Low-level pure-tone masking: A comparison of “tuning curves” obtained with simultaneous and forward masking

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Simultaneous and forward pure-tone masking are compared, using a fixed-level probe of 20 ms and a 200-ms masker. For a 1-kHz probe of 30 dB SPL the required masker level \( L_m \) is measured as a function of the time interval \( \Delta t \) between masker offset and probe onset. When masker and probe have equal frequencies a monotonic relationship is found for phase \( \pi/2 \) but not for phase \( 0 \). When the masker frequency \( f_m \) is 50 or 100 Hz below the probe frequency \( f_p \) a nonmonotony is found, with a minimum at \( \Delta t = 0 \), the transition between simultaneous and forward masking. When \( f_m \) is 50 or 100 Hz above \( f_p \), however, the relationship of \( L_m \) to \( \Delta t \) is monotonic. In the case of simultaneous masking the iso-\( L_m \) curves, which give \( L_m \) as a function of \( f_m \), show a typical asymmetry around \( f_m = f_p \), leading to the positive shift of the maximum masking frequency MMF previously reported for stationary pure-tone maskers. In the case of forward masking, however, this asymmetry ceases to exist. We conclude that simultaneity of probe and masker is a necessary condition for the occurrence of a low-level positive MMF shift. The results are discussed in the light of psychoacoustical and neurophysiological data on two-tone suppression. A possible interpretation of the nonmonotony and of the positive MMF shift is suggested in terms of the physiological asymmetry in two-tone suppression.

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INTRODUCTION

In the previous paper (Vogten, 1978) we reported some new phenomena in simultaneous pure-tone masking. We found that with a stationary sine-wave masker and a tone-burst probe, phase locked to the masker, the strongest masking or probe threshold shift generally occurs when probe and masker frequency do not coincide. At low stimulus levels there is a masking asymmetry, resulting in a shift of the maximum masking frequency MMF of 5%-8% above the probe frequency. The magnitude of this "positive MMF shift" depends on the probe frequency and to some extent on the subject, and is independent of the probe duration. From the shape of the low-level asymmetry a possible connection was suggested with two-tone suppression. In the present paper this possibility is analyzed in more detail and we compare simultaneous with forward masking to provide an indication of the contribution of two-tone suppression to simultaneous masking.

Psychoacoustical experiments on nonsimultaneous masking (Houtgast, 1972, 1973, 1974; Shannon, 1976) have shown that the threshold shift of a probe presented just after the masker is decreased when a second masker of proper amplitude and frequency is added, provided the second masker coincides temporally with the first. In neurophysiology as well, two-tone suppression is a familiar phenomenon (Nomoto et al., 1964; Sachs and Kiang, 1968; Liff and Goldstein, 1970; Arthur et al., 1971). The spike rate in an auditory nerve fiber, activated by a tone at the fiber's characteristic frequency, decreases when a second tone of proper amplitude and frequency is added. Note that simultaneity of the two tones, or in the psychoacoustical experiments of the two maskers, is a necessary condition for the occurrence of the suppression effect. For nonsimultaneous tones the suppression is absent (Arthur et al., 1971; Houtgast, 1974).

Returning to our simultaneous masking it is clear that the stimulus consists in fact of two tones, viz., masker and probe. Thus it is quite possible a priori that the two-tone suppression mechanism also plays a part in the masking phenomenon. Within certain frequency intervals the stronger masker may have a direct suppressing effect on the activity in the probe channel(s), thus contributing to the masking of the probe. This suppression, however, occurs only when probe and masker overlap temporally. Thus a direct comparison between simultaneous and nonsimultaneous masking (e.g., forward masking) may indicate to what extent two-tone suppression contributes to simultaneous masking.

There exists an extensive literature on nonsimultaneous masking, partly summarized by Duifhuis (1973). Most of these experiments concern broadband stimuli or bandpass noise. Pure tones have been used by Miller (1947), Munson and Gardner (1950), Samoilova (1959), Zwischen and Fastl (1959), Ehmer and Ehmer (1969), Thornton (1972), Zwickler and Fastl (1972), Duifhuis (1973), and Fastl (1974). All these experimenters used a fixed masker level and determined the probe threshold shift as a function of either the time interval between masker and probe or the probe frequency or both. We are rather interested in the masker level, necessary for masking a fixed probe, as a function of the time interval between masker and probe. A simple deduction of this relationship from the available data for fixed maskers is not possible because (a) forward masking is a nonlinear process (Houtgast, 1974; Fig. 5.1, Fig. 7.1; Duifhuis, 1976) and (b) we are interested in low-level data which, as far as we know, have not yet been published.

Therefore, in a pilot experiment we measured the masker level \( L_m \) required to mask a 1-kHz probe of 30 dB SPL as a function of the time interval \( \Delta t \) between masker offset and probe onset. Details of the stimulus
FIG. 1. Masker and probe as used in the experiments. Probe onset was locked to a fixed phase (0 or \( \pi \)) of the masker carrier. Probe carrier started at zero phase. The stimulus was the sum of probe, presented once per second, and masker, presented twice per second.

and the method used will be presented in Sec. I, the results in Sec. II. On the basis of these results we chose the \( \Delta t \) values for the main experiment dealing with a direct comparison between simultaneous and forward masking. For \( \Delta t = -20 \) ms (simultaneous masking) and for \( \Delta t = +10 \) ms (forward masking) we determined low-level iso-\( L \) curves for three subjects; show in Sec. III the masker level \( L_m \) as a function of the masker frequency \( f_m \). Large differences were found between the results of the two kinds of masking, and in Sec. V they are discussed in relation to two-tone suppression. We arrive at the tentative conclusion that this two-tone suppression is the underlying mechanism for the low-level asymmetry in simultaneous pure-tone masking.

I. STIMULUS AND METHOD

Because of the waveform interaction between probe and masker in simultaneous masking experiments it is important to use strictly defined signals. Therefore we employed a probe, the onset of which always coincided with a fixed phase of the masker carrier irrespective of the masker frequency. The probe envelope was Hanning (\( \cos^2 \)) shaped with an effective duration of 10 ms (Fig. 1); the probe frequency \( f_p \) was fixed and its onset phase was fixed at zero. Masker offset was locked to the probe onset with a time difference of \( \Delta t \) ms, as Fig. 1 illustrates. Negative \( \Delta t \) means simultaneous masking and positive \( \Delta t \) forward masking. Masker onset and offset flanks were also Hanning (\( \cos^6 \)) shaped with a duration of 10 ms (equal to those of the probe), and the masker had an effective duration of 200 ms ± 1 carrier cycle.

Both probe and masker were presented monotonically to the subject through Sennheiser headphones HD414 in a sound-treated booth, the masker twice and the probe once per second.

A modified method of adjustment was used, the details of which have been described in Vogten (1978). In the pilot experiment the subject adjusted the masker level \( L_m \) at a given \( \Delta t \), so that the probe was just inaudible. Each data point is the average of six adjustments, obtained in two sessions on different days with three adjustments per data point per session. The standard deviation was estimated from the range divided by 2.53 (Mandel, 1967). For clarity not all the 95% confidence intervals (length 4 \( \sigma \)) are shown in the figures. The intervals selected are typical for the data.

The results are of three observers: the author, and two students who participated after a period of training, all with normal hearing.

II. PILOT EXPERIMENT: \( L_m \) AS A FUNCTION OF \( \Delta t \)

In order to make a well-founded choice of the time interval \( \Delta t \) to be used in the main experiment, we first measured the masker level \( L_m \) needed for just masking a fixed probe of 30 dB SPL as a function of the time interval \( \Delta t \) between masker offset and probe onset.

A. Results

The results for a masker frequency of 1 kHz \( (f_m = f_p) \) are plotted in Fig. 2 for phases 0 and \( \frac{\pi}{2} \).

Three regions can be distinguished.

1. A region of simultaneous masking with negative \( \Delta t \). For \( \Delta t < -20 \) ms the required \( L_m \) is constant, viz., 43 dB SPL when the phase is 0 and 32 dB SPL when the phase relation between probe and masker is \( \frac{\pi}{2} \).

2. A region of forward masking with positive \( \Delta t \). Here \( L_m \) increases monotonically with \( \Delta t \), starting from...

The first important result is that the course of the curves for masker frequencies above \( f_p \) differs qualitatively from that for maskers below \( f_p \). With 900- and 950-Hz maskers there is a dip in the region around \( \Delta t = 0 \), whereas with 1050- and 1100-Hz maskers \( L_m \) increases monotonically with \( \Delta t \).

A second finding is that in the case of forward masking the time constant at masker frequencies above \( f_p \) is much smaller than below \( f_p \). With 1050- and 1100-Hz maskers the time constant is about 40 ms and with 900- and 950-Hz maskers about 90 ms. These values differ considerably from the 70-ms time constant found at equal frequencies of masker and probe. Only in this case, when \( f_m = f_p = 1 \text{ kHz} \), is the time constant of the forward-masking process about the same as the 75 ms indicated by Duifhuis (1973; Fig. 21) in his survey of data for constant masker levels.

**B. Discussion**

1. **The \( f_m = f_p \) case (Fig. 2)**

A first noteworthy fact is that in Fig. 2, with \( f_m = f_p \), for phase zero the relation between \( L_m \) and \( \Delta t \) is nonmonotonic. In the vicinity of \( \Delta t = 0 \) it is found that \( L_m \) first decreases and then increases with \( \Delta t \). This nonmonotonic relationship stems from the fact that the subject detects the probe using the cue of a just noticeable difference in amplitude. At phase \( \frac{1}{2} \pi \) and in the case of nonsimultaneous masking the cross term in the energy increment of the stimulus is zero. Thus, starting from small positive \( \Delta t \) for phase zero a decrease of \( \Delta t \) causes the energy difference in the stimulus to increase because of the cross term coming into operation. Consequently, \( L_m \) required for masking the probe, has to increase also. For simultaneous masking we found \( L_m = 43 \text{ dB SPL} \) for a probe level \( L_p \) of 30 dB SPL; thus the just noticeable probe-to-masker amplitude ratio \( P_0 \) is 0.22. The energy difference in the stimulus is derived by Vogten (1972) as \( 10 \log(1 + 2/P_0) \). This calculated 10 dB is in good agreement with the experimental results of Fig. 2 for \( \Delta t = -20 \text{ ms} \), where the difference between phases 0 and \( \frac{1}{2} \pi \) is \( 11 \pm 2 \text{ dB} \).

2. **Masker and probe frequency differences 50 and 100 Hz (Fig. 3)**

A second noteworthy and, as far as we know, new result is that in Fig. 3, for \( f_m \neq f_p \) (phase zero), a qualitative difference can be observed between the curves for masker frequencies above \( f_p \) compared with those below \( f_p \). For \( f_m > f_p \) the course of \( L_m \) vs \( \Delta t \) is monotonic, whereas for \( f_m < f_p \) the required \( L_m \) first decreases up to \( \Delta t = 0 \) and then increases with \( \Delta t \).

It is difficult to conclude whether these results are compatible with pure-tone forward-masking data from the literature. For constant probe levels no pure-tone data are available. Reconstruction of these data from data for constant masker level is not possible because for small frequency separations between probe and masker and low probe levels we found no data at all. An interpretation of the nonmonotonic course in terms of the cross term in the energy difference of the stimulus, as suggested above for \( f_m = f_p \), meets objections. Frequency differences of 50 and 100 Hz, combined with a probe duration of 20 ms, make the magnitude of the cross term negligible. Moreover, when \( f_m \) is above \( f_p \) its magnitude is equal to that when \( f_m \) is below \( f_p \), so the cross term can never have led to the qualitative difference between \( f_m \) above and below \( f_p \), as shown in Fig. 3.

We suggest that the different course of \( L_m \) for \( f_m \) above \( f_p \) compared with that for \( f_m \) below \( f_p \) is a manifestation of the asymmetry of the two-tone suppression mechanism. When masker and probe, simultaneously presented, are at low levels, the masker may suppress the activity in the probe channel in an asymmetrical way:
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For \( f_m \) below \( f_p \), the suppression is smaller than for \( f_m \) above \( f_p \) (cf. Sache and Kiang, 1968; Arthur et al., 1971; Houtgast, 1974; Shannon, 1976). If we accept for the moment the assumption that two-tone suppression contributes to the probe threshold shift in simultaneous masking, then this contribution is also asymmetrical and we may expect some difference between the required masker level above and below \( f_p \). For \( f_m \) above \( f_p \), the suppression by the masker is more effective than below \( f_p \), and thus above \( f_p \) a lower \( L_m \) will be required to mask the probe than below \( f_p \). This is not in contradiction with the experimental results shown in Fig. 3 for \( \Delta t < -20 \) ms and may be an interpretation of the qualitatively different course of \( L_m \) above and below \( f_p \). The possible link between suppression and masking will be discussed in greater detail in Sec. V.

C. Conclusion

From the results of Figs. 2 and 3 we conclude that time intervals of \(-20\) ms for simultaneous masking and \(+10\) ms for forward masking are adequate for further experiments. At \( \Delta t = -20 \) ms \( L_m \) has its "stationary" level and from \(+10\) ms on \( L_m \) increases monotonically with \( \Delta t \) at all masker frequencies. For these two time intervals there is just no temporal overlap between flanks of masker and probe.

III. MAIN EXPERIMENT: \( L_m \) AS A FUNCTION OF \( f_m \): ISO-\( L_P \) CURVES

The two time intervals \(-20\) and \(+10\) ms were used for further investigations on a direct comparison of forward and simultaneous masking. We determined low-level iso-\( L_P \) curves, showing the masker level \( L_m \) required for masking a fixed probe, as a function of the masker frequency \( f_m \). In Fig. 4(a) some points of these iso-\( L_P \) curves are constructed from the data in Fig. 3 at \(-20\) and \(+10\) ms. More extensive curves for three subjects are plotted in Figs. 4(b) and 4(c) for a 1-kHz probe of about 30 dB SPL. The solid curves concern forward masking with \( \Delta t = +10 \) ms and the dotted curves give simultaneous masking with \( \Delta t = -20 \) ms. The results can be characterized as follows:

1. On the high-frequency side \((f_m > f_p)\) the frequency
region within which the probe is masked is much narrower for forward masking than for simultaneous masking. Flank slopes of the curves are about 560 dB/oct for forward masking and 150 dB/oct for simultaneous masking.

(2) On the low-frequency side \( f_m < f_p \) we find also a difference between the two kinds of masking. Flank slopes depend on masker frequency, and at \( f_m = 800 \) Hz they are about 20 dB/oct in the simultaneous-masking case and about 45 dB/oct in the forward-masking case.

(3) The flanks of the low-frequency side intersect at about 800 Hz, and between 0.8 and 1-kHz masking of a simultaneously presented probe requires a higher masker level than masking of a probe that is presented 10 ms after the masker. This means that for the masker frequency between 0.8 \( f_p \) and \( f_p \) forward masking is more effective than simultaneous masking.

(4) The asymmetry as found previously (Vogten, 1978) with a stationary sine wave, leading to a positive shift of the maximum masking frequency, exists also for a pulsed masker of 200-ms duration but only in the case of simultaneity of probe and masker. For subject LV [Fig. 4(b)] and JvS [Fig. 4(c), upper panel] it can be seen that the minimum of the iso-\( L_p \) curve for forward masking is symmetrically situated around \( f_p \). This means that the low-level positive MMF shift ceases to exist, if not immediately then at least 10 ms after termination of the masker. Although no detailed measurements are presented for \( f_m \) near \( f_p \) for subject HvL, his data support this general trend. The above findings are for the 1-kHz probe. At other probe frequencies they also apply. For subject LV we determined iso-\( L_p \) curves for which the probe of 0.5, 2, 4, and 8 kHz had a sensation level, without masker, of about 15 dB SL. The results are shown in Fig. 5.

Although the difference between the forward and the simultaneous masking is much smaller at the lower probe frequency of 500 Hz than at 1 kHz, here too the asymmetry occurs only in the case of simultaneous masking. Similar results were found at probe frequencies of 2, 4, and 8 kHz. At the higher probe frequencies the steep side of the iso-\( L_p \) curve changes dramatically. The slope increases from about 200 dB/oct in simultaneous masking to about 1000 dB/oct in forward masking. Again, only in the simultaneous case is there any low-level masking asymmetry. With nonsimultaneous masking we found no such asymmetry.

IV. SUMMARY OF RESULTS

The results for simultaneous and forward masking at low levels can be characterized as follows:

(1) The level \( L_m \) of a 1-kHz masker required to mask a 1-kHz probe shows a monotonic relationship with the time interval \( \Delta t \) between masker and probe for phase \( \frac{\pi}{2} \). For phase zero we found a dip in the transition region between simultaneous and forward masking, with a minimum at \( \Delta t = 0 \).

(2) Maskers with frequencies slightly different from the 1-kHz probe frequency show qualitatively different results above and below \( f_p \). Maskers of 1050 and 1100 Hz show a monotonic course of \( L_m \) as a function of \( \Delta t \).
whereas maskers of 950 and 900 Hz show a nonmonotonic course in the transition region between simultaneous and forward masking.

(3) Although detailed data were not presented around $f_m = f_f$ for all subjects, a direct comparison between the iso-$L_p$ curves for $\Delta t = -20$ ms (simultaneous masking) and $\Delta t = +10$ ms (forward masking) showed that the masking asymmetry around $f_m = f_f$ occurs only in the case of simultaneous masking. The low-level positive MMF shift, which occurs in simultaneous pure-tone masking, is not present in the case of forward masking.

(4) When the masker frequency is between about 0.8 $f_f$ and $f_f$, forward masking is up to 6 dB more effective than simultaneous masking. Outside that range simultaneous masking is much more effective, resulting in a much broader iso-$L_p$ curve compared with forward masking.

V. GENERAL DISCUSSION

In this section we first relate our experimental data to two other psychoacoustical studies. Then two possibilities are discussed in order to explain the results: the detection of combination tones and the mechanism of two-tone suppression. Two-tone suppression turns out to be the more serious candidate for the interpretation of our low-level masking results.

A. Comparison with related studies

From psychoacoustics we know of two related studies the results of which can be compared with ours.

Houtgast (1974) applied different masking paradigms to a pure-tone masker and used a 2AFC up-down procedure. In his Fig. 4.1 two iso-$L_p$ curves are presented for a 1-kHz probe of 23 dB and an effective duration of 17 ms, one for simultaneous masking ($\Delta t = -18$ ms) and one for forward masking ($\Delta t = +16$ ms).

In case of simultaneous masking his curve shows a large asymmetry with a minimum at about 100 Hz above $f_f$, in contrast with his forward-masking iso-$L_p$ curve which is symmetrical around $f_f$. There is also a significant difference between the two curves between 0.9 $f_f$ and $f_f$. In this range forward masking is up to 10 dB more effective than simultaneous masking. These data are in good agreement with our Figs. 4(a)–4(c).

Rodenburg et al. (1974; Fig. 8) compared simultaneous and forward masking, using a 20-ms probe of 1 kHz and 57 dB SPL. The results for $f_m$ above $f_f$ agree with our Fig. 4. In the range between 0.8–1 kHz masking frequency, however, they found no significant difference between simultaneous and forward masking, whereas in Houtgast's Fig. 4.1 and in our Fig. 4 the flanks of the iso-$L_p$ curves intersect at about 0.9 and 0.8 kHz, respectively. This different finding may be attributed to the facts that Rodenburg et al. (1974) used (a) a higher probe level and (b) a stimulus in which probe and masker were not completely separated in time.

B. Possible interpretation of low-level simultaneous masking asymmetry in terms of two-tone suppression

The most important result of Sec. III is the large difference between the iso-$L_p$ curves for simultaneous and forward masking. The latter being much narrower with the minimum symmetrically situated around $f_m = f_f$. In the previous paper Vogten (1978) stated that for simultaneous masking an interpretation of the low-level asymmetry in terms of the detection of combination products is inadequate for two reasons: (1) Combination products are weak or absent at low stimulus levels and grow with increasing level of the primaries and (2) measurements with a bandpass noise of 50-Hz bandwidth, the center frequency of which was situated at $2f_m - f_p$, showed that the low-level asymmetry remained, even when the combination product was masked by the bandpass noise.

In Sec. III we have seen that simultaneity is a necessary condition for the occurrence of a low-level positive MMF shift. The same is true for two-tone suppression, which is known to be highly asymmetrical in the same direction. Therefore it seems apparent that these two phenomena are related. A possible interpretation of the masking results can then be given as follows.

Suppose a particular nerve fiber is being stimulated by two tones of fixed levels $L_1$ and $L_2$. The first tone is tuned to the fiber's best frequency $f_1$; the second tone has a variable frequency $f_2$, both are of moderate levels. The activity $R$ of the fiber as a function of $f_2$ is given by the solid curve in Fig. 6(a) (cf. Sachs and Kiang, 1968). At very high $f_2$, above point (6), and at very low $f_2$, below (1), the activity is determined only by the level $L_1$ of the first tone: $R = R_1$. In general there exist two frequency ranges of $f_2$, within which the second tone causes a reduction of the fiber's response below $R_1$. One suppression interval (4)—(6) is above $f_1$ and the other interval (1)—(3) is below $f_1$. In the intermediate range (3)—(4) the activity is primarily determined by the second tone.

Now let us examine what implications this pattern of activity may have for psychoacoustical experiments. In simultaneous masking, the subject has to detect a probe of fixed frequency $f_p$ in the presence of a masker of variable frequency $f_m$. Suppose, for the sake of simplicity, that only one fiber plays a part in the detection process: the one tuned to $f_p$. The subject focuses, as it were, on that channel. Assume further that probe and masker have a moderate level so that Fig. 6(a) applies, in which $f_p$ corresponds to $f_1$ and $f_2$ to $f_3$. Then, according to Houtgast (1974), we may expect suppression effects in the probe channel if probe and masker are presented simultaneously. The frequency range within which the probe will be inaudible (masked) can now be deduced from Fig. 6(a). The activity of probe + masker is indicated by the solid lines, and the dotted curve applies to the activity of the masker alone.

Suppose that the probe is detected when probe + masker activity in the probe channel differs by more than a critical amount $\Delta$ from the masker-alone activity. When we start from point (5) and increase the masker...
frequency $f_m$ ($=f_0$), then the probe + masker activity starts to increase while the masker-alone activity decreases. So (5) indicates a frequency boundary below which the probe will be inaudible. The same applies *mutatis mutandis* to point (2). Between (2) and (5) the probe is masked for these particular levels of probe and masker.

What happens when we decrease the level of the first and second tone?

A first effect is that, when $L_0$ is low enough, the low-frequency suppression interval (1)–(3) in Fig. 6(a) disappears and only the high-frequency interval (4)–(6) remains [Fig. 6(b)]. There results an asymmetry which is typical of two-tone suppression. A second effect is that when $L_t$ is low enough the spike rate may be suppressed to the level of the spontaneous activity and thus the probe falls below the threshold of audibility. Starting from high values of $f_m$, point (5') now indicates the “upper” frequency boundary and the interval (0)–(5') will be substantially broader than the interval (3)–(0). This means that at these low levels the iso-$L_t$ curve is asymmetrical. For a particular (low) $L_m$ the frequency interval within which the probe is masked is much larger above $f_0$ than below $f_0$. This is precisely the type of the asymmetry found in our low-level simultaneous-masking experiments of Figs. 4 and 5.

In simultaneous masking we found a dip in the iso-$L_m$ curves at exactly $f_m=f_p$ [Figs. 4(a) and 4(c) and Vogten, 1978]. This dip, and the asymmetry around $f_m=f_p$, may lead to a shift of the minimum, resulting in a positive MMF shift. We shall not go into quantitative details but confine ourselves to remarking that a positive MMF shift of $5\%$–$10\%$ of $f_p$ (Vogten, 1978) seems compatible with physiological data on two-tone suppression.

**Summarizing:** When probe and masker are simultaneously present in pure-tone masking and the masker level is increased, we find (a) a decreasing ratio of the probe-to-masker activity and (b) a decrease of the probe activity itself (“suppression”). Both can contribute to the ultimate threshold shift or masking of the probe. Furthermore, when the frequencies of probe and masker are equal or almost equal the masker can cause an “extra,” phase-dependent, change in the stimulus intensity, owing to waveform interaction. The dip in masking curves, iso-$L_m$ curves, or iso-$L_p$ curves at exactly $f_m=f_p$ (Vogten, 1978) is closely related to this waveform interaction and to the amplitude criterion used by the subject at $f_m=f_p$.

**C. Simultaneous versus forward masking**

The suppression (b) is restricted to one or two ranges of the masker frequency, depending on the levels of masker and probe, and it exists only simultaneously with the masker. Qualitatively the difference between simultaneous and forward masking, found in the data of Figs. 4 and 5, can be interpreted with the help of Fig. 6. Let us assume that in the low-level forward-masking case the probe is detected when a certain just noticeable difference is exceeded between the residual effect of the masker and the activity of the probe. Then points (3) and (4) in Fig. 6(a) roughly indicate the frequencies between which the probe is inaudible. At low probe levels the range (3)–(0) is almost equal to the range (0)–(4), as Fig. 6(b) illustrates. This is in agreement with the masking results of Figs. 4 and 5. The iso-$L_m$ curve, obtained with forward masking, is (a) narrower than the one obtained by simultaneous masking, and (b) symmetrical around $f_p$, provided the stimulus level is low enough. At somewhat higher probe levels we have previously found (Vogten, 1978) that the MMF shift disappears. At higher $L_0$ this is to be expected because

(a) the suppression no longer reaches the level of spontaneous activity. The $f_1$ ($=f_m$) boundary at which the

FIG. 6. (a) Diagrammatic representation of the fiber activity $R$ under two-tone stimulation (solid curve) as a function of the second tone’s frequency $f_2$ (cf. Sachs and Kiang, 1968). The first tone (or probe) is tuned to the best frequency $CF$ of the fiber, $f_1=CF$. $R_1$ is the level of activity owing to the first tone (probe) alone. The activity owing to the second tone (masker) alone is represented by the dashed line, $R_2$ is the level of spontaneous activity of the fiber. The shaded regions refer to where the addition of the second tone (masker) causes the activity $R$ to decrease below the activity $R_1$ of the first tone alone. The critical difference between probe + masker activity and masker-alone activity is symbolized by A and determines in simultaneous masking the frequency boundaries of the masker within which the probe is inaudible. (b) As (a), but now for lower levels of first and second tone. The low-frequency suppression area is absent. In psychophysical masking experiments the probe, with frequency $f_p=f_1=CF$, will be inaudible when the masker, with frequency $f_m=f_2$, is between (3) and (5') in simultaneous masking and between (3) and (4) in forward masking.
probe becomes audible shifts down from (5') in Fig. 6(b) to point (5) in Fig. 6(a);

(b) at the low-frequency side we also have suppression of the activity in the probe channel [Fig. 6(a)];

(c) the low-frequency slope of the excitation becomes shallower with increasing stimulus level (more asymmetry of the flanks). Therefore, when the level is raised, the interval (2)–(3) in Fig. 6(a) becomes broader while (4)–(5) remains virtually unaffected.

In order to verify the interpretation given above, we need more quantitative data about two-tone suppression, both from physiology and from psychophysics. The curves in Fig. 6 would be especially interesting for a wide range of levels L and in psychoacoustics Lp.

The interpretation of the positive MMF shift in terms of the physiological asymmetry in two-tone suppression raises the question as to why the latter is so asymmetrical. In his "second-filter" model, Duifhuis (1974, 1976) suggested that the tuning disparity between the hydromechanical frequency selectivity and the second filter at hair cell level is responsible for the typical asymmetry in two-tone suppression. Thus, this tuning disparity may be the underlying mechanism of the low-level asymmetry in psychophysical simultaneous masking. This interpretation, of course, also needs further verification.

An interesting problem remains with respect to the results of Figs. 3–5. There we have found that for masker frequencies between 0.8–0.9 f<sub>0</sub> and f<sub>0</sub> forward masking is more effective than simultaneous masking. Thus, in this frequency region L<sub>m</sub> as a function of the time interval At shows a nonmonotonicity for all subjects tested and for subject LV for all probe frequencies tested.

Up to now we have no satisfactory explanation for this result. Detection of combination tones indeed would increase the required simultaneous masker level for f<sub>m</sub> < f<sub>0</sub>, thus making simultaneous masking less effective than forward masking. However, we have already argued that combination tones do not play a significant role in our low-level experiments. More experimental data for different time intervals and intensities of probe and masker are required in order to make a more extensive discussion fruitful.

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1According to Vogten (1978) the maximum masking frequency MMF is defined as that masker frequency for which the masking effect is maximum, under the assumption that probe detection is based on changes of the stimulus amplitude, not the energy increment.


