

# Psychophysical tuning curves measured in simultaneous and forward masking

Brian C. J. Moore

*Department of Experimental Psychology, University of Cambridge, Cambridge, CB2 3EB England*  
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The level of a masker necessary to mask a probe fixed in frequency and level was determined as a function of masker frequency using a two-interval forced-choice technique. Both simultaneous- and forward- masking techniques were used. Parameters investigated include the level of the probe tone and the frequency of the probe tone. The general form of the psychophysical tuning curves obtained in this way is quite similar to that of single-neurone tuning curves, when low-level probe tones are used. However, the curves obtained in forward masking generally show sharper tips and steeper slopes than those found in simultaneous masking, and they are also generally sharper than neurophysiological tuning curves. For frequencies of the masker close to that of the probe a simultaneous masker was sometimes less effective than a forward masker. The results are discussed in relation to possible lateral suppression effects in simultaneous masking, and in relation to the observer's use of pitch cues in forward masking. It is concluded that neither the simultaneous-masking curves nor the forward- masking curves are likely to give an accurate representation of human neural tuning curves.

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## INTRODUCTION

In recent years a number of workers have exploited masking techniques to derive psychophysical analogues of neurophysiological single-neurone tuning curves (Chistovich, 1957; Small, 1959; Zwicker, 1974; Vogten, 1974a, 1974b; McGee *et al.*, 1976). Neural tuning curves are derived by determining the level of the exciting tone required to produce a fixed increment in spike count (although the temporal pattern of firing may vary) from the neurone as a function of the frequency of the exciting tone. In the psychophysical analogy a signal (probe tone) of fixed frequency and a fixed level is used. If the level of the probe is sufficiently low then only a small group of neurones with characteristic frequencies (CF) close to that of the probe will be excited. The level of a masking tone required to just mask the probe is determined as a function of masker frequency. It is usually assumed that masking will occur when the masker produces a fixed amount of activity in those channels which would normally respond to the probe. Thus the curve plotting masker level as a function of frequency should be analogous to a neural tuning curve.

Most commonly, psychophysical tuning curves have been obtained for probes presented simultaneously with the masker. Unfortunately, this complicates the interpretation of the results, since the masking effect may be produced by lateral suppression of the probe by the masker, rather than (or as well as) by the masker evoking neural activity in the probe channels. There is both neurophysiological and psychophysical evidence for such suppression (Harris *et al.*, 1976; Houtgast, 1974). Since a suppressing tone can have a marked effect when it lies outside the excitatory area of a neurone, the effect of this would be to produce a psychophysical tuning curve wider than the corresponding neural curve. In addition, simultaneous masking may be complicated by the intervention of beats and combination tones (Greenwood, 1971).

Houtgast has argued that nonsimultaneous masking techniques can give a more accurate indication of the

"internal spectrum" of a stimulus, and his own work has made extensive use of such techniques, and particularly the pulsation-threshold technique (Houtgast, 1972, 1973). In a technique such as forward masking it is assumed that the threshold of a probe tone is determined by the amount of activity evoked by the preceding masker in the neural channels responding to the probe. Provided that any lateral suppression decays rapidly with time, the threshold of the probe will not be directly affected by lateral suppression, although such suppression may have played a role in determining the distribution of neural activity evoked by the masker.

Although some of the differences between simultaneous and forward masking are quite dramatic (Houtgast, 1972, 1973; Shannon, 1976), there has been some disagreement over the extent and nature of the differences between psychophysical tuning curves measured with the two techniques. Houtgast (1974, p. 20) and Vogten (1974 b) have each reported data for one subject showing steeper slopes for the forward-masking technique, particularly on the high-frequency side, but the psychophysical data obtained by McGee *et al.* (1976) for the chinchilla reveal no significant difference. Rodenburg *et al.* (1974) found similar slopes for the two masking techniques, except for masker frequencies less than 0.8 of the probe frequency. However, they used a relatively high probe level, and attributed this difference to combination tones. Wightman *et al.* (1977) found steeper slopes in forward masking, particularly on the high-frequency side of the curves, but found that the differences were reduced for listeners with hearing losses of cochlear origin. A number of other workers have determined psychophysical tuning curves in hearing-impaired listeners (Hoekstra and Ritsma, 1977; Leshowitz and Lindstrom, 1977; Zwicker and Schorn, 1977), but only using the simultaneous-masking technique.

Given the increasing interest in the psychophysical tuning curve, and its use in clinical situations, one aim of the present experiment was to provide more information about the differences between simultaneous and for-

ward masking by a detailed comparison of psychophysical tuning curves in the same subjects. Particular attention was paid to mapping the shapes of the tips of the tuning curves (which are usually presented as being sharply pointed), so as to allow detailed comparisons with neurophysiological data and with other psychophysical data giving estimates of auditory "filter shape" (Patterson, 1976).

One problem in determining psychophysical tuning curves is the choice of an appropriate probe level. If the probe level is too high then it will excite neurones with a range of CF's, and so the neural channels involved in its detection become uncertain. If the probe level is too close to absolute threshold, then variations in absolute sensitivity might influence the results. A second aim of the present experiments was to find an appropriate compromise between the two.

In pilot experiments it was found that the cues used by the observer to detect the probe in a forward-masking situation are often difficult to pick up at first. The best performance was usually achieved by starting off with the probe well above masked threshold, and gradually increasing the level of the masker. Visual feedback was also found to be useful in this respect. These features were incorporated in the method used in the main experiment.

## I. METHOD

A two-interval forced-choice task was used to determine the level of the masker giving 75% correct detections of the probe, which was fixed in frequency and in level. A "staircase" method, similar to that described in Moore (1975) was used. The step size was 5 dB until the first reversal occurred, when it was decreased to 2 dB. The masker in the first block of trials was always at a level at least 20 dB below the threshold value. In the forward-masking situation, for maskers on the high-frequency side of the probe, it was sometimes necessary to start with the masker 30 dB below the threshold level, in order to ensure that performance on the first block of trials was 100% correct. Visual feedback was provided by means of red and green lights. Each threshold value is based on at least two runs of 70–80 trials. When the means of the two runs differed by 2 dB or more, additional runs were taken, until the standard error was reduced to 2 dB or less. This was necessary most often for maskers higher in frequency than the probe, and for probes at very low levels (5 dB SL). In forward masking the variability also increased at the highest probe level (30 dB SL). In some cases up to five additional runs were used. The standard deviation of the runs for a given threshold was typically 0.8 dB for maskers with frequencies close to or below that of the probe and 2.0 dB for maskers on the steeply sloping high-frequency side of the tuning curves.

The experiment was run by a computer (PDP 12) which controlled the timing of the stimuli in conjunction with a Farnell pulse-generating system, and set the masker level via a programmable attenuator. Stimuli were presented to the left earphone of a Sennheiser HD 424 headset. The sound system was calibrated using a

Brüel & Kjær microphone (type 4134) and probe tube at the entrance to the ear canal. The system was flat within  $\pm 5$  dB from 200 to 10000 Hz, showing a broad peak around 2–3 kHz. Data presented are corrected for the response of the system. Overall distortion at the entrance to the ear canal was 0.5% at a level of 90 dB SPL. This distortion was mainly at the third harmonic, and was largely introduced by the headphone.

The maskers had steady-state durations of 300 ms and linear rise and fall times of 17 ms. The interval from the cessation of one masker to the beginning of the next was 800 ms. The probe tone had linear rise and fall times of 17 ms and a total duration of 34 ms (no steady-state portion). In the simultaneous-masking conditions the peak of the probe was coincident with the start of the fall of one or the other of the maskers. Thus the cessation of the probe coincided with the cessation of this masker. In the forward-masking conditions the probe started immediately after the cessation of one or the other of the maskers (no silent interval).

Five subjects were used, three of whom had extensive previous practice in psychoacoustic tasks. All subjects were given at least five hours of practice. All subjects had thresholds within 10 dB of the 1964 ISO standard at all frequencies used, except for subject JS, who had a loss of 20 dB at 6 kHz. Not all subjects took part in all conditions.

Probe thresholds were determined using the same forced-choice method, with observation intervals marked by lights. At each frequency the threshold was measured twice on each of the three days and the mean of the six values was used throughout as the probe threshold.

## II. RESULTS

### A. Effect of probe level in simultaneous masking

Tuning curves were mapped out for a 1-kHz probe at four sensation levels (SL): 5, 10, 20, and 30 dB. For the lowest probe level variations in absolute sensitivity from day to day proved to be a problem, causing an increase in the variability of the data. To reduce this problem the absolute threshold for the probe was measured at the start of each session and the lowest probe level was only used if the threshold for that session fell within 1 dB of the previously determined mean threshold.

Results for one subject are shown in Fig. 1. Very similar results were obtained for two other subjects. The data points fall on smooth lines (fitted by eye) except for maskers within about 20 Hz of the frequency of the probe. This is the result of the random phase relationship between the masker and probe. At these short probe durations the relative phase of the masker and probe will not vary greatly in a single trial when the frequency separation is less than about 20 Hz, but on some trials the probe will result in an increment in energy and on others a decrement. This variability in the effect of the probe makes it difficult to detect. Generating the probe in phase with the masker, when the masker frequency equals that of the probe, results in a point lying *above* the smooth curve (as opposed to below for

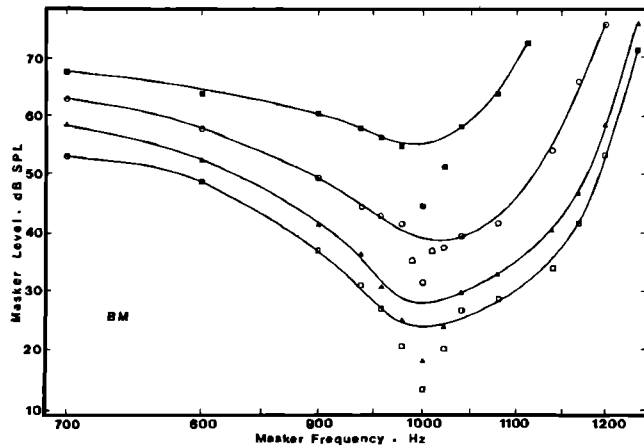


FIG. 1. Simultaneous-masking curves for subject BM. Probe frequency was 1 kHz and probe level was either 5, 10, 20, or 30 dB SL. The peak level of the probe at absolute threshold was 14 dB SPL. The curves have been drawn by eye ignoring data points for masker frequencies in the range 980–1020 Hz.

the random phase relationship). Vogten (1974a) has reported that these irregularities do not occur when the starting phase between masker and probe is set to  $90^\circ$ .

Some clear nonlinear effects are apparent in the data, particularly for the higher probe levels. For example, when the probe level is increased from 20 to 30 dB, an increase in masker level of 22 dB is necessary at 1080 Hz, while at 700 Hz only a 5-dB increase is necessary. In general the masker level grows more rapidly than the probe level on the high-frequency side, and less rapidly on the low-frequency side of the tuning curve. Similar effects have been reported by Rodenburg *et al.* (1974) and by Vogten (1974a). However, this nonlinearity is not apparent at the lowest probe levels. The tuning curve for the 10-dB probe is almost exactly parallel to

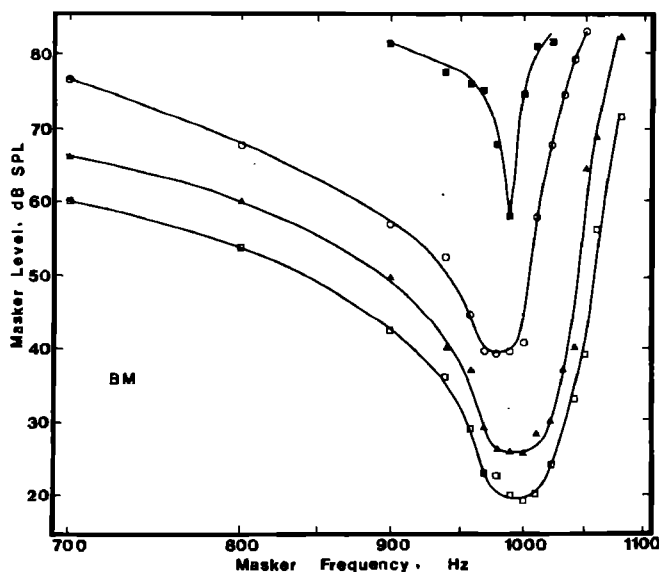


FIG. 2. Forward-masking curves for subject BM. Probe frequency was 1 kHz and probe level was either 5, 10, 20, or 30 dB SL.

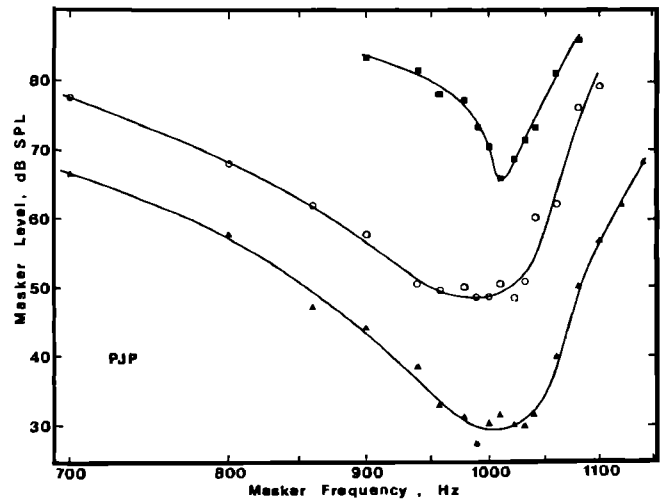


FIG. 3. Forward-masking curves for subject PJP. Probe frequency was 1 kHz and probe level was either 10, 20, or 30 dB SL. The peak level of the probe at absolute threshold was 15 dB SPL.

that for the 5-dB probe, and is separated from it by 5 dB. Whether the nonlinearity in the data results from level-dependent changes in the slopes of the "excitation patterns" evoked by the masker and probe, or from the detection of the probe in neurons with CF's different from that of the probe (or both) is not clear, but the effect does not seem to be important below a probe level of 10 dB SL. A probe level of 10 dB SL seems then to give a good compromise between avoiding nonlinear effects at high levels, and avoiding effects due to variations in absolute sensitivity at very low levels.

#### B. Effect of probe level in forward masking

Again tuning curves were mapped out at four sensation levels: 5, 10, 20, and 30 dB SL. Variations in absolute sensitivity proved to be even more of a problem for the 5-dB probe level, and only one subject was fully tested at this level. [The effect of this variability in simultaneous masking may be less marked because the probe is physically superimposed on the masker, giving a stimulus whose total energy is well above threshold; Compare the "negative masking" effect of Leshowitz and Raab (1967).] Results for this subject are shown in Fig. 2. Results for a second subject are shown in Fig. 3, for probe levels of 10, 20, and 30 dB SL (subject PJP). PJP had broader tuning curves than the other subjects at this frequency, but the form of his results is similar. Results for a third subject (JS) fell between the two sets of results shown. As probe level increases the tip of the tuning curve becomes more sharply pointed but there is no significant trend in the slopes of the curves. The masker level does not increase proportionally with the probe level at any frequency, although for subject BM the curve for the 5-dB probe is nearly parallel with the curve for the 10-dB probe. Although more data at probe levels below 10 dB would have been desirable, it seems that once again a probe level of 10 dB gives a reasonable compromise between the conflicting requirement mentioned earlier.

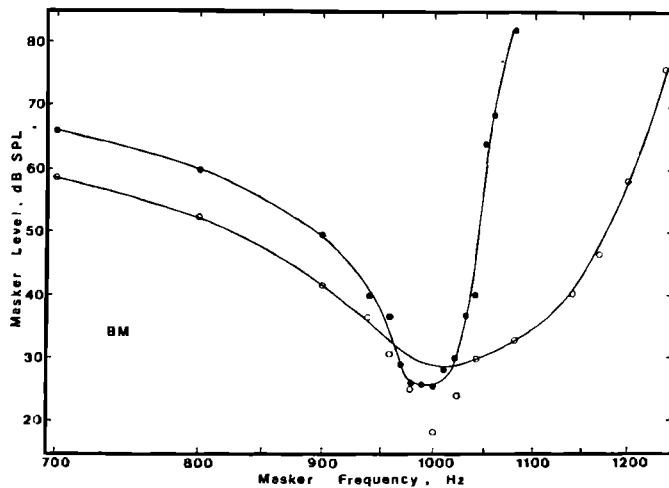


FIG. 4. Comparison of simultaneous (open circles) and forward (filled circles) masking curves for a 1-kHz probe at 10 dB SL. Subject BM.

### C. Comparison of simultaneous and forward masking at 1 kHz

Figures 4–6 compare simultaneous- and forward-masking curves for subjects BM and PJP at a probe level of 10 dB SL and for subject JS at a probe level of 20 dB SL. In each case smooth curves have been fitted to the data by eye, ignoring the data for masker frequencies within 20 Hz of 1 kHz in the case of simultaneous masking. In every case the frequency selectivity revealed in the forward-masking situation is greater than that revealed in the simultaneous-masking situation. The following measures of frequency selectivity were derived from the smooth curves drawn through the data points for probes at 10 dB SL. They are based on results from five subjects:

(a)  $Q$  10-dB values, defined as the center frequency divided by the bandwidth at the 10-dB down points, range from 3.6 to 4.9 (mean 4.1) for the simultaneous curves and from 7 to 14 (mean 11.2) for the forward-masking curves.

(b) Bandwidths at the 3-dB down points range from 110 to 150 (mean 130) Hz for the simultaneous curves and from 35 to 77 (mean 48) Hz for the forward-masking curves.

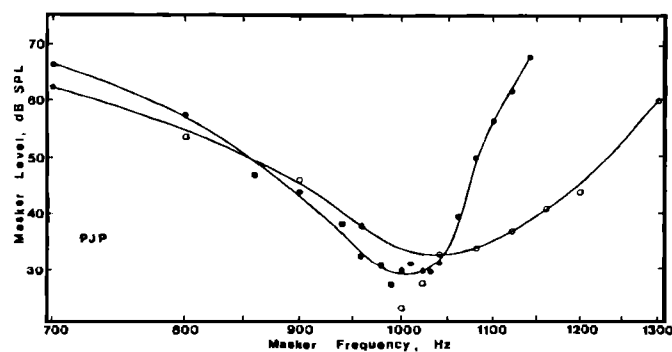


FIG. 5. As Fig. 4 but for subject PJP.

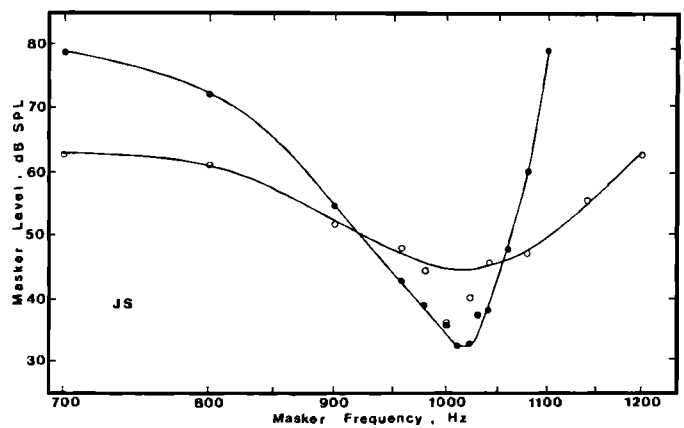


FIG. 6. As Fig. 4 but for subject JS at a probe level of 20 dB SL. The peak level of the probe at absolute threshold was 16 dB SPL.

(c) Low-frequency (LF) slopes, measured between 5 and 25 dB down from the tips of the curves, are from 34 to 72 (mean 55) dB/oct for simultaneous masking and from 90 to 180 (mean 135) dB/oct for forward masking.

(d) High-frequency (HF) slopes, measured in the same way, are from 100 to 150 (mean 130) dB/oct for simultaneous masking and from 310 to 650 (mean 390) dB/oct for forward masking.

Given the variability in the individual data points, and the fact that curves were fitted by eye to the data points, the  $Q$  10-dB values are probably accurate to within 10%, and the 3-dB bandwidths within 15%. Slopes up to 100 dB/oct are accurate to within 12%, while those above 100 dB/oct are accurate to within 15%. It should be noted that the "slopes" as measured here are not true slopes, but are derived by approximating the curves as straight-line segments (on a log-frequency scale) between the 5- and 25-dB down points. This gives measures analogous to those used by neurophysiologists. Slopes derived as tangents to the curves may be either steeper or shallower than the stated values, depending on the part of the curves chosen.

There is a tendency for the minimum in the simultaneous-masking curves to fall at a frequency slightly above 1 kHz. This is an effect which has been noted previously for low-level probes by Vogten (1974a). For the forward-masking curves the minimum is always very close to 1 kHz. It is of interest that when the masker frequency is close to that of the probe the forward masker may be more effective than the simultaneous masker, i. e., it produces masking at a lower level. This is particularly marked for subject JS. This finding, which also occurs for other probe frequencies, argues strongly against models of forward masking in which it is assumed that the forward-masking effect is produced by a monotonic decay of the excitation evoked by the masker (as proposed, for example, by Shannon, 1976). Such models would predict that simultaneous masking is always more effective than forward masking.

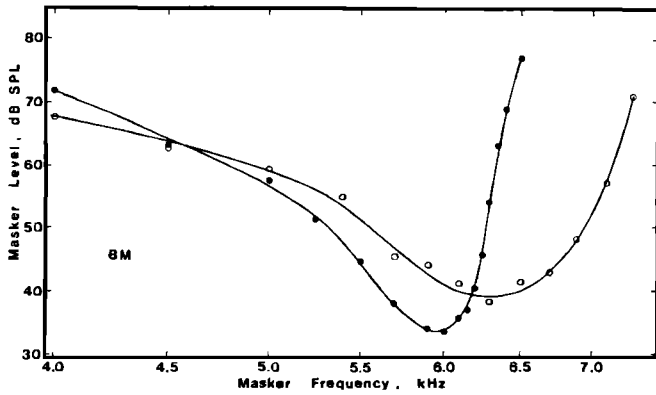


FIG. 7 Comparison of simultaneous- (open circles) and forward- (filled circles) masking curves for a 6-kHz probe at 10 dB SL. Subject BM. Peak level of the probe at absolute threshold was 22 dB SPL.

#### D. Comparison of simultaneous and forward masking at 6 kHz

Figures 7–9 compare simultaneous- and forward-masking data for three subjects at a probe level of 10 dB SL. The general pattern of the results, including the marked differences in frequency selectivity revealed in the two types of masking, is similar to that at the lower frequency. Subject JS, who had a 20-dB threshold elevation at this frequency, produced curves with very flat slopes on the low-frequency side. Her simultaneous-masking curve had the form of a “W” for masker frequencies close to 6 kHz, so that the maximally effective maskers lay slightly above and below 6 kHz. Curves having a similar form have been reported by Leshowitz and Lindstrom (1977) and Hoekstra and Ritsma (1977) for listeners with sensorineural hearing losses.

Measures of frequency selectivity, again for probes at 10 dB SL were as follows:

- (a)  $Q$  10-dB values were from 7 to 11 (mean 9) for simultaneous and from 14 to 19 (mean 16) for forward masking.
- (b) 3-dB bandwidths were from 400 to 830 (mean 670) Hz

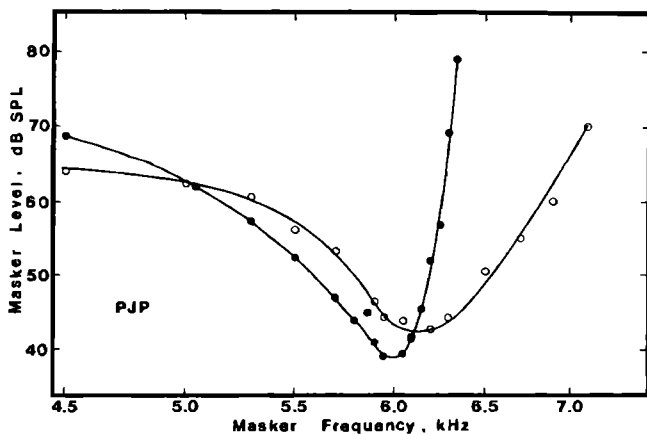


FIG. 8. As Fig. 7 but for subject PJP. Peak level of the probe at absolute threshold was 26 dB SPL.

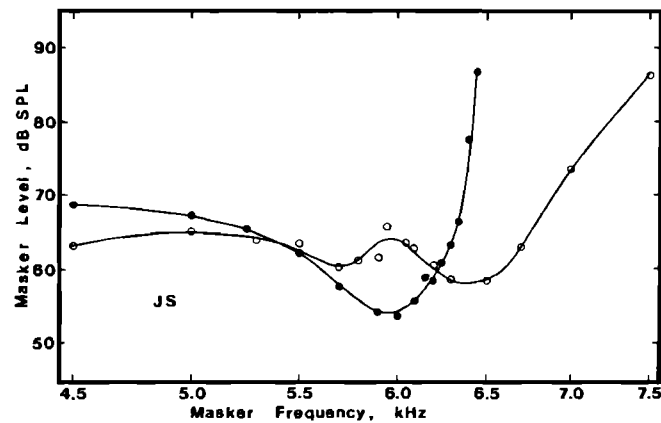


FIG. 9. As Fig. 7 but for subject JS. Peak level of the probe at absolute threshold was 40 dB SPL.

for simultaneous masking and from 230 to 380 (mean 330) Hz for forward masking.

(c) LF slopes were from effectively 0 (JS) up to 48 (median 43) dB/oct for simultaneous and from 31 to 150 (mean 90) dB/oct for forward masking.

(d) HF slopes were from 155 to 210 (mean 185) dB/oct for simultaneous and from 420 to 590 (mean 520) dB/oct for forward masking.

For all subjects the minimum in the simultaneous-masking curves lies significantly above 6 kHz. Further, there is a range of frequencies, from a few hundred hertz above the probe frequency to between 500 and 1000 Hz below it, where the forward masker is more effective than the simultaneous masker. This underlines the point made earlier that the elevation of probe threshold in forward masking is not produced by the monotonic decay of excitation evoked by the masker.

#### E. Tuning curves in forward masking as a function of probe frequency

Two subjects were tested in the forward-masking paradigm for 10-dB-SL probes at frequencies of 0.5, 1.0, 2.0, 4.0, and 8.0 kHz. Their tuning curves are shown in Figs. 10 and 11. Data points around the tips have been omitted for clarity, but the scatter of the data points is very similar to that of previous figures. Each curve was generated from 16 to 22 data points. The general form of the curves does not change greatly with frequency, but on the logarithmic frequency scale used there is a tendency for the curves to increase in sharpness up to a probe frequency of 4 kHz, with a decrease in sharpness at 8 kHz. This is shown more clearly in Table I, which gives high- and low-frequency slopes,  $Q$  10-dB values, and 3-dB bandwidths. There are clear individual differences between the two subjects, with PMP generally showing a greater frequency selectivity than SB, but these differences show up more in the slopes of the curves than in their bandwidths around the tips. At probe frequencies of 0.5, 1.0, and 8 kHz, the  $Q$  10 dB's and 3-dB bandwidths are very similar for the two subjects, although at 2.0 and 4.0 kHz PMP has

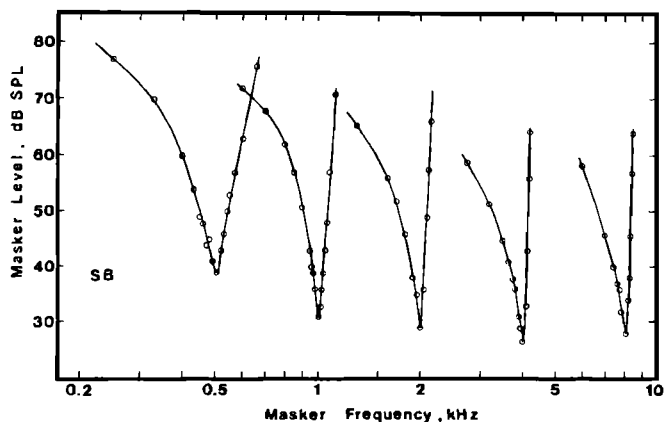


FIG. 10. Forward-masking curves for probes at 10 dB SL. Subject SB. Frequencies of the probes, with peak SPL's at absolute threshold in brackets, were 0.5 (31 dB), 1.0 (21 dB), 2.0 (19 dB), 4.0 (15 dB), and 8.0 (20 dB) kHz.

smaller bandwidths. PMP shows extremely steep HF slopes at 2.0 and 4.0 kHz, the value at the latter frequency being 2800 dB/oct. Of course, such steep slopes are difficult to measure with any degree of accuracy, and the error in this case could be as large as 40%. Also it should be noted that this steep slope is obtained only over a small portion of the curve.

### III. DISCUSSION

The results show very clear and consistent differences between simultaneous- and forward-masking curves. In general the latter show steeper slopes, particularly on the high-frequency side, and the tip bandwidths are narrower. This is consistent with the idea that in simultaneous masking the threshold of the probe may be influenced by lateral suppression. The masking tone may suppress the activity evoked by the probe without itself producing an excitatory effect in the channels responding to the probe. Thus the simultaneous-masking curve will not be analogous to the neural tuning curve, but rather will represent the boundaries of the "suppression areas."

For simultaneous masking, the frequency producing maximum masking is generally somewhat above the frequency of the probe, as has been noted previously by Vogten (1974a). This effect may be related to the asymmetry in two-tone suppression which has been observed both neurophysiologically (Sachs and Kiang, 1968) and psychophysically (Shannon, 1976). At low levels suppression is only observed from high frequencies to lower ones, and not the other way round. If the masking of the probe is partly determined by such suppression effects, this would mean that a masking tone above the frequency of the probe would be a more effective masker than a tone below this frequency, which is exactly the effect observed psychophysically. It is noteworthy that for forward masking, where lateral suppression presumably plays no role, the frequency of maximum masking is always close to the frequency of the probe. A more detailed argument relating the shift in the maximum masking frequency to two-tone suppression has been presented by Vogten (1974b).

TABLE 1. For each pair of figures, the upper one refers to subject PMP and the lower one to subject SB.

	Probe frequency (kHz)				
	0.5	1.0	2.0	4.0	8.0
High-frequency slope (dB/oct)	190	350	1820	2800	760
Low-frequency slope (dB/oct)	50	122	160	230	83
$Q_{10}$ dB	7	11	24	37	12
	6	12	13	13	11
3-dB bandwidth (Hz)	28	35	40	42	213
	33	40	53	130	250

If the peripheral filtering mechanism in the ear behaves in a linear manner, then the tuning curves derived from simultaneous masking should be very similar in form to the "auditory filters" derived by Patterson (1976) using noise maskers. In fact the 3-dB bandwidths and the shapes of the curves close to the tips are quite close to those derived by Patterson. However, for points more than 10–15 dB from the tip the tuning curves show a marked asymmetry, whereas Patterson assumed a filter which was symmetric on a linear frequency scale. Part of this asymmetry could be related to nonlinearities which result in changes in the shape of the excitation pattern evoked by the masker at high stimulus levels. It should be noted that the technique used by Patterson is mainly concerned with the measurement of the central part or tip of the auditory filter, and it is not very sensitive to asymmetries on the skirts of the filter.

If it is accepted that lateral suppression provides an explanation for at least some of the differences between the simultaneous- and forward-masking tuning curves, then the similarities described above between Patterson's "filter shapes" and our simultaneous-masking data probably indicate that lateral suppression also plays a part in the masking of tones by wide-band noise. This

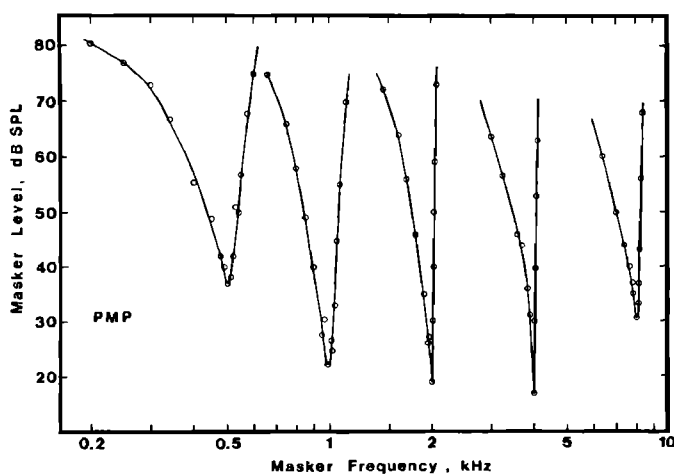


FIG. 11. As Fig. 10 but for subject PMP. Frequencies of the probe, with peak SPL's at absolute threshold in brackets, were 0.5 (24 dB), 1.0 (16 dB), 2.0 (14 dB), 4.0 (12 dB), and 8.0 (25 dB) kHz.

would be in line with the theoretical conclusions of Duifhuis and Simons (1976). Since lateral suppression is a markedly nonlinear process, it is unlikely that a simple linear filter model will give an adequate description of masking for all types of stimuli. However, this may not be too important in practice for broadband maskers.

The tuning curves obtained in forward masking generally have quite sharp tips, with bandwidths which are considerably narrower than conventional critical bandwidth estimates, and with very steep slopes, particularly on the high-frequency side. The shapes of the tips appear to be quite similar to those of neural tuning curves except that the former are more sharply pointed. The 3-dB bandwidths vary from 35% to 55% of the 10-dB bandwidths (mean about 45%), which compares with an average of 58% for auditory nerve fibers in the cat (J. P. Wilson, personal communication). If the 10-dB bandwidths are converted to distances on the basilar membrane (using frequency position coordinates supplied by D. D. Greenwood), they vary comparatively little as a function of frequency, with a mean of 0.59 mm and a standard deviation of 0.2 mm. However, this distance does seem to be somewhat larger at 500 Hz (0.92 and 0.77 for the two observers). The  $Q$  10-dB values are generally larger than those obtained in neurophysiological experiments (Evans, 1975) at the same frequencies, but if the comparison is made at corresponding points on the basilar membrane, and in terms of distances along the membrane, the discrepancy becomes considerably less. Even when expressed in this way, however, there is still a tendency for the psychophysical bandwidths to be less than those measured neurophysiologically. This could mean that neurones in man are more sharply tuned than those in the animals which have been investigated, but it seems more likely that some factor other than the selectivity of primary neurones enters into the determination of the psychophysical tuning curve. Support for this viewpoint comes from the data of Dallos *et al.* (1977) obtained from chinchillas with kanamycin-induced hair-cell losses. Such animals may show very broad, and clearly abnormal, neural tuning curves, while showing relatively normal psychophysical tuning curves in forward masking.

Let us consider some of the possible reasons for this discrepancy. It is generally assumed that forward-masking results either from a persistence of the neural activity evoked by the masker at some level in the auditory system, or from a reduced tendency to fire in recently stimulated cells, as a result of adaptation or fatigue. Since the neural activity is assumed to decay monotonically, and since recovery from fatigue or adaptation is also generally monotonic, we would expect that a forward masker would always be less effective than a simultaneous masker. Any suppression effects would increase the effectiveness of the simultaneous masker relative to the forward masker. In fact, however, for masker frequencies close to that of the probe, the reverse was sometimes true. The masker level had to be higher in the simultaneous-masking case than in the forward-masking case. Similar effects can be discerned in the data of Vogten (1974b) for one normal-hearing listener, and of Wightman *et al.* (1977) for hear-

ing-impaired listeners. Thus there is some factor which makes the detection of the probe in forward masking more difficult than would be expected from a simple decay-of-excitation or fatigue hypothesis, when the frequency of the masker is similar to that of the probe.

One problem facing the observer in a forward-masking situation is that of distinguishing the neural activity evoked by the probe from that evoked by the masker. If the probe is very close in frequency to the masker then the transition from masker to probe will not produce a shift in the position of the peak in the neural excitation pattern, or a marked change in the distribution of interspike intervals. Thus the probe can only be detected as a slight lengthening in duration of the masker or as a slight amplitude perturbation at the end of the masker. This would make it difficult to detect the probe. When the frequency of the probe differs substantially from that of the masker, then the probe will produce a pattern of neural activity which peaks in a different place from that of the masker, and which differs in its distribution of interspike intervals. These factors might provide the observer with additional cues that something "different" occurred at the cessation of the masker, i.e., that the probe was present. We may express the same idea at a more cognitive level: Pitch differences between the masker and probe may act as cues which enhance the detectability of the probe relative to the case where pitch differences are minimal or absent. The result of this would be that the tuning curve derived psychophysically would be sharper than the "true" neural tuning curve. The possibility that pitch cues play a role in forward masking has been discussed previously by Terry and Moore (1977).

A second problem in interpreting the forward-masking data derives from the assumption that a given elevation in probe threshold is produced by a fixed amount of masker-evoked activity at the probe frequency. This implies that the masking effect decays at the same rate for all conditions, independently of whether it is produced by a low-level masker close in frequency to that of a probe, or a high-level masker somewhat different in frequency from the probe. Unfortunately, the experimental evidence bearing on this question is difficult to interpret. Rodenburg (1977) has presented data showing that the shape of the tuning curve measured in forward-masking changes as the delay time between masker and probe is altered. Vogten (1974b) has shown similar effects for selected masker frequencies on the high- and low-frequency sides of the tuning curve. As delay between the masker and probe is increased, the level of the masker required to mask the probe increases more rapidly for maskers above the probe frequency than for maskers below this frequency. At first sight these data would seem to indicate that the assumption of equal decay rates is not valid. However, at longer delay times higher masker levels are necessary, and there is evidence (Verschuure, 1977) that the shape of the "excitation pattern" evoked by the masker changes with level; the low-frequency (steep) slope increases with increasing level, while the high-frequency slope decreases. In order to produce a constant effect at the probe frequen-

cy, as delay time between masker and probe is increased, a greater increase in masker level would be needed for maskers above the probe frequency than for maskers below this. Thus the effects described by Rodenburg and by Vogten could be produced entirely by nonlinear changes in the shape of the excitation pattern evoked by the masker, as the masker level is changed. If the masking effect does not decay at an equal rate for all maskers, then the most accurate representation of the "true" tuning curve would be obtained for very short delay times between masker and probe, so that decay is minimized. In the present experiment there was no silent interval between masker and probe, but the masker had a relatively long fall time (17 ms), and the total duration of the probe was 34 ms. Thus some decay of the masking effect must have occurred. This problem could be reduced by shortening the duration of the probe and the fall time of the masker, but only at the expense of increased "energy splatter" in the stimuli. This splatter might well affect the shapes of the masking curves. In addition, if the probe follows too rapidly after the masker then temporal overlap of the vibration patterns on the basilar membrane might influence the results (Duifhuis, 1973). Thus there is no easy answer to this problem.

Finally, there is one further problem in comparing these results to single-neurone tuning curves. The responses of the listener will be determined by the activity over an array of neurones, rather than by the activity in any single neurone. For low-level probes this array will be limited in extent, but it will still have a finite spread. For maskers of higher frequency than that of the probe the listener could improve the "signal-to-masker" ratio by listening to neurones with CF's slightly below the probe frequency, while for low-frequency maskers the reverse would be true. In Patterson's (1976) terms, the listener could shift his "auditory filter" so as to optimize the signal-to-masker ratio. The result of this would be to produce a psychophysical tuning curve with a sharper tip than the corresponding neurophysiological tuning curve. At very low probe levels the opportunities for such shifting are probably very small, since the observer would have to integrate information over the whole array of nerve fibers responding to the probe, in order to detect the probe at all. Thus the psychophysical tuning curve does not change shape as a function of level for very low probe levels. However, at higher probe levels such effects might well be substantial, and this could account for the very sharply pointed tips which are observed for the forward-masking curves at higher probe levels (Figs. 2 and 3). It is not clear why similar effects are not observed in simultaneous masking.

In conclusion, although tuning curves determined in simultaneous and forward masking resemble single-neurone tuning curves in shape, it seems likely that neither give a satisfactory estimate of the shape of human neural tuning curves. The simultaneous-masking curves may be determined in part by lateral suppression effects, and/or by beats and combination tones. The forward-masking curves may be influenced by the ability of the observer to use cues associated with pitch differences

between masker and probe, and by factors associated with the decay of the masking effect. Both types of curves may be influenced by the observer's integration of information over an array of neurones, and/or by shifts in the "auditory filter" so as to optimize signal-to-masker ratios. Nevertheless, these curves do seem to provide useful measures of the frequency selectivity of the auditory system, and as such they may well prove to be valuable in the clinic.

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