates probe threshold. Each panel contains data for a different probe level. Probe frequency is 1000 Hz.

Tuning curves for increasing probe levels are arranged in each figure from left to right. At each probe level, two tuning curves are plotted together. The lower curve is for the 42-msec delay-time condition, the upper curve is for the 80-msec condition.

A. Delay time

The major result of increasing masker-probe delay time was an increase in the masker levels that were required to mask the probe tones, an increase that was dependent upon the frequency ratio between masker and probe. Long delay times required higher masker levels, more so for maskers near to and just below the probe frequency than for maskers remote from the probe. This result occurred at all probe levels and in all three listeners, although there were differences in the magnitude of those changes among listeners. As a consequence, tuning curves for the long delay times appear broader than those obtained with the short delay times. Kidd and Feth's (1981) listeners demonstrated similar results, even to the extent that individual differences in the shapes of tuning curves among their listeners were similar to those seen here. Two of their listeners (S1 and S5 in their Fig. 4)

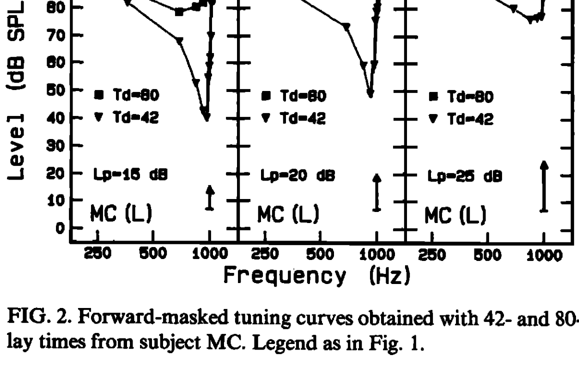

FIG. 2. Forward-masked tuning curves obtained with 42- and 80-msec delay times from subject MC. Legend as in Fig. 1.

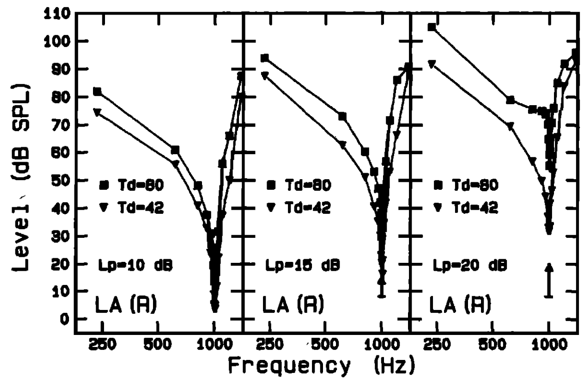

FIG. 3. Forward-masked tuning curves obtained with 42- and 80-msec delay times from subject LA. Legend as in Fig. 1. The data point at 232 Hz for $Td = 80$ msec in the right-most panel is at 105 dB, which indicates the failure to mask at this *Fm* at the limits of the equipment.

showed a complete loss of the sharp tip region of the tuning curves when delay times were lengthened and higher masker levels resulted, as in our listener MC. One of their listeners (S4) retained the sharp tip region for masker frequencies very near the probe frequency, as in our listener LA (Fig. 3), and their fourth listener (S2) was in between those extremes. In some cases, shifts were apparent in the maximum masking frequency (MMF), along with slight decreases in high-frequency slopes (listener MC). However, for all four of their listeners and for all three of ours, the low-frequency slopes of the tuning curves were flatter for the long delay time than for the short delay time, a result that was always associated with more intense masker levels.

B. Probe level

Changes in tuning-curve shapes that occurred with changes in probe level can be seen by examining consecutive panels in Figs. 1–3. The changes with probe level are similar to those reported in previous investigations (Widin and Viemeister, 1979; Nelson, 1980; Green *et al.*, 1981). What is interesting is that increased probe level had effects similar to those resulting from increased delay time. As probe level was increased, more intense masker levels were required. Again, increases in masker level with increased probe level were largest for masker frequencies near to and just below the probe frequency. Consequently, tuning curves appear more broadly tuned at higher probe levels.

The effects of increasing probe level on tuning-curve shapes can be seen in Figs. 1–3 only over a 10-dB range of probe levels for any one delay time. Those effects were more pronounced for tuning curves obtained with the 80-msec delay than the 42-msec delay. In order to demonstrate the effects of probe level over a larger intensity range, a probe-level series of PTCs for a delay time of 42 msec is shown in Fig. 4 for two subjects. Subject SC did not participate in the previous delay-time experiment, subject MC did. Subject MC's level-series data shown in Fig. 4 were obtained sometime before the delay-time data shown in Fig. 2. As probe level increased, more intense masker levels were required. The effects of probe level on tuning-curve shape are not linear over the entire range of probe levels tested. At low probe

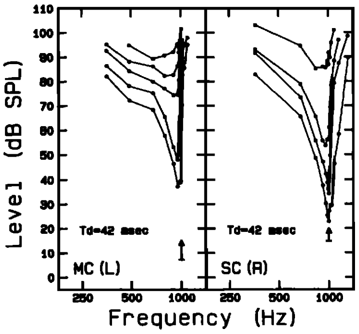

FIG. 4. Forward-masked tuning curves for a series of probe levels in two normal-hearing subjects. Probe levels were 15, 20, 25, 30, and 35 dB SPL for subject MC, shown in the left panel. Probe levels were 20, 25, 30, and 35 dB SPL for subject SC, shown in the right panel. The upward arrows indicate probe frequency and the lowest probe level tested. The base of the arrow is probe threshold.

levels, changes in tuning-curve shape are small. As probe level continues to increase, the effect on tuning-curve shapes becomes progressively greater and more obvious. Here it can be seen that the tuning-curve shapes become significantly broader when, at masker frequencies near to and just below F_p, high probe levels require masker levels above 50–60 dB SPL. The broad tuning curves obtained by using high probe levels and a short delay time (42 msec) in these two subjects are qualitatively similar to the broad tuning curves shown earlier in Figs. 1 and 2 using low probe levels but a long delay time (80 msec).

III. DISCUSSION

Two different manipulations of stimulus parameters in the forward-masking paradigm appear to produce the same general effects on forward-masked tuning curves. Increases in delay time between masker and probe broaden the tuning curve; likewise, increases in probe level broaden the tuning curve. Both manipulations require the use of higher masker levels. In the case of an increase in delay time, more intense masker levels are needed to maintain the same amount of masking. In the case of an increase in probe level, more intense masker levels are needed to produce more masking. These observations led us to suspect that masker level *per se* is the primary determinant of tuning-curve shape. To explore this possibility further we examined several conceptual models of forward masking to determine the model characteristics that would be necessary to predict broadened tuning curves with either lengthened delay time or increased probe level.

A. Linear filtering

If one were to propose a simple two-stage system to model these effects, a system consisting of a linear filter (in dB/Bark)[1] followed by an exponential decay (in dB/sec), one would obtain the same filter response characteristic no matter what input level was used to measure the filter response. Similarly, since a tuning curve is essentially a plot of the input levels required to maintain a constant output, one would obtain the same tuning-curve shape no matter what output level was used as a constant output criterion. Because the decay process follows the filtering process, increased delay time would require a higher filter output level to maintain the same amount of masking, and as a result successively higher level tuning curves would be obtained for successively longer delay times. But no change in tuning-curve shape would occur, since the underlying filter is linear.[2]

This, of course, is not the result we obtained for forward-masked tuning curves from real auditory systems. As shown earlier, tuning curves become broader as delay time is increased. Therefore, at the very least, one of the assumptions in our simple two-process model must be false. Either the filter is not linear or the decay process does not follow the filtering process.

We can quickly dispense with whether the decay process precedes or follows the filter. If the exponential decay process preceded the filter, then tuning curves would become sharper at longer delay times. In that case, the decay process would operate on the input to the filter. In order to maintain a constant filter output (constant amount of masking), input level would have to increase with delay time. Because of the exponential decay (in dB/sec), the rate of decay would increase as input level increases and more decay would occur at those frequencies that require more input, namely frequencies remote from the center frequency of the filter (probe frequency). As a consequence, larger increases in masker level would be necessary to keep the output of the filter constant at remote frequencies. The result would be a narrower tuning-curve shape at longer delay times, just the opposite of what we have demonstrated in real ears. We are then left with the possibility that the filter is nonlinear.

B. Nonlinear filtering

If the filtering process is nonlinear, that is, if the filter response becomes broader as input level increases, then increases in delay time between masker and probe would result in broader tuning curves. This is because increased delay time would require a higher filter output level to maintain the same amount of masking. An example of this situation is shown in Fig. 5.

The filter function used in this simulation is asymmetrical. It is also nonlinear in the sense that its asymmetry grows

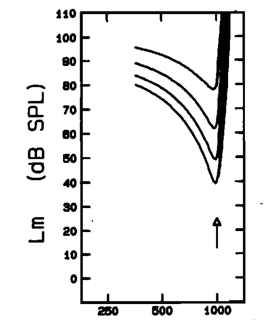

FIG. 5. Simulated tuning curves from a simple two-process model of forward masking. Curves are shown for four different delay times: 40, 55, 70, and 85 msec between masker offset and probe offset. The 40-msec curve is at the bottom. The ordinate represents the input level to the filter that is required to maintain a constant filter output level. To produce this simulation, a nonlinear filter was followed by an exponential decay with only one time constant. Details of the model and values used for the simulation are given in the Appendix.

with intensity. It is essentially derived from Zwicker's (1970) excitation pattern equation as described by Terhardt (1979), but is modified by a rounded exponential weighting function to smooth the peak, and by a frequency-dependent intensity function similar to that used by Schöne (1977) for pure tones. As before, the exponential decay process follows the filtering process and employs only a single time constant as in Nelson and Turner (1980) and Vogten (1978). A complete description of the model and list of the parameters used for this simulation can be found in the Appendix.

Simulated tuning curves calculated using Eq. (A4) in the Appendix are shown in Fig. 5 for delay times between masker offset and probe offset of 40, 55, 70, and 85 msec. The lowest tuning curve is for a delay time of 40 msec. The highest tuning curve is for a delay time of 85 msec. With a nonlinear filtering process that is followed by an exponential decay process, a long delay time predicts a broader tuning curve than a short delay time, which is essentially the major finding we demonstrated earlier in real ears.

C. Equivalent masker level

One outcome of this type of two-stage process, a nonlinear filter followed by an exponential decay process, is that the shape of the tuning curve is determined entirely by the output level used to measure it. Delay time and probe level *per se* have no direct effect on tuning-curve shape. Only when changes in delay time and probe level require different filter output levels will they indirectly affect filter shape.

The results in Figs. 1–3 demonstrate that increases in probe level and increases in delay time have a common effect: they both require higher masker levels at masked threshold. If, when masker frequency equals probe frequency, we assume that the masker level at masked threshold represents the output of the filter, then one should be able to choose different combinations of probe level and delay time that require the same masker levels at the probe frequency and, therefore, the same filter output levels. Equating masker levels in this fashion should equate filter outputs; with this particular model of forward masking, equal filter outputs would result in tuning curves that have identical shapes.

Since we did not initiate these experiments with this "equivalent masker level" hypothesis in mind, our probe levels and delay times were not chosen to require exactly the same masker levels. However, because we manipulated probe level and delay time for each subject, we could make some qualitative comparisons of tuning curves that have *similar* masker levels near the probe frequency. For each subject, tuning curves with similar masker levels near the probe frequency, but obtained with different probe-level/delay-time combinations, were selected for comparison. According to our earlier assumption, if the masker levels near Fp are similar this would mean that the filter output levels are similar. Two tuning curves could then be compared, one obtained with a high probe and a short delay time, the other obtained with a low probe and a long delay time. Those pairs of tuning curves are plotted together in Figs. 6 and 7 for different subjects. Even though the overall masker levels differed among subjects, from low overall masker levels for LA(R) in Fig. 6 to high overall masker levels for MC(L) in Fig. 7, the gross similarity in the shapes of the two tuning curves for each subject supports the notion that when masker levels near the probe frequency are equated, in this case only nearly so, tuning-curve shapes are very nearly the same.

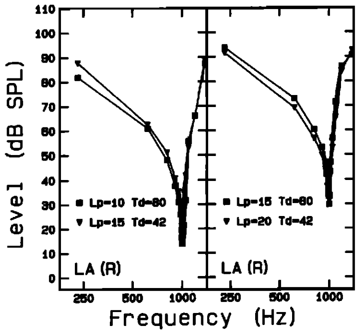

FIG. 6. Comparison of tuning curves obtained with different combinations of probe level and delay time for subject LA. Tuning curves that showed nearly equivalent masker levels near the probe frequency are compared. Probe level (Lp) is given in dB SPL; delay time (Td) is given in msec.

In order to test the equivalent masker level concept further, two additional subjects were tested using probe-level/delay-time combinations that were specifically chosen to require equal masker levels at the probe frequency. First a forward-masked tuning curve ($Fp = 1000$ Hz) was obtained using a low-level probe and a long delay time ($Td = 80$ msec), referred to as a "low-probe/long-delay" tuning curve. Then a growth-of-masking function at $Fm = Fp$ was obtained using the short delay time (42 msec) in order to estimate the probe level needed to achieve the same masker level that had just been obtained in the previous low-probe/long-delay tuning curve. This procedure selected a high level probe condition, at the short delay time, that should produce the same masker level (filter output) at the probe frequency. That combination of probe level and delay time was then used to obtain a "high-probe/short-delay" tuning curve. If the equivalent masker level concept is reasonable, the low-probe/long-delay tuning curve should be identical to the high-probe/short-delay tuning curve. The results for both subjects are shown in Fig. 8 by the two high-level tuning curves that superimpose. For all practical purposes the two tuning curves are identical, which lends support to the equivalent masker level concept introduced here.

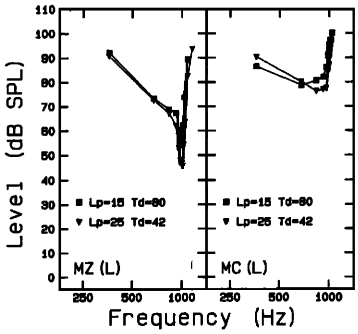

FIG. 7. Comparison of tuning curves obtained with different combinations of probe level and delay time for subjects MZ and MC.

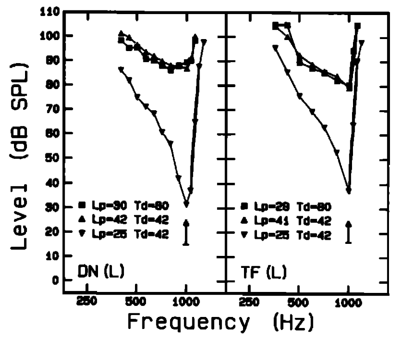

FIG. 8. Forward-masked tuning curves, from two normal-hearing subjects, obtained at probe-level/delay-time combinations that produced equivalent masker levels near the probe frequency. The low-probe/long-delay tuning curve (squares) is essentially identical to the high-probe/short-delay tuning curves (triangles). A low-probe/short-delay tuning curve is shown (inverted triangles) to demonstrate the sharp tuning curve that is typically obtained at low masker levels. The upward arrow indicates the level and frequency of the probe tone used to obtain that low-level tuning curve. The base of the arrow indicates probe threshold without a preceding masker.

Theoretically, the masker-level thresholds for $Fm = Fp$ represent filter outputs at the center of the filter, and can be used to equate tuning curves. However, forward-masking thresholds for Fm very near Fp are often influenced by other psychophysical phenomena, such as pitch cues (Moore, 1981) and shifts in the minimum-masking frequency (MMF) with level (Zwislocki and Pirodda, 1952; Vogten, 1978). These "tip" phenomena can confound the estimate of filter output, and may be involved in the present data. In Figs. 6 and 7, at masker frequencies very near the probe frequency, there are some significant differences between the masker levels in each pair of tuning curves. Yet, masker levels more remote from the probe frequency are remarkably similar. It could be that the differences near the probe frequency are influenced by tip phenomena, and might be ignored for our purposes here. Also, in Fig. 8 for subject DN, where an attempt was made to choose the delay-time and probe-level combinations that would require the same masker level at Fp, careful examination of the masker-level thresholds at Fp indicates that we miscalculated slightly and that the low-probe/long-delay condition required about 3 dB more masker level than the high-probe/short-delay condition, i.e., the masker-level thresholds are not exactly the same. Despite this, the masker levels at remote frequencies are nearly identical. Here again, the small differences in masker level at Fp may have been influenced by tip phenomena, in this case an MMF shift due to the large level difference between masker and probe in the low-probe/long-delay condition. Whatever the confounding factors near the tip of the tuning curve, it appears from the comparisons shown here, that matching masker-level thresholds at masker frequencies just below the probe frequency may serve as a reasonable estimate of masker-level equivalence.

D. Model predictions

The changes in the shapes of the simulated tuning curves shown in Fig. 5 that occur with increases in masker level are qualitatively similar to the changes that are seen in the real data of Figs. 1–3 with increases in masker level. In order to examine the quantitative similarities between the model predictions and actual forward-masking data, estimates for the parameters in Eq. (A4) were made for each of the three subjects whose data are shown in Figs. 1–3. Parameter estimates were made in two stages.

First, estimates were made for the two parameters that are assumed to be independent of the frequency ratio between masker and probe: the time constant T and the M term. To accomplish this, masker levels at the tips of the six tuning curves (one tuning curve for each of two delay times at three probe levels) were subjected to a least-squares parallel-fitting procedure that estimated a single time constant T to best describe the data at all three probe levels. This procedure also provided a predicted masker level at a delay time of zero. That predicted masker level at a delay time of zero was then used to derive the M term from Eq. (A4), without the exponential or any of the frequency-dependent terms. This first procedure provided estimates of the masker level at the tip of the simulated tuning curve for each combination of probe level and delay time.

Second, with estimates of the frequency-independent parameters of Eq. (A4) in hand, estimates could then be made of the frequency-dependent parameters. This was done by trial and error until the "best fitting" functions were obtained at all probe levels and delay times. Estimates of frequency-dependent parameters are largely subjective. We have not yet developed objective procedures for obtaining estimates of either the slopes of the filter, represented by the terms p and q, the tip-to-tail ratio of the two sections of the filter w, or the rate at which the slope of the growth of masking changes with frequency differences between masker and probe, which is given by the term a.

Comparisons between the model predictions and the actual forward-masking data are shown for individual subjects in Figs. 9–11. The solid curves are the model predictions, the symbols the actual data. Inverted triangles indicate the results for the short delay-time condition, $Td = 42$ msec; squares indicate the results for the long delay-time condition, $Td = 80$ msec. Level of the probe varies in each panel as in Figs. 1–3.

The model predictions are fairly accurate representa-

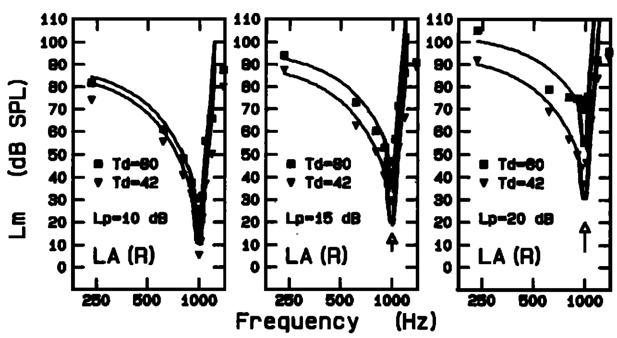

FIG. 9. Comparisons of model predictions with forward-masked tuning curves from subject LA. Pairs of tuning curves are shown for each probe level in separate panels. Solid curves are the model predictions, symbols represent the actual data. The upper curve in each panel and the square symbols are for the 80-msec delay time; the lower curve and the inverted triangles are for the 42-msec delay time. Probe levels are 10, 15, and 20 dB SPL in respective panels from left to right. Parameters used for the tuning-curve predictions are listed in Table AI.

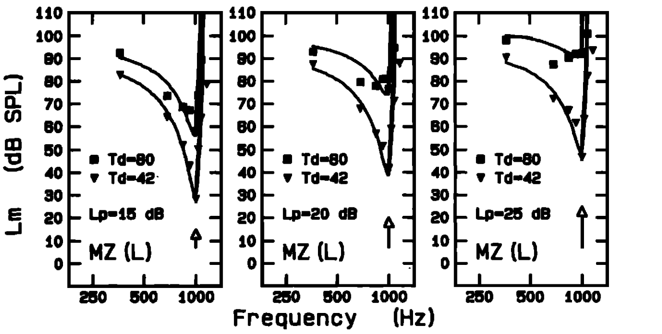

FIG. 10. Comparisons of model predictions with forward-masked tuning curves from subject MZ. Probe levels are 15, 20, and 25 dB SPL in respective panels from left to right. Legend as in Fig. 9.

tions of the actual data as long as the masker level at the tip of the tuning curve, considered here to be the filter output level, is at low to moderately intense sound pressure levels. This can be seen in the tuning curves for the short delay-time condition (42 msec) at all probe levels for all three subjects (the lower curve in each panel of Figs. 9–11). Good agreement between model predictions and actual data can also be seen in the tuning curves for the long delay-time condition (80 msec) at all three probe levels for subject LA (the upper curves in Fig. 9) and at the lower two probe levels for subject MZ (the upper curve in the left two panels of Fig. 10).

Model predictions begin to fail when the masker level at the tip of the tuning curve approaches more intense sound pressure levels, somewhere above 70 dB SPL in these data. One observation is that the shape of the predicted tuning curve is no longer appropriate at these higher levels. This is evident in the tuning curve for the long delay-time condition in subject MZ at the highest probe level (right-hand panel of Fig. 10, top curve). It is also evident in the long delay-time tuning curves at all probe levels for subject MC (top curve in each panel of Fig. 11). It appears that the changes in the low side of the tuning curve that are produced by the "nonlinear" filtering process in Eq. (A4) are not sufficient to account for the additional "rounding" of the filter shapes that are evident in the data at masker levels above about 70 dB. We have avoided including an intensity term in the frequency weighting function, since that would complicate transformations between excitation patterns, Eq. (A1), and tuning curves, Eq. (A4). However, it appears that much better predictions

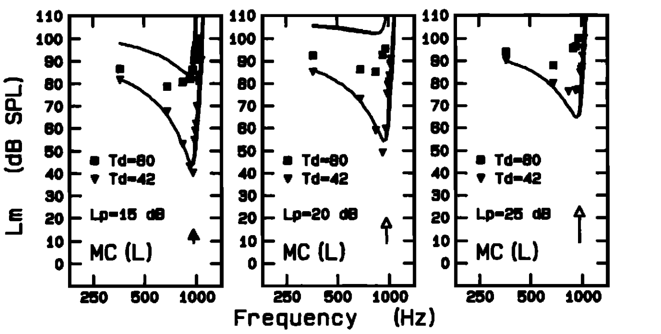

FIG. 11. Comparisons of model predictions with forward-masked tuning curves from subject MC. Probe levels are 15, 20, and 25 dB SPL in respective panels from left to right. Legend as in Fig. 9.

would result if we were to make the slopes of the weighting function directly dependent upon intensity.

Another characteristic of very intense masker levels can be seen in the data of subject MC in Fig. 11. Here the model performed well with the 42-msec delay-time condition at all probe levels, but it failed miserably on the 80-msec conditions. This subject is unusually resistant to forward masking at low levels, which is evident by the large M term of 14.3. At high probe levels that resistance to forward masking is not evident. The model predicts masker levels near the limits of our equipment for the upper two probe-level conditions, while the actual data tend to stay between 80–100 dB SPL. Furthermore, a large negative shift in the maximum masker frequency (MMF) is evident in the data for this subject at high masker levels. The model does not allow for such MMF shifts. It appears as if additional mechanisms not included in the model may be contributing to forward masking at masker levels above 80 or 90 dB SPL. It also appears as if these high-level effects are more obvious in those subjects that are most resistant to forward masking.

IV. SUMMARY

It has been demonstrated that when tuning curves are compared at equivalent masker levels the shapes of those tuning curves are essentially the same. When higher-level masking tones are required, either because of an increase in delay time between masker and probe, or because of an increase in probe level, broader tuning curves are obtained. Tuning curve shapes appear to be largely dependent upon the levels of the masking tones used to measure them.

A two-stage model of forward masking (see the Appendix) was used to describe this dependence of tuning-curve shape on masker level. It was demonstrated that a linear filter could not predict the results; neither could an exponential decay process that preceded the filter. In order to predict this dependence on masker level, a nonlinear filter is required, which is then followed by an exponential decay. Comparisons of model predictions with actual data indicate that the particular type of nonlinear filter included in the present model can accurately account for tuning-curve shapes as long as the masker levels near the tip of the tuning curves remain at low to moderately intense sound pressure levels (<70 dB SPL). When masker levels near the tip are at very high levels (>70 dB SPL), additional mechanisms may be involved which require more broadly tuned filtering and more compressive nonlinearities than are presently included in the model.

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APPENDIX: DESCRIPTIVE MODEL OF FORWARD MASKING

The model used to simulate forward-masking tuning curves in Fig. 5 is based upon several general assumptions:

(1) Sinusoidal stimuli produce patterns of excitation in which each stimulus excites different frequency regions in the auditory system with different magnitudes of excitation. Excitation magnitude is dependent upon the filter shape that exists at each of those different frequency regions. Those patterns of excitation are qualitatively similar to the excitation patterns described by Zwicker (1970) and Terhardt (1979) for simultaneous masking, with additional modifications for sinusoidal stimuli and level dependencies as described by Schöne (1977).

(2) Excitation in any particular frequency region produces a sensory response that is dependent upon the amount of excitation that is above sensory threshold at that frequency region.

(3) Sensory response leads to an adaptation process that recovers over time.

(4) If a probe tone is to be detected after a masking tone is turned off, the sensory response produced by the probe must be sufficient to overcome the adaptation that remains.

An equation for forward-masking patterns, which incorporates these general assumptions, is given below as Eq. (A1).

$$Lp - Ltpp = \{[1 + a(dZ)]Lm + W(z) - Ltpm\}e^{-t/T} - M. \quad \text{(A1)}$$

The amount of excitation produced by a masker at some frequency region, one that is dZ Barks removed from the masker frequency, is determined by two terms: $W(z)$, the linear "frequency" weighting function, and $[1 + a(dZ)]Lm$, the frequency-dependent growth of masking, where Lm is the masker level in dB SPL.

The term $[1 + a(dZ)]$, which is similar to that used by Schöne (1977), describes changes in the symmetry of excitation patterns that occur with stimulus level. It is essentially a frequency-dependent slope for the growth of masking. When $Fp > Fm$ the slope is greater than 1.0. When $Fp < Fm$ the slope is less than 1.0. The amount by which the slope departs from 1.0 depends upon dZ, where $dZ = Zp - Zm$, the relative difference in Barks (Zwicker and Terhardt, 1980) between the probe and the masker.

The combined term, $[1 + a(dZ)]Lm + W(z)$, represents the excitation level at a particular frequency that is dZ Barks removed from the masker frequency. It defines a pattern of excitation across frequency, expressed in Bark units, that is nearly symmetrical at very low masker levels and becomes progressively asymmetrical as level is increased. This combined term produces level-dependent excitation patterns, which result in derived filter patterns that are broader at higher intensities. Therefore, we refer to the filter as a nonlinear filter, even though the frequency weighting function by itself is linear.

Sensory response to the masker is defined as the amount of excitation above sensory threshold, where $Ltpm$ is the threshold level of a tone at the probe frequency and masker duration. The combined term, $[1 + a(dZ)]Lm + W(z) - Ltpm$, defines sensory response at the probe frequency, which is dZ Barks removed from the masker frequency.

It is assumed that adaptation is linearly related to sensory response and recovers exponentially in time, as in Eq. (A1), with the time constant T.

The M term determines how much forward masking, or adaptation, is required before any shift in the sensory response to the probe is measurable. In order to detect a probe tone at some time t following masker offset, the sensory response to the probe, $Lp - Ltpp$, is equated with the remaining adaptation at time t that is larger than M. In this case, Lp is the level of the probe at masked threshold in dB SPL, and $Ltpp$ is the threshold level of a tone at the probe frequency and the probe duration.

$$W(z) = 10 \log[(1 + pz)e^{-pz} + w(1 + qz)e^{-qz}]. \quad \text{(A2)}$$

The "frequency" weighting function, given in Eq. (A2), consists of two rounded exponential functions with different slopes. This particular weighting function uses the Bark scale, where $z = |Zp - Zm|$, the absolute difference in Barks between the probe and the masker. Since it uses the Bark scale instead of a linear frequency scale, this weighting function is not intended to directly represent the shape of the auditory filter as in Patterson *et al.* (1982). It is used here as an alternative to Terhardt's (1979) weighting function, which is also linear in dB/Bark.

Note particularly that there are two rounded exponentials in the weighting function. Usually the first function, with slope p, is sufficient to describe the data. However, when a very sharp peak is called for, the first function is made steeper than the second, so that the second function, with slope q, produces a more gradual sloping tail to the excitation pattern, with a tip-to-tail ratio determined by w.

The general equation for forward-masking patterns can be rewritten to reveal some interesting hypothetical properties of the model, as in Eq. (A3).

$$\ln\{Lp - Ltpp + M\} = \ln\{[1 + a(dZ)]Lm + W(z) - Ltpm\} - t/T. \quad \text{(A3)}$$

Instead of a linear transform between excitation, sensory response, and adaptation, followed by an exponential recovery from adaptation, as in Eq. (A1), one can view the system as if a nonlinear transform exists between excitation and sensory response. This is more obvious in Eq. (A3), where we have simply taken the natural logarithm of both sides of Eq. (A1) to remove the exponential in favor of a logarithmic compression on the amount of excitation above sensory threshold. Sensory response to the masker is now a logarithmic transform of the amount of excitation above sensory threshold. Adaptation is still considered to be a linear transform of sensory response, but in this case it recovers linearly over time. The sensory response to the probe, also a logarithmic transform of excitation, must then be sufficient to overcome any remaining adaptation at any particular recovery time. Conceptually, Eq. (A3) is an attractive way to view the system, since the nonlinear transform of excitation into sensory response is grossly similar to how auditory-nerve response rates change with stimulus intensity.

To generate the simulated tuning curves shown in the body of this manuscript, filter patterns were derived by rewriting Eq. (A1) to solve for Lm, as shown in Eq. (A4). Parameter values chosen for the simulations are listed in Table

TABLE AI. Parameter values used for tuning-curve simulations.

	T	M	a	p	w	q	$Ltpp$	$Ltpm$
Fig. 5	57.0	4.5	0.32	8.5	0.00	0.0	12.8	5.9
Fig. 9	59.2	1.4	0.23	16.0	0.01	6.9	7.6	0.4
Fig. 10	60.5	8.2	0.55	13.8	0.00	0.0	7.2	−3.2
Fig. 11	55.2	14.3	0.35	9.2	0.00	0.0	9.3	1.6

AI. Delay time was specified as the time between masker offset and probe offset.

$$Lm = [(Lp - Ltpp + M)e^{t/T} - W(z) + Ltpm]/[1 + a(dZ)]. \quad \text{(A4)}$$

[1]In actuality, an excitation pattern with slopes in units of dB per Bark, is not a linear filter at all. Frequency has been transformed into Barks using a nonlinear function (Zwicker and Terhardt, 1980), and intensity has been transformed into decibels using a nonlinear function. For our purposes here, both dimensions, frequency and intensity, have been linearized into a Bark scale and a decibel scale. The linear filter we refer to here is a weighting function with symmetrical slopes that are linear in units of dB/Bark. Furthermore, this linear filter does not change its slopes with intensity, as does the nonlinear filter we refer to later.

[2]In addition to the forward-masked tuning curves that Kidd and Feth (1981) reported, they also measured masking patterns (constant masker level and masker frequency with variable probe frequency and level) as a function of delay time between masker and probe. Their masking patterns became broader with increased delay time. One straightforward interpretation might be that the underlying filter function becomes broader as delay time becomes longer. However, when an exponential decay process (in dB/sec) follows a linear filter, broader masking patterns would be expected at longer delay times, while, as noted earlier, tuning curves would not change with delay time. This is because in the masking-pattern experiment, filter output varies with probe frequency, while in the tuning-curve experiment filter output is constant. In the exponential decay process, the absolute amount of decay (in dB) is a function of the input level to the decay process (output of the filter). Since the input level to the decay process is higher at the peak of the masking pattern, more decay will occur there than at the remote frequency edges of the masking pattern. Consequently, at longer delay times the masking pattern will appear broader, even though the underlying filter functions at each probe frequency do not change with delay time.

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