Low-level pure-tone masking : a comparison of "tuning curves" obtained with simultaneous and forward masking

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 Δt 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 Δt is monotonic. In the case of simultaneous masking the iso-L_p 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[1] 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), Zwislocki *et al.* (1959), Ehmer and Ehmer (1969), Thornton (1972), Zwicker 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 Δt between masker offset and probe onset. Details of the stimulus

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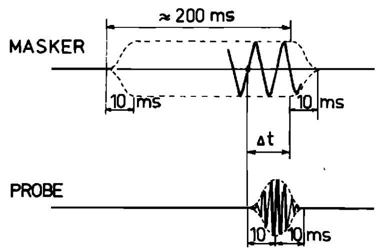

FIG. 1. Masker and probe as used in the experiments. Probe onset was locked to a fixed phase (0 or $\frac{1}{2}\pi$) of the masker carrier. Probe carrier started at zero phase. The stimulus was the sum of probe, presented once per second, and masker, presented twice per second.

and the method used will be presented in Sec. I, the results in Sec. II. On the basis of these results we chose the Δt 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_p 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 Δt ms, as Fig. 1 illustrates. Negative Δt means simultaneous masking and positive Δt forward masking. Masker onset and offset flanks were also Hanning ($\cos^2$) 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 monotically 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 Δt, so that the probe was just inaudible. In the main experiment the steep parts of the *iso*-L_p curves were determined by the adjustment of the masker frequency f_m, while for f_m near f_p the masker level L_m was adjusted at a given f_m. The threshold criterion was nothing audible with a repetition rate of 1/s. The positions of frequency and level knobs could not be recognized by the subject. The adjusted values were printed outside the booth. 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 σ) 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 Δt

In order to make a well-founded choice of the time interval Δt 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 Δt 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 $\frac{1}{2}\pi$.

Three regions can be distinguished.

(1) A region of simultaneous masking with negative Δt. 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 $\frac{1}{2}\pi$.

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

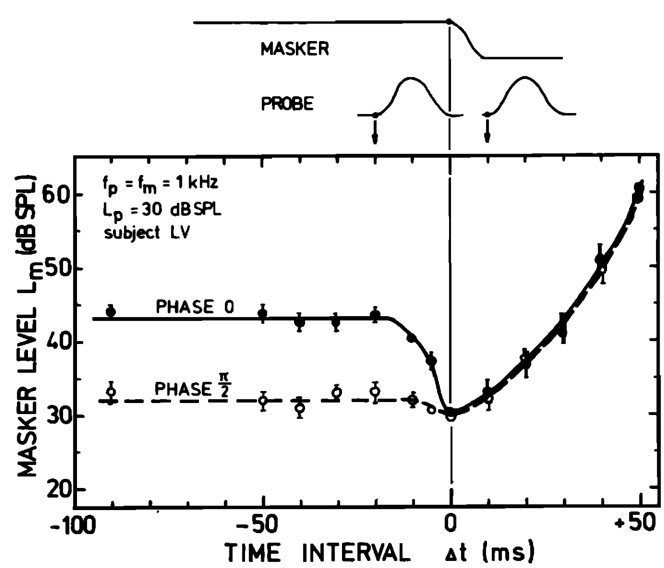

FIG. 2. The masker level L_m necessary to mask a 1-kHz probe of 30 dB SPL as a function of the time interval Δt between masker offset and probe onset, for subject LV. Masker frequency was 1 KHz. The solid curve holds for phase 0, the dotted curve for phase $\frac{1}{2}\pi$. Negative Δt means simultaneous masking and positive Δt forward masking. Vertical bars indicate the 95% confidence intervals.

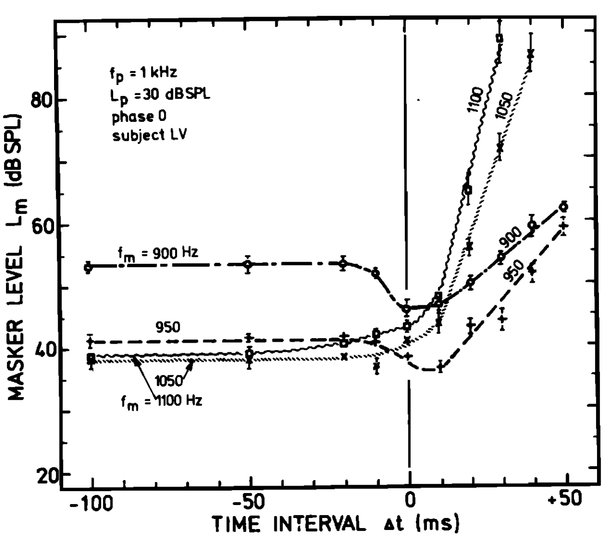

FIG. 3. As Fig. 2, but now for masker frequencies different from 1 kHz. Masker phase at probe onset was 0. Bars indicate the 95% confidence intervals. Subject LV. Note the steep slopes for maskers of 1050 and 1100 Hz for $\Delta t > 0$ (forward masking) and the nonmonotony around $\Delta t = 0$ for maskers of 900 and 950 Hz.

$L_m = 30$ dB SPL at $\Delta t = 0$. Fitted by an exponential curve the time constant is about 70 ms. Between $\Delta t = 0$ and $\Delta t = +10$ ms no detailed measurements have been carried out, but from $\Delta t = 10$ ms on, the phase no longer affects the probe threshold. For both phases the same L_m is needed for masking the probe.

(3) A region around $\Delta t = 0$, the transition region between simultaneous and forward masking. At $\Delta t = 0$ the probe is just inaudible when the masker has exactly the same amplitude as the probe. The rising flank of the probe now coincides with the falling one of the masker. In fact the stimulus consists of only one tone burst with a duration of 210 ms instead of 200 ms. The probe is not separately audible and can be detected only as a difference in duration instead of as an increment in amplitude. This difference in duration is not audible, so at $\Delta t = 0$ the subject adjusts L_m equal to L_p.

For phase 0 we determined the required L_m as a function of Δt at masker frequencies slightly different from 1 kHz and the results are plotted in Fig. 3.

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 Δt.

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 $f_m = f_p = 1$ 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 Δt is nonmonotonic. In the vicinity of $\Delta t = 0$ it is found that L_m first decreases and then increases with Δt. 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 Δt for phase zero a decrease of Δt 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 $L_m = 43$ 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 $\Delta t = -20$ ms, where the difference between phases 0 and $\frac{1}{2}\pi$ is 11 ± 2 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 Δt is monotonic, whereas for $f_m < f_p$ the required L_m first decreases up to $\Delta t = 0$ and then increases with Δt.

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:

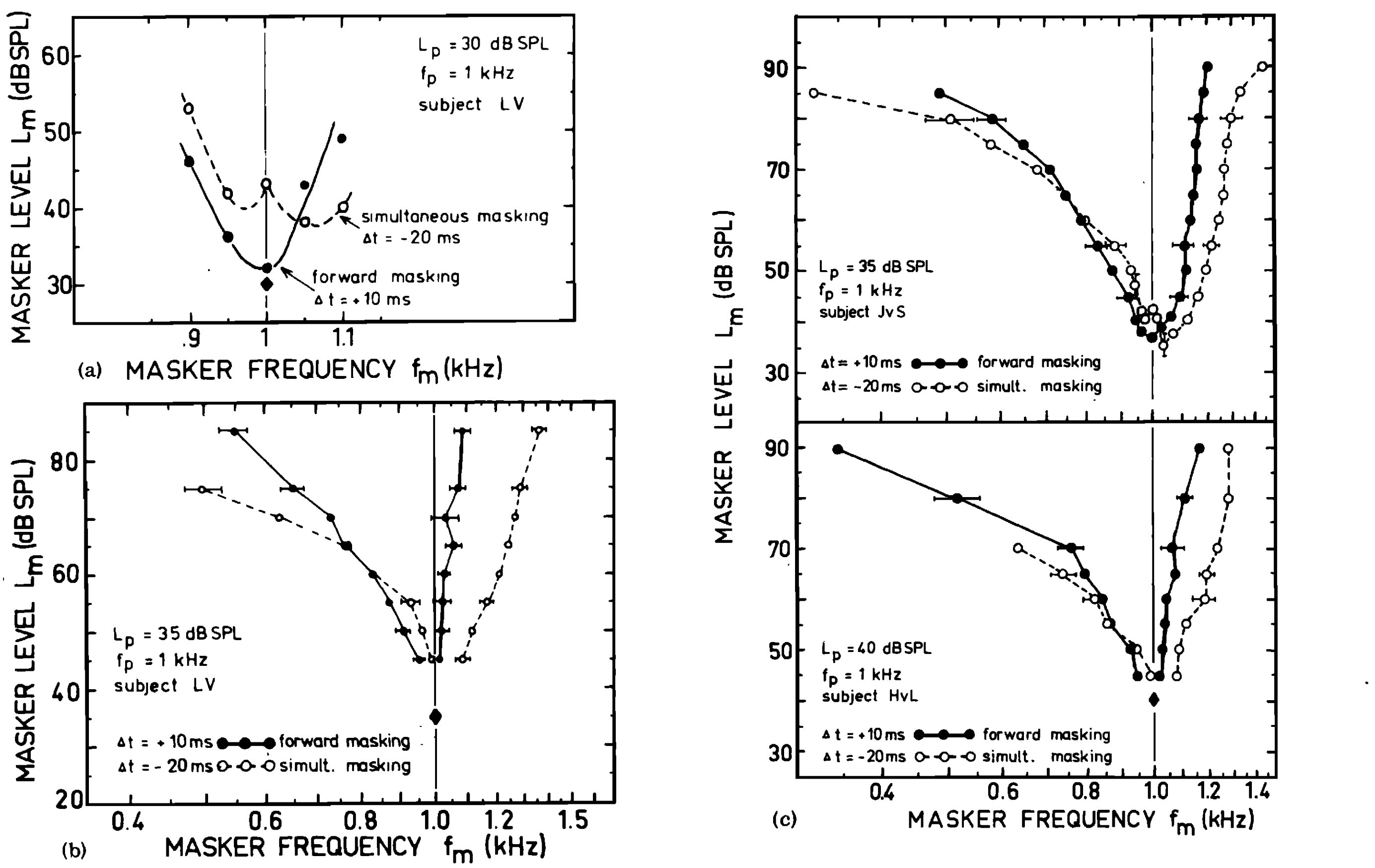

FIG. 4. (a) Parts of two *iso*-L_p curves for subject LV. The masker level L_m, required for masking a 30-dB-SPL probe of 1 kHz, is plotted as a function of the masker frequency f_m for phase 0. The data points are derived from the data of Figs. 2 and 3 at $\Delta t = +10$ ms (solid curve, forward masking) and at $\Delta t = -20$ ms (dotted curve, simultaneous masking). The diamond indicates level and frequency of the probe. The dotted line (fitted by eye) resembles the *iso*-L_p curve for a stationary sine wave masker of Fig. 4(a) in Vogten (1978). (b) *Iso*-L_p curve: the masker level at probe threshold as a function of the masker frequency for a 35-dB-SPL probe of 1 kHz. Subject LV, phase 0. Bars indicate the 95% confidence intervals. (c) As (b), but now the subjects JvS (top) and HvL (bottom). For subject JvS in the region around $f_m = 1$ kHz the masker level was adjusted at fixed masker frequencies; the remaining parts of the curves were determined by adjustment of the masker frequency at given levels.

For f_m below f_p the suppression is smaller than for f_m above f_p (cf. Sachs 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 Δt 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 SL. 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

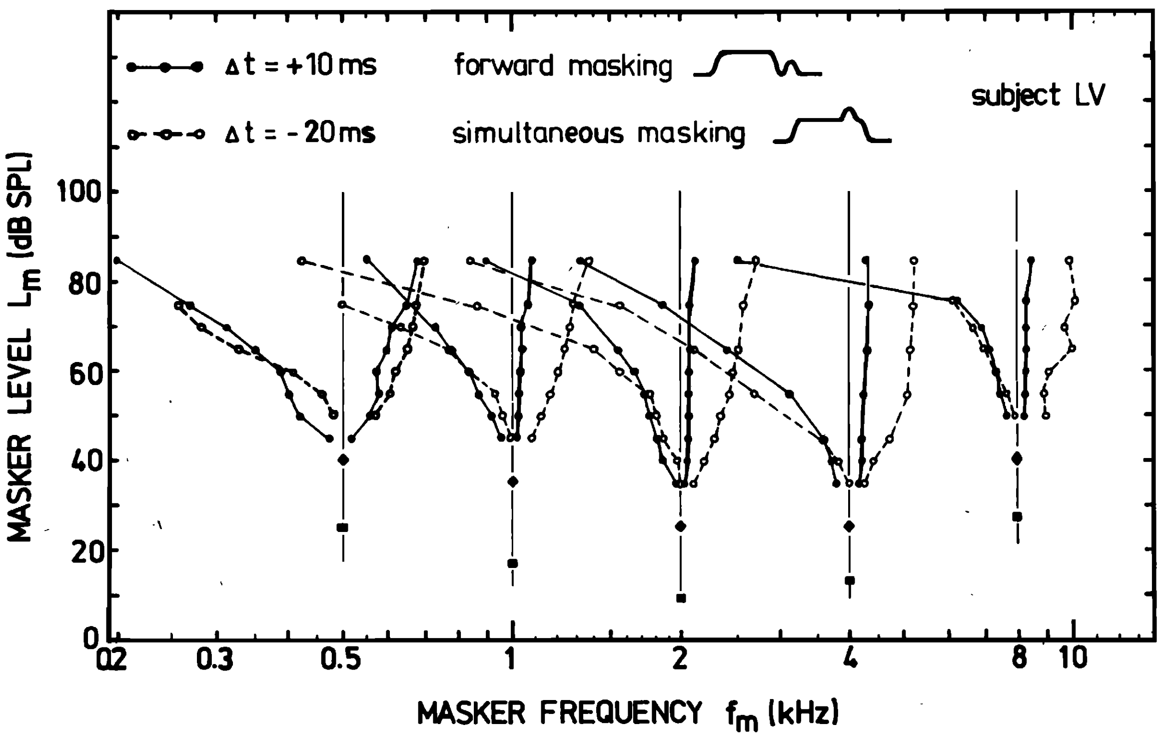

FIG. 5. *Iso-*L_p curves for several probes of about 15-dB sensation level for subject LV. Probe level and frequency are indicated by diamonds; squares indicate the probe's threshold of audibility without masker. Dotted curves: simultaneous masking with $\Delta t = -20$ ms. Solid curves: forward masking with $\Delta t = +10$ ms.

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 Δt between masker and probe for phase $\frac{1}{2}\pi$. 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 Δt,

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 $f_m = f_p$ 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 aysmmetry around $f_m = f_p$ 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 $0.8 f_p$ and f_p 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_p, in contrast with his forward-masking iso-L_p curve which is symmetrical around f_p. There is also a significant difference between the two curves between 0.9 f_p and f_p. 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_p agree with our Fig. 4. In the range between 0.8- and 1-kHz masker 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 $f_m = f_p$. 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_m to f_2. 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 Δ from the masker-alone activity. When we start from point (5) and increase the masker

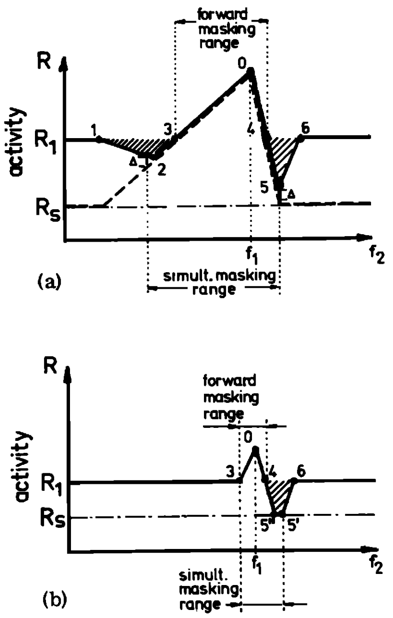

FIG. 6. (a) Diagrammatic representation of the fiber activity R under two-tone stimulation (solid curve) as a function of the second tone's frequency f_2 (cf. Sachs and Kiang, 1968). The first tone (or probe) is tuned to the best frequency CF of the fiber, $f_1=CF$. R_1 is the level of activity owing to the first tone (probe) alone. The activity owing to the second tone (masker) alone is represented by the dashed line, R_s 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 Δ 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.

frequency f_m ($=f_2$), 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_2 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_1 is low enough the spike rate may be suppressed to the spontaneous level. According to Kiang *et al.* (1965; p. 126) the spontaneous activity in primary neurones itself shows no suppression. Thus, for low levels the lower bound of the fiber activity in the remaining high-frequency suppression area is given by the spontaneous activity.

In our simultaneous-masking experiments this pattern of activity implies that for $f_m>f_p$ we have the (additional) range (5″)–(5′) where the probe activity is 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_p curve is asymmetrical. For a particular (low) L_m the frequency interval within which the probe is masked is much larger above f_p than below f_p. 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_p 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_p curves, or iso-L_m 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_p 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_p this is to be expected because

(a) the suppression no longer reaches the level of spontaneous activity. The f_2 ($=f_m$) boundary at which the 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_1 and in psychoacoustics L_p.

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 $0.8-0.9 f_p$ and f_p forward masking is more effective than simultaneous masking. Thus, in this frequency region L_m as a function of the time interval Δt 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 $f_m < f_p$, 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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[1]According 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.

Arthur, R. M., Pfeiffer, R. R., and Suga, N. (1971). "Properties of 'Two-Tone Inhibition' in Primary Auditory Neurones," J. Physiol. (London) 212, 593–609.

Duifhuis, H. (1973). "Consequences of Peripheral Frequency Selectivity for Nonsimultaneous Masking," J. Acoust. Soc. Am. 54, 1471–1488.

Duifhuis, H. (1974). "An Alternative Approach to the Second Filter," in *Facts and Models in Hearing*, edited by E. Zwicker and E. Terhardt (Springer, Berlin).

Duifhuis, H. (1976). "Cochlear Nonlinearity and Second Filter: Possible Mechanisms and Implications," J. Acoust Soc. Am. 59, 408–422.

Ehmer, R. H., and Ehmer, B. J. (1969). "Frequency Patterns of Residual Masking by Pure Tones Measured on the Békésy Audiometer", J. Acoust. Soc. Am. 46, 1445–1448.

Fastl, H. (1974). "Transient Masking Pattern of Narrow Band Maskers", in *Facts and Models in Hearing*, edited by E. Zwicker and E. Terhardt (Springer, Berlin).

Houtgast, T. (1972). "Psychophysical Evidence for Lateral Inhibition in Hearing," J. Acoust. Soc. Am. 51, 1185–1894.

Houtgast, T. (1973). "Psychophysical Experiments on 'Tuning Curves' and 'Two-Tone Suppression,'" Acoustica 29, 168–179.

Houtgast, T. (1974). "*Lateral Suppression in Hearing*," Doctoral thesis (Free University, Amsterdam) (unpublished).

Kiang, N. Y. S., Watanabe, T., Thomas, E. C., and Clarck, L. F. (1965). *Discharge Patterns of Single Fibers in the Cat's Auditory Nerve* (MIT, Cambridge, MA).

Liff, H. J., and Goldstein, M. H. (1970). "Peripheral Inhibition in Auditory Fibers in the Frog," J. Acoust. Soc. Am. 47, 1538–1547.

Mandel, J. (1967). *The Statistical Analysis of Experimental Data* (Wiley, New York).

Miller, R. L. (1947). "Masking Effect of Periodically Pulsed Tones as a Function of Time and Frequency," J. Acoust. Soc. Am. 19, 798–807.

Munson, W. A., and Gardner, M. B. (1950). "Loudness Patterns—A New Approach," J. Acoust. Soc. Am. 22, 177–190.

Nomoto, M., Suga, N., and Katsuki, N. (1964). "Discharge Patterns and Inhibition of Primary Auditory Nerve Fibers in the Monkey," J. Neurophysiol. 27, 768–787.

Rodenburg, M., Verschuure, J., and Brocaar, P. M. (1974). "Comparison of Two Masking Methods," Acustica 31, 99–106.

Sachs, M. B., and Kiang, N. Y. S. (1968). "Two-Tone Inhibition in Auditory Nerve Fibers," J. Acoust. Soc. Am. 43, 1120–1128.

Samoilova, I. K. (1959). "Masking of Short Tone Signals as a Function of the Time Interval between Masked and Masking Sounds," Biophys. USSR 4, 44–52 (English transl.).

Shannon, R. V. (1976). "Two-tone unmasking and suppression in a forward-masking situation," J. Acoust. Sco. Am. 59, 1460–1470.

Thornton, A. R. D. (1972). "PSM studies I; Post-Stimulatory Masking of Pure Tones," J. Sound Vib. 22, 169–181.

Vogten, L. L. M. (1972). "Pure-Tone Masking of a Phase locked Tone Burst," I. P. O. Ann. Progr. Rep. 7, 5–16.

Vogten, L. L. M. (1978). "Simultaneous Pure-Tone Masking; The Dependence of Masking Asymmetries on Intensity," J. Acoust. Soc. Am. 63, xxx–xxx.

Zwicker, E., and Fastl, H. (1972). "Zur Abhängigkeit der Nachverdeckung von der Störimpulsdauer," Acustica 26, 78–82.

Zwislocki, J., Pirodda, E., and Rubin, H. (1959). "On Some Poststimulatory Effects at the Threshold of Audibility," J. Acoust. Soc. Am. 31, 9–14.