Effects of stimulus level on forward-masked psychophysical tuning curves in quiet and in noise

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Forward-masked psychophysical tuning curves were obtained from normal-hearing listeners at different probe levels in quiet and in a broadband background noise. In quiet, tuning-curve shape changed with probe level. For six listeners, tuning curves became broader with increasing probe level, primarily due to a decrease in the low-frequency slopes. For one listener, tuning curves became narrower with increasing probe level. The addition of a background noise, which was presented continuously at a level 10 dB below the noise level required to mask the probe tone, reduced the masker levels required to mask the probe tone. The reduction was greater near the tip of the tuning curve than on the tail, so that tuning curves in background noise were narrower than those obtained in quiet. Tuning curves with comparable masker levels near the tip of the tuning curve ($Lm_{\rm tip}$) were similar in shape, regardless of probe level or whether tuning curves were obtained in quiet or noise. Comparisons of tuning-curve characteristics derived by fitting tuning curves with least-squares procedures, indicated that low-frequency slopes decreased with $Lm_{\rm tip}$. As a consequence, $Q_{10\ \rm dB}$ values decreased with $Lm_{\rm tip}$. These results are consistent with the interpretation that tuning-curve shapes are determined by the intensities of the maskers required to mask the probe tone. The addition of a background noise restricted (partially masked) the excitation pattern of the probe so that lower masker intensities were required to "forward mask" the probe tone, and narrower tuning curves resulted from less intense maskers. The results are well described by a two-process model of auditory excitation patterns.

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INTRODUCTION

Psychophysical tuning curves have become increasingly popular for estimating the frequency-resolving capabilities of listeners with impaired hearing (Leshowitz *et al.*, 1975, 1976; Carney and Nelson, 1976, 1983; Wightman *et al.*, 1977; Hoekstra and Ritsma, 1977; Schorn *et al.*, 1977; McGee, 1978; Zwicker and Schorn, 1978; Florentine, 1978; Nelson and Turner, 1980; Nelson, 1980a,b; Florentine *et al.*, 1980; Stelmachowicz *et al.*, 1985; Moore and Glasberg, 1986). In these investigations of impaired hearing, psychophysical tuning curves from regions of hearing loss were, by necessity, obtained with high-SPL signals. On the other hand, tuning curves from regions of normal-hearing usually employed low-SPL signals, except for the studies by Carney and Nelson (1976, 1983), Stelmachowicz and Jesteadt (1984) and Moore and Glasberg (1986). Comparisons of tuning curves from the two types of listeners indicate that tuning curves from hearing-impaired listeners are usually broader than from normal-hearing listeners, which leads to the general conclusion that hearing loss is accompanied by poor frequency-resolving capabilities. However, that general conclusion is usually based upon the results of experiments carried out at different stimulus intensities. Since frequency resolution is level dependent in normal-hearing listeners, then the association between hearing loss and poor frequency resolution may not be quite as strong as previously implied.

A comparison of psychophysical tuning curves obtained at comparable SPLs in normal-hearing and hearing-impaired listeners (Carney and Nelson, 1983) has questioned the generality of that conclusion for *simultaneous* masking conditions, because combination tones and combination bands in the normal ear may lead to excessively narrow estimates of tuning in the normal ear. A recent investigation using simultaneous masking (Nelson and Fortune, 1991a) demonstrated that, when the influences of combination tones and combination bands were minimized with appropriate additional masking noise, or when combination bands were minimized with sufficiently wide narrow-band noise maskers (Nelson and Fortune, 1991b), tuning curves from normal-hearing listeners were more broadly tuned at high SPLs than at low SPLs. As a consequence, for simultaneous masking conditions, comparisons of tuning from impaired ears with appropriately obtained estimates of high-level tuning in normal ears may not reveal such dramatic tuning deficits, at least on the low-frequency side of the tuning curve.

Since *nonsimultaneous* masking is not influenced by combination tones and combination bands at high levels, tuning curves obtained with forward masking procedures may provide more direct answers to questions about frequency resolution in the normal ear at high SPLs. However, investigations of forward-masked tuning curves at different signal (probe) levels have yielded mixed results. Some subjects showed broader tuning curves for higher-level probe tones (Widin and Viemeister, 1979; Nelson, 1980a; Small and Busse, 1980; Green *et al.*, 1981; Kidd and Feth, 1981), while others showed narrower tuning curves (Moore, 1978). In addition, off-frequency listening cues and confusion effects have been identified as possible confounding factors in forward masking (O'Loughlin and Moore, 1981a,b; Moore, 1980a; Weber *et al.*, 1980). It was shown that the reduction of some of those cues with a continuous broadband background masking noise altered the shapes of high-SPL forward-masked tuning curves (Nelson, 1980a; Green *et al.*, 1981; Wightman, 1982). Green *et al.* (1981) concluded that forward-masked tuning curves are invariant with probe level when continuous background noise was used to mask off-frequency listening cues. However, the tuning curves they obtained in background noise were narrower than those obtained in quiet, which is just the opposite effect realized with notched background noise gated with the masker to restrict off-frequency listening and minimize confusion effects (O'Loughlin and Moore, 1981a,b; Moore *et al.*, 1984). To examine some of these issues further, forward-masked psychophysical tuning curves were obtained from normal-hearing listeners for a range of probe levels, both in quiet and in the presence of a broadband masking noise.

I. METHODS

Seven adults participated as listeners. All had bilaterally normal hearing (<15 dB HL *re*: ANSI, 1969) for frequencies between 250 and 4000 Hz. None had a history of middle-ear disorders. Before beginning final data collection, listeners received extensive practice in forward-masking tasks. The thresholds reported here are the means of three or more replications obtained during separate listening sessions.

In this experiment, signal (probe) levels were held constant and masker level was adjusted to achieve masked threshold. Those "masker-level thresholds" will be referred to as masked thresholds. Masked thresholds were measured with a four-interval four-alternative forced-choice (4AFC) adaptive procedure, which utilized a two-up-one-down stepping rule and a 2-dB step size. This procedure estimates the masker level required to achieve 70.7% correct detection of the probe tone. Threshold was taken as the average of the masker levels on the last six out of nine reversals. All thresholds reported are the averages of at least three threshold determinations. Masking tones were 200 ms in duration; probe tones were 20 ms. Both were gated with 10-ms rise and decay times. The gating waveform was a nonlinear function that approximated a quarter cycle of a squared cosine. Durations were specified as the period of time a waveform was larger than 90% of peak amplitude; rise–decay times were specified as the time required to change from 10% to 90% of peak amplitude. Thus the time delay between masker offset and probe offset was 42 ms, specified as the time between 10% of masker (offset) amplitude and 10% of probe (offset) amplitude (offset–onset temporal separation was 2 ms). Silent intervals of 300 ms followed each listening interval in a 4AFC trial. Correct answer feedback was given following each trial. Background masking noise, when used, was produced by a General Radio 1390-B random noise generator. Pure tones were produced by Krohn-Hite 4141R programmable oscillators. All signals were delivered through a TDH-49 earphone that was mounted in an MX-41/AR cushion. Listeners were seated in a double-walled IAC sound chamber during testing. All testing procedures were controlled by a minicomputer.

Forward-masked tuning curves for 1000-Hz probe tones were obtained for a range of probe levels, in 5 dB steps, under two experimental conditions: in a quiet background and in a noise background. The order in which experimental conditions were tested varied across listeners, probe levels, and type of background condition (quiet or noise). Two absolute thresholds and one complete tuning curve were all obtained during a single test session that lasted between 30 and 40 min. If a tuning curve was to be obtained in background noise, the level of continuous noise required to mask a 20-ms 1000-Hz probe tone at a specific SPL was determined with an adaptive procedure identical to that used to obtain tuning curves, i.e., the probe-tone level was held constant while noise level was adapted to reach masked threshold. The noise level required to mask the 20-ms probe was then reduced by 10 dB and was subsequently used as the level of background noise that was presented continuously to the test ear during the acquisition of the noise-masked tuning curve. Tuning curves obtained in background noise will be referred to as "noise" (*NS*) tuning curves; those obtained without background noise will be referred to as "quiet" (*QT*) tuning curves.

II. RESULTS

A. Tuning curves in quiet versus background noise

Direct comparisons of tuning curves obtained in quiet with those obtained in background noise are shown in Figs. 1 and 2 for all seven subjects. Each row of panels displays tuning curves obtained at progressively higher probe levels, from left to right, for each of the seven subjects. Within each panel the tuning curve obtained in a quiet background (squares) is the upper curve, the tuning curve obtained in a noise background (inverted triangles) is the lower curve.

Two general results stand out. Tuning curves tended to broaden with increasing probe level in the quiet background condition, and the noise background reduced the masker levels primarily around the tuning-curve tip. Examination of data from individual subjects in Figs. 1 and 2 reveals large individual differences, both in terms of the amount of broadening of tuning curves with probe level in quiet and the decreases in masker levels that resulted with the introduction of a noise background. Six of the subjects demonstrated broadened tuning curves with increased probe level, evidenced largely by flattening of the low-frequency sides of the tuning curves. Four of those subjects showed strong broadening at higher probe levels (MC, DH, JH, SC) and two of them showed moderate broadening at higher probe levels (BA, XH). One subject (JG) showed narrower tuning curves with increased probe level, which is similar to results reported by Moore (1978) from two subjects who showed very sharp tip segments at a high probe level.

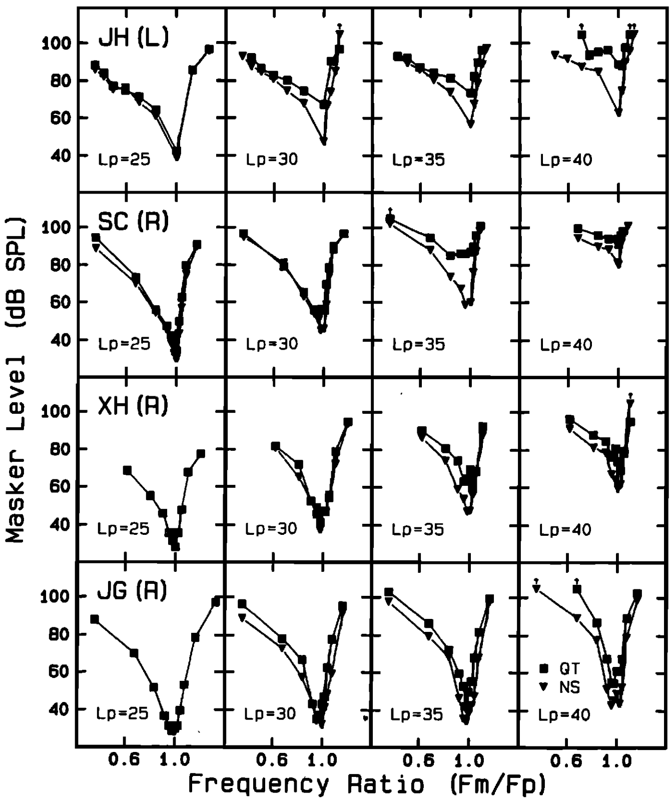

FIG. 1. Comparisons of forward-masked tuning curves obtained in a quiet background with those obtained in a continuous broadband noise background. Data are from four normal-hearing listeners. Each row of panels shows tuning curves from a single subject, with tuning curves for progressively higher probe levels arranged from left to right. Within each panel, tuning curves obtained in quiet (*QT*) are the upper curves (closed squares), tuning curves obtained in a background noise (*NS*) are the lower curves (inverted triangles).

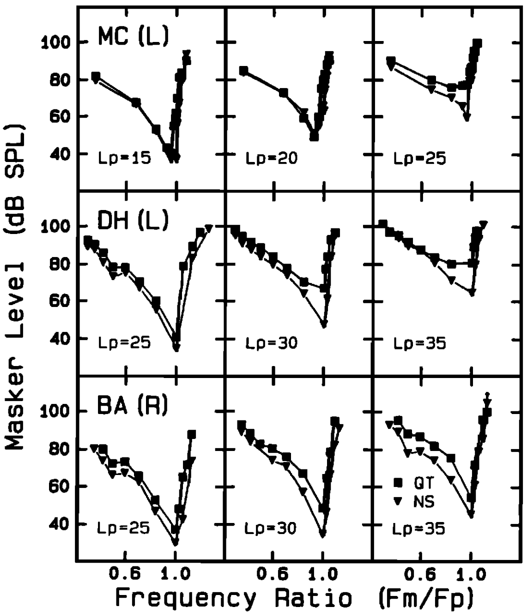

FIG. 2. Comparisons of forward-masked tuning curves obtained in a quiet background with those obtained in a continuous broadband noise background. Data are from three normal-hearing listeners. Legend as in Fig. 3.

The principal effect of the background noise was a reduction in masker level, which for most subjects was greater for masker frequencies near the probe than for masker frequencies below the probe. The introduction of background noise had little or no effect on masker levels for the lowest probe levels (15–25 dB SPL), where the level of the probe was about the same sensation level in quiet as it was in noise. The background noise had its strongest effect at the higher probe levels, where the probe tones were at the highest sensation levels in quiet. At the higher probe levels, tuning curves in background noise were generally more narrowly tuned than tuning curves obtained in a quiet background at comparable probe levels. A notable exception was subject JG.

Two observations from the comparisons shown in Figs. 1 and 2 are particularly interesting. First of all, the most significant broadening of tuning curves with probe level in quiet occurred in those subjects who needed the highest masker levels to mask the probe tone. This generally occurred when masker levels near the tips of the tuning curves exceeded 60 dB SPL. The broadening with probe level in quiet was strongest for subjects MC, DH, JH, and SC. They were the subjects who demonstrated the best performance, as evidenced by the masker/probe ratios near the tips of the tuning curves. Subjects BA and XH demonstrated only moderate broadening of tuning curves with probe level. Their masker/probe ratios near the tip also tended to be smaller. Subject JG showed narrowing of tuning-curve shapes with level. His masker/probe ratios near the tips of the tuning curves were the smallest. He was the worst of the seven subjects at performing forward masking tasks in that the probe tones were most easily masked. From this it appears that subjects with the largest masker/probe ratios near the tips of the tuning curves, consequently the highest masker levels at the tips of the tuning curves, demonstrated the most broadening with increasing probe level.

It is of interest to note that subject JG, who demonstrated no broadening of tuning curves with probe level, never required masker levels near the tips of the tuning curves that exceeded 60 dB SPL. Compared with the other subjects, maskers levels near the tips of the tuning curves remained relatively low. For this subject, the probe tone was very easily masked by forward maskers near the tip of the tuning curve. The narrow tuning curves suggest that he had particular difficulty detecting the short probe following the masker, particularly when the masker and the probe were similar in frequency. Perhaps he was unusually susceptible to "confusion" effects (Neff, 1985) in the absence of "quality difference cues" between masker and probe (Terry and Moore, 1977; Moore, 1980a; Weber and Moore, 1981). Because JG performed differently than the other six listeners, his results were not included in the analysis by tip level described later.

Another noteworthy observation from Figs. 1 and 2 is that the background noise had the most marked effect on tuning-curve shape when tuning curves at comparable probe levels in quiet exhibited strong broadening with probe level, which were those tuning curves with the highest masker levels near the tuning-curve tip. The principal effect of the background noise was a reduction in masker level. However, the reduction in masker level was strongly dependent on the masker/probe frequency ratio, being greatest for masker/

probe frequency ratios close to one, i.e., when the masker was near the tip of the tuning curve. Consequently, the masker-level reduction was accompanied by a narrowing of the tuning curve. This reduction in masker level near the tip, with the concomitant narrowing of the tuning curve, was the largest for subjects MC, DH, JH, and SC.

Both broadening with increasing probe level and changes in tuning with background noise seem to be associated with the levels of the maskers near the tips of the tuning curves. Broadening with increasing probe level only occurred when masker levels near the tip were rather high, and decreases in tuning with background noise only occurred when masker levels near the tip were rather high. Qualitatively, it appears that when masker levels near the tip are nearly equivalent, tuning curves obtained in noise with high-level probe tones are similar in shape to tuning curves obtained in quiet with lower level probe tones.

B. Tuning curves at equivalent tip levels

These observations suggest that tuning-curve shape is closely associated with the level of the masker that is required to mask the probe tone when the masker frequency is near the probe frequency, i.e., the masker level at the tip of the tuning curve, referred to here as Lm_{tip} or tip level.

To examine that possibility further, individual tuning curves from each subject were categorized according to tip level. They were then grouped according to Lm_{tip} range: Tuning curves with similar tip levels were plotted together regardless of the probe level used to obtain them or whether they were obtained in quiet or in a noise background. If tip level is the primary determinant of tuning-curve shape, one would expect tuning curves with similar tip levels to cluster together.

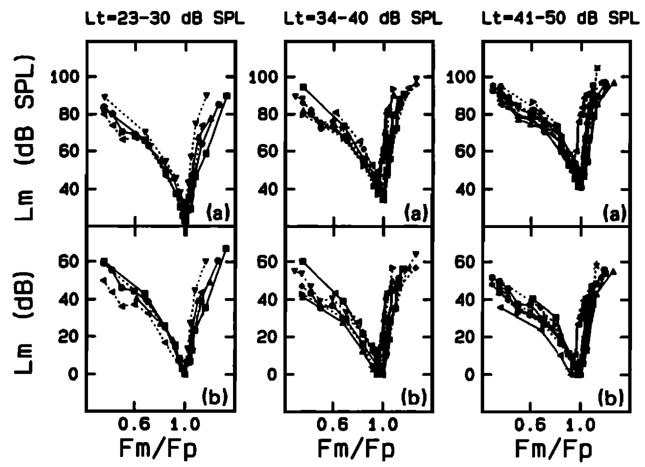

FIG. 3. Forward-masked tuning curves grouped by tip level (Lm at the tip of the tuning curve): low to moderate tip levels. Tuning curves with similar tip levels are plotted together, regardless of the probe level or whether they were obtained in quiet or in a noise background. Each pair of panels contains tuning curves for a range of tip levels. They are arranged from left to right with higher tip-level categories to the right. The top panel [(a)] plots masker levels in dB SPL, the bottom panel [(b)] plots masker level normalized to tip level. Masker levels obtained in quiet are connected by solid lines; those obtained in a noise background are connected by dashed lines. The graph illustrates that tuning curves with similar tip levels have similar shapes. For these low to moderate tip-level ranges, tuning-curve shapes are fairly uniform.

Figures 3 and 4 display tuning curves replotted according to Lm_{tip} range. Figure 3 shows three lower level Lm_{tip} ranges and Fig. 4 shows three higher level Lm_{tip} ranges. Level of the masker is plotted in dB SPL in the top panels [labeled (a)]. Level of the masker relative to the level at the tip of each tuning curve is plotted in the bottom panels [labeled (b)] to allow easier visual comparisons of tuning-curve shapes. Examination of Figs. 3 and 4 shows that tuning curves with equivalent masker levels at their tips cluster together; they have remarkably similar shapes, regardless of the probe level used or whether the tuning curve was obtained in quiet or in a noise background.

As shown in Fig. 3, even when Lm_{tip} range increased from 23–30 up to 41–50 dB SPL, very little change in tuning-curve shape was apparent, even though large differences existed in probe level and tip level (labeled Lt). In each panel, tuning curves obtained in quiet (connected by solid lines) are indistinguishable from those obtained in noise (connected by dashed lines). Notice that the tuning curve obtained from one subject (MC) in quiet, shown in the rightmost column of panels, demonstrated a significant downward shift in minimum masker frequency (MMF) compared to the other tuning curves within the Lm_{tip} range of 41–50 dB SPL. In this case the MMF shift was most likely related to this subject's report of a large difference in the pitch of masker and probe when they were both at the same frequency (Moore, 1980b). This is also consistent with the relatively large masker/probe intensity ratio at masked threshold of 30 dB seen in this subject, compared with the 11- to 18-dB masker/probe ratios seen for the other subjects.

As shown in Fig. 4, when Lm_{tip} range increased from 54–63 up to 73–85 dB SPL, large changes in tuning-curve

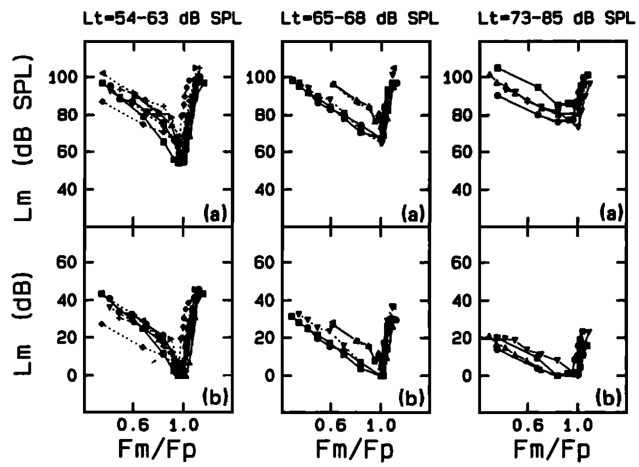

FIG. 4. Forward-masked tuning curves grouped by tip level: high tip levels. Legend as in Fig. 5. The graph illustrates that tuning curves with similar tip levels have similar shapes, and that tuning curves with high tip levels tend to broaden with tip level.

shapes resulted, although within an Lm_{tip} range tuning-curve shapes remained similar regardless of probe level or whether the tuning curve was obtained in quiet or in a noise background. Tuning-curve shapes with tip levels in the Lm_{tip} range of 54–63 dB SPL (leftmost panels of Fig. 4) were only slightly narrower than tuning curves that fell in the Lm_{tip} range of 41–50 dB SPL (rightmost panels of Fig. 3). Tuning curves within the 54–63 dB Lm_{tip} range were remarkably similar, again, except for the tuning curve from subject MC in a noise background, which demonstrated a negative MMF shift. In this case, the masker/probe ratio for subject MC was 35 dB, compared to 19–27 dB for the other curves.

When tip levels were well above 60 dB SPL, for Lm_{tip} ranges of 65–68 and 70–85 dB SPL, obvious broadening of tuning curves was seen. In the 65–68 dB Lm_{tip} range (center panels of Fig. 4), tuning curves obtained from the same ear for different probe levels, one in quiet and the other in noise, are shown for two different subjects (DH and XH). Notice that the tuning curves obtained in noise are identical to those obtained in quiet. In the 73–85 dB Lm_{tip} range (rightmost panels of Fig. 4), only tuning curves in quiet are seen. At these high masker levels tuning curves are the broadest.

These qualitative comparisons of tuning-curve shapes within equivalent Lm_{tip} ranges indicate that tuning-curve shape depends upon the masker level at the tip of the tuning curve. At tip levels below about 60 dB SPL, tuning-curve shapes remain approximately invariant with tip level. At higher tip levels, tuning-curve shapes broaden to become broad low-pass curves for tip levels above about 70 dB SPL.

C. Tuning-curve characteristics and tip level

A more quantitative examination of the relation between tuning-curve shape and level of the masker at the tip of the tuning curve was accomplished by using least-squares criteria to fit each tuning curve with three linear segments, as was done by Stelmachowicz and Jesteadt (1984) and Nelson and Fortune (1991a,b). In this case, tuning-curve slopes were fitted on a frequency-ratio scale, and then transformed to dB/oct slopes using the probe frequency (Fp) as the octave reference for *high-frequency slope* (S_{hf}) and *low-frequency slope* (S_{lf}), and 0.8 Fp as an octave reference for the *tail slope* (S_t). Results of those tuning-curve slope calculations are plotted as a function of Lm_{tip} in Fig. 5, along with $Q_{10\ dB}$ estimates derived from S_{lf} and S_{hf} interpolations of 10-dB bandwidths.

Tuning-curve characteristics shown in Fig. 5 support the qualitative observations described earlier. As shown in the bottom left panel of Fig. 5, tuning characterized by $Q_{10\ dB}$ values remained relatively constant, with $Q_{10\ dB}$ values between 8.0 and 11.0, until Lm_{tip} reached about 60 dB SPL. For Lm_{tip} values greater than about 60 dB SPL, $Q_{10\ dB}$ decreased rapidly to values as low as 2.0, which means that tuning-curve 10-dB bandwidth for one subject was as broad as 500 Hz. No consistent differences in $Q_{10\ dB}$ were evident for tuning curves obtained in quiet (open symbols) or in a noise background (closed symbols) at comparable tip levels.

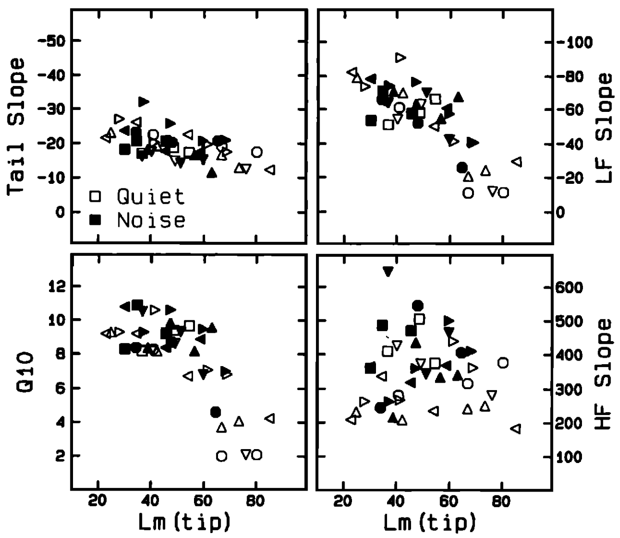

FIG. 5. Scattergrams of tuning-curve characteristics estimated with three-segment least-squares fits of individual forward-masked tuning curves. Tuning-curve characteristics from tuning curves obtained in quiet are shown by open symbols; those obtained in a noise background are shown by closed symbols. The independent variable is the level of the masker at the tip of the tuning curve [*Lm* (tip)].

Background noise reduced the masker levels required to mask the probe, and those reduced masker levels were associated with narrower tuning. However, noticeably narrower tuning under background noise only occurred if the tip level in quiet was greater than about 60 dB SPL.

The change in tuning with tip levels above 60 dB SPL was due primarily to decreases in low-frequency slopes. This is seen in the upper right panel of Fig. 5. Tuning curves broadened primarily through a decrease in the low-frequency slope with tip levels above 60 dB SPL, from a steep low-frequency slope of around -60 to -100 dB/oct for tip levels less than 60 dB SPL, to slopes as gradual as -11 dB/oct for tip levels above 60 dB SPL. The low-frequency slopes essentially merged into tail slopes at high tip levels. Tail slopes decreased only slightly with tip level. There was some tendency for high-frequency slopes to increase and then decrease with Lm_{tip} in some subjects, but that tendency did not hold across subjects.

III. DISCUSSION

A. Excitation patterns

These results indicate that masker level, not probe level, is the primary determinant of tuning-curve shape. An explanation for broadened tuning curves based upon changes in masker excitation patterns was proposed by Nelson and Freyman (1984), after the ideas put forth earlier by Zwicker (1956, 1970) and Verschuure (1981a,b). Nelson and Freyman suggested that the change in shape with probe level is a true reflection of the tuning characteristics of the auditory system, i.e., the auditory system is more broadly tuned at high than it is at low stimulus intensities. Their explanation attributed changes in tuning-curve shapes with probe level, or with masker/probe delay time, to changes in excitation patterns of the masking tones, which broaden with increased intensity. The same reasoning can be used to explain both the changes in tuning-curve shape with probe level and the effects of background noise seen here.

Several assumptions about auditory excitation patterns are necessary. First of all, it is assumed that an internal representation of excitation, along some spatial dimension in the auditory system, can be inferred from simultaneous masking patterns. Zwicker's conceptualization of excitation patterns (Zwicker, 1956; Zwicker and Feltdkeller, 1967; Zwicker, 1970; see also Maiwald, 1967) is one example. At low stimulus levels, the excitation pattern is narrow and more or less symmetrical, i.e., the spread of excitation to both lower and higher frequency regions is quite steep. At higher stimulus levels, the slope of excitation toward lower frequency regions becomes slightly steeper (Schöne, 1977), while the slope of excitation toward higher frequency regions becomes more gradual, resulting in increasingly asymmetric excitation patterns as stimulus level is increased. The growth of excitation at the peak of the excitation pattern (at the stimulus frequency) is assumed to be linear with a slope near unity, and the peak of excitation remains at the same frequency as level increases.

Given these assumptions, one can predict changes in psychophysical tuning curves that would be expected at different probe levels. However, since Zwicker's excitation patterns were inferred from simultaneous masking patterns, one can only use Zwicker's excitation patterns to predict tuning curves in a simultaneous masking situation. In order to predict tuning curves from excitation patterns for nonsimultaneous masking conditions, as is the case with the present data, additional assumptions are required about the recovery from forward masking. To represent those assumptions, a single-time-constant exponential recovery process was employed (Zwislocki *et al.*, 1967; Duifhuis, 1973; Widin and Viemeister, 1979; Nelson and Turner, 1980; Nelson and Freyman, 1987; Nelson and Pavlov, 1989). Using the modified equations for Zwicker's auditory excitation patterns that were reported by Terhardt (1979), and a subsequent exponential recovery process for the recovery from forward masking as reported by Nelson and Freyman (1984), simulated tuning curves were calculated for probe-tone levels between 20 and 45 dB SPL. The detailed equations for this two-process excitation-pattern model are given elsewhere (Nelson and Freyman, 1984).

The simulated tuning curves derived from the two-process model are shown in Fig. 6. It can be seen that the most obvious changes in the shapes of tuning curves with probe level are predicted from the two-process model, although some of the more subtle changes with probe level seen in forward-masked tuning curves are not predicted.

The flattening of low-frequency slopes with probe level, seen in actual data, is well accounted for by the model. As probe level increases, the low-frequency tuning-curve slope predicted from masker excitation patterns becomes more gradual, the result being a broadening of tuning curves at higher probe levels. Here, the changes are principally predicted by only one characteristic in the model, the level-dependent high-frequency slope of the excitation pattern. At high levels of acoustic stimulation, the high-frequency slope

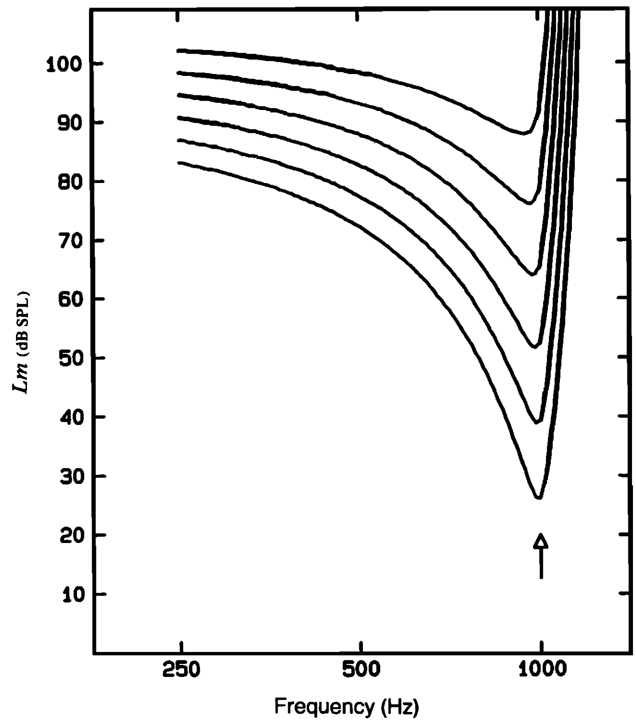

FIG. 6. Simulated forward-masked tuning curves for probe levels from 20 to 45 dB SPL in 5-dB steps. Tuning curves were calculated from the two-process auditory excitation-pattern descriptive model proposed by Nelson and Freyman (1984). The model predicts broadened tuning curves with increased probe level, primarily because of increased spread of excitation from higher level maskers.

of an excitation pattern becomes more gradual; or stated differently, as stimulus level increases, excitation above the masker frequency grows with a slope greater than unity.

In this conceptualization, broader tuning curves are due to the broader spread of excitation from the masker, not the probe. As probe level increases, higher masker levels are required to mask the probe tone, just as they are when the delay time between masker and probe is increased (Nelson and Freyman, 1984; Moore *et al.*, 1984). The excitation pattern from the higher level masker is broader; therefore, maskers on the low-frequency tail of the tuning curve are relatively more effective than they were at lower masker levels. Consequently, lower relative masker levels are required, and more gradual low-frequency tuning-curve slopes result.

There are other level-dependent changes in forward-masked tuning curves that cannot be predicted by this model without additional assumptions. For example, excitation patterns do not predict shifts in MMFs at high levels. In order to account for MMF shifts, additional mechanisms must be considered. For example, pitch shifts with intensity, as reported by listener MC in the present experiment, might account for MMF shifts (Moore, 1980b). Alternately, a shift in the peak of forward masking toward higher frequencies as stimulus level is increased could account for an MMF shift toward lower frequencies. Forward masking patterns have shown peak shifts toward higher frequencies (Zwislocki and Piroda, 1952), but the mechanisms underlying those peak shifts and how those mechanisms relate to excitation patterns are questions that remain to be answered.

The two-process excitation-pattern model can also account for narrower tuning curves in the presence of a background noise. This is largely due to changes in the masker levels required in the presence of the background noise. The background noise reduces the loudness of the probe tone. This is clear from subjective reports, but the exact mechanism is not clear. It could be due to a reduction in the fiber population differentially excited by the probe tone in the presence of the background noise, a phenomenon not unlike that postulated with off-frequency listening (Johnson-Davies and Patterson, 1979). Or the background noise might actually reduce the effective level of the probe tone through suppression. Whatever the mechanism, the important characteristic is that the probe tone is more easily masked; lower level masking tones are required to reach masked threshold when the background noise is present. Based upon the same excitation-pattern arguments presented earlier, lower level masking tones would have narrower excitation patterns, which would predict steeper low-frequency slopes, and, consequently, narrower tuning curves.

We have proposed that the changes in forward-masked tuning curves that occur with increased probe level are primarily due to the asymmetry and nonlinearity of excitation patterns for high-level masking tones. The effects of high-level probe tones on tuning-curve shapes are indirect. High-level probe tones require higher level masking tones, and it is the spread of excitation from the high-level masking tones that produces broader tuning curves. We do not suggest that all of the detailed characteristics of high-level forward-masked tuning curves are explained by an excitation-pattern model, only the most obvious characteristic changes. Changes in MMF with probe level and the exact details of the tuning curve near the tip frequency may indeed be determined by the spectral details of the short probe tone, by off-frequency listening, or by quality difference cues between masker and probe. These are discussed in more detail below.

B. Off-frequency listening

Some of the effects observed above might be explained by "off-frequency listening" concepts. Originally, the term referred to the detection of spectral splatter in a short probe tone when masked by a long masking tone (Leshowitz and Wightman, 1971). More recently, the term has been used to refer to the detection of excitation at frequencies away from the probe frequency caused by the internal spread of activity inherent in auditory excitation patterns (Johnson-Davies and Patterson, 1979; O'Loughlin and Moore, 1981a,b; see Moore and O'Loughlin, 1986, for an exceptionally thorough review). Generally, off-frequency listening is thought to sharpen tuning curves because the auditory analyzing filter can be shifted away from the probe frequency to regions where the signal-to-noise ratio is more favorable, on the opposite side of the probe frequency from the masker frequency. This shift in the auditory filter to maximize the signal-to-noise ratio results in higher masker levels at masker frequencies away from the probe frequency than near the probe frequency. Consequently, tuning curves with off-frequency listening cues are sharper than those without them, especially in forward masking (O'Loughlin and Moore, 1981a).

In the present study, tuning curves obtained in quiet broadened with probe level. When the background noise was introduced, the tuning curves became narrower, not broader as might be expected if the background noise had restricted the use of auditory filters tuned away from the probe frequency. Therefore, it does not seem likely that the broadening of tuning curves with level was due simply to larger shifts in the auditory filter with level.

However, an alternative version of off-frequency listening, along the lines of Verschuure's (1981b) excitation-pattern model, may explain some of the changes in tuning-curve tips seen at higher probe levels. At low stimulus levels, auditory excitation patterns are more or less symmetrical; as stimulus level increases, excitation patterns become asymmetrical toward higher frequencies, with more gradual slopes toward higher frequency regions and steeper slopes toward lower frequency regions (Maiwald, 1967; Zwicker, 1956, 1970, 1980; Verschuure, 1981a,b). Therefore, as probe level is increased its excitation pattern becomes more and more asymmetrical toward higher frequency regions providing more and more opportunity for off-frequency listening to occur along its high-frequency tail. For masker frequencies below the probe frequency, the asymmetric upward spread of excitation from the higher level maskers would easily swamp the cues contained in the high-frequency tail of the probe excitation pattern. A similar situation would exist for the higher level masker frequencies above the probe frequency. However, when the masker and probe frequencies are very close in frequency their excitation patterns are more nearly the same. Under these conditions, a small difference in the internal spread of excitation from the probe, relative to the masker, could result in a situation that would be favorable for the use of off-frequency cues. Such could be the case in forward-masking conditions where the probe tone is considerably shorter in duration that the masking tone, with the probe exciting a slightly broader spatial region of the auditory system. In that case, the masker would have to be raised higher, relative to the probe, to mask the cues from the high-frequency tail of the probe excitation pattern, but only for masker frequencies near the probe frequency. Consequently, tuning curves would become broader around their tips at higher probe levels. The addition of broadband background noise would essentially restrict the probe excitation to a narrow region around the probe frequency, eliminating the off-frequency cues along the high-frequency tail of its excitation pattern, thereby sharpening the tip of the tuning curve.

An additional finding of the present study also bears further discussion. The presence of the background noise had very little effect on the shapes of tuning curves at low probe levels. On the other hand using a "notched noise" as a background, and 100-Hz-wide noise bands as maskers, O'Loughlin and Moore (1981a) found that, at low probe levels, the tips of tuning curves in the notched-noise background were elevated from what they were in quiet, and masker levels remote from the tips were reduced by the background noise. This difference between the results of the two studies at low probe levels could be due to a difference in the manner of presentation and/or the type of background noise employed. O'Loughlin and Moore (1981a) gated their background noise with the masker, and they used a notched noise as a background, with a 300-Hz-wide notch centered at the probe frequency. From this, it appears that a gated notched noise represents a different manipulation of detection cues than is accomplished with a broadband background noise.

Recall that the purpose of the present study was to compare tuning curves obtained with high-level probe tones to those obtained at low levels. The broadband background noise was intended to make the high-level conditions more comparable to those that usually exist at low probe levels just above absolute threshold. The lack of a large difference with the addition of background noise at low levels, in the present experiment, suggests that the broadband background noise did simulate the types of listening restrictions imposed by absolute threshold. The results reported by O'Loughlin and Moore (1981a) indicate that a gated notched noise would not.

C. Cuing effects

Quality difference cues between masker and probe may also have contributed to the effects shown here. Moore (1980a) and Moore and Glasberg (1982) have demonstrated that the provision of a pitch cue or quality difference cue between masker and probe can affect forward-masked measures of frequency resolution. According to their arguments for the tuning-curve case, when masker and probe are very close or equal in frequency, very few cues exist to detect the addition of a probe tone to the end of the masker, except an extension of masker duration. As the masker is moved away from the probe in frequency, the resulting pitch differences between the masker and the probe make the probe tone easier to hear, which results in higher masker levels at masker frequencies remote from the probe relative to those masker levels obtained near the probe. Essentially the lack of cuing exaggerates the sharpness of the tuning-curve tip. This cuing effect is particularly strong when the fluctuating amplitude envelope of narrow-band maskers obfuscates the end of the masker (Neff, 1985), as was the case in the studies by Moore (1980a) and Moore and Glasberg (1982).

In the present experiment, which used pure-tone maskers, the excitation patterns of the short probe tones were symmetrical and limited by absolute threshold at low probe levels. Consequently, the pitches of the probe and the masker were similar when their frequencies were the same, resulting in a lack of cuing that presumably could have sharpened the tuning curve tips for low-level probe tones. As probe level increased, in the quiet background, the broader spectrum of the short probe may have ellicited a broader excitation pattern than the longer-duration masker, resulting in quality difference cues even when the masker and probe tone were at the same frequencies. This additional cuing could have resulted in higher masker levels near the tip, where at lower levels the cuing was not available. Consequently, as probe level increased, the tips of the tuning curves (in quiet) might have become less sharp. When the broadband background noise was added at a relative level that reduced the probe sensation level in noise to 10 dB, the broader excitation patterns of the higher level probe tones were partially masked, making the pitch or quality of the probe tone more similar to the masker. This would tend to reduce the quality difference cues and sharpen the tips of the tuning curves. If this were the case, then the tuning curves obtained in noise could be interpreted as having exaggerated tips. Had an additional cue been added by gating a contralateral high-frequency tone or noise with the masker, the tips may have been more rounded. However, the main finding that tuning curve shape is related to the overall levels of the maskers should not have changed under these hypothetical conditions, since the cuing effect would have rounded the tips of the tuning curves at all levels.

IV. CONCLUSIONS

Our results indicate that forward-masked psychophysical tuning curves from normal-hearing listeners are dependent upon the levels of the tones used to measure them; at higher levels forward-masked tuning curves are broader. This general conclusion is supported by data from other studies (Widin and Viemeister, 1979; Nelson, 1980a; Small and Busse, 1980; Green *et al.*, 1981; Kidd and Feth, 1981). We have also shown that the broadening that occurs with level is highly listener dependent. Most of our normal-hearing listeners (11 out of 12, including one listener from Nelson, 1980a, and four others whose data are not shown here) demonstrated broader tuning curves at higher levels, by an amount that depended upon the listener. Furthermore, our findings indicate that this broadening with level can be characterized primarily by decreased low-frequency tuning-curve slopes. In some cases shifts in the maximum masker frequency toward lower frequencies are also seen for higher level probe tones.

Comparisons of tuning curves at equivalent masker levels indicated that tuning curves with comparable tip levels ($Lm_{\rm tip}$) had similar shapes, regardless of the probe level or whether the tuning curve was obtained in quiet or in a background noise. Comparisons of tuning-curve characteristics as a function of tip level indicated that tuning curves with $Lm_{\rm tip}$ values below about 60 dB SPL have steep low-frequency slopes and are relatively invariant with level. Those with $Lm_{\rm tip}$ values above 60 dB SPL have progressively flatter lowfrequency slopes as $Lm_{\rm tip}$ increases. In normal-hearing listeners, tuning curves broaden considerably when tip levels much above 60 dB SPL are required.

These results are well described by a two-component excitation-pattern model of masking, which attributes changes in tuning curves to the increased spread of excitation with level that is a fundamental characteristic of the auditory periphery.

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