Simultaneous pure-tone masking: The dependence of masking asymmetries on intensity

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Phase locking between probe and masker was used in a series of pure-tone masking experiments. The masker was a stationary sine wave of variable frequency; the probe a fixed-frequency tone burst. We have observed that for small frequency separation the masking behaves asymmetrically around the probe frequency. This asymmetry depends on intensity. For a 1-kHz probe at low stimulus levels there is a maximum masking effect at about 60 Hz above the probe frequency, whereas at high levels maximum masking is produced at a frequency definitely below the probe frequency. These results are discussed in relation to current neurophysiological and psychophysical data. For the high-level asymmetry possible interpretations are suggested in terms of two changes in the excitation pattern of the basilar membrane, (a) a shift of the top and/or (b) a slope asymmetry, both increasing with level. The low-level asymmetry will be treated in a second paper [Vogten, J. Acoust. Soc. Am. 63, 1521-1528 (1978)].

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INTRODUCTION

Wegel and Lane (1924) published the first quantitative results of auditory masking and since then studies of the masking phenomenon have substantially contributed to our insight into the peripheral frequency analysis of the auditory system.

A classical experimental difficulty in simultaneous pure-tone masking is the waveform interference between probe and masker. The occurrence of beats (Wegel and Lane, 1924; Egan and Hake, 1950; Zwicker, 1967; Greenwood, 1971) has induced experimenters either to avoid small frequency differences between the probe and masker, or to use a bandpass noise as a masker. Both situations, however, have drawbacks if one is interested in details of the masking process (cf. Bos and de Boer, 1966).

The subject of the present paper is a detailed exploration of the masking process for small frequency separations between probe and masker. Rather than the stochastic approach with noise we chose a completely deterministic stimulus. The new element in the present study is the use of a phase-locking technique. If we keep the probe starting phase constant with respect to the masker phase, uncontrolled intensity fluctuations are avoided and amplitude and energy increments are exactly known. With these strictly deterministic stimuli we studied the masking produced by a stationary sine wave upon a probe consisting of a short, but spectrally narrow, tone burst.

In the present paper we mainly concentrate on the effect of intensity upon masking for small frequency separations between probe and masker. Details of the stimulus and experimental procedure are presented in Sec. I. In Sec. II some new phenomena are reported which give rise to a distinction between results for high and low stimulus intensities. Section III considers this in relation to data from cochlear and neural physiology, resulting in a proposal for two possible interpretations of the high-level phenomena. The low-level phenomena will be treated in detail in Vogten (1978).

I. STIMULUS AND METHOD

A. Energy increment in the stimulus

The increment energy $\Delta E$ is the energy difference between stimuli with and without probe. For a rectangular probe envelope it can be written as (Vogten, 1972)

$$\Delta E = E_p + MPT \frac{2f_p}{2f_p + \Delta f} \frac{\sin \varphi T}{\pi \Delta f T} \cos (\pi \Delta f T + \varphi) ,$$

(1)

with $E_p = \frac{1}{2} P^2 T$ the probe energy, $P$ the probe amplitude, $T$ the probe duration, $M$ the masker amplitude, $f_p$ the probe frequency, $\Delta f = f_m - f_p$ with $f_m$ the masker frequency, and $\varphi$ the phase of the masker at probe onset. Expression (1) holds for an integration time of $T$ or more. In case of equal frequencies of probe and masker (1) becomes ($\Delta f = 0$):

$$\Delta E = E_p + MPT \cos \varphi .$$

(1a)

For different frequencies $\varphi = 0$ (1) becomes

$$\Delta E = E_p + MPT \frac{2f_p}{2f_p + \Delta f} \frac{\sin 2\pi \Delta f T}{2\pi \Delta f T} ;$$

(1b)

with $\varphi = \frac{1}{2} \pi$

$$\Delta E = E_p + MPT \frac{2f_p}{2f_p + \Delta f} \frac{\cos 2\pi \Delta f T - 1}{2\pi \Delta f T} .$$

(1c)

From these expressions we can learn that the energy increment is given by the sum of probe energy $E_p$ and a cross term, the latter strongly depending on phase and
Theoretical effect of phase upon the increment energy as a function of the frequency separation $\Delta f$ between probe and masker. The duration of the (rectangular) probe is 50 ms, the probe to masker amplitude ratio $P/M$ is 0.06. There is a difference between the two phase conditions for $\Delta f = (0, 10, 30, 50, \ldots)$ Hz, decreasing with increasing $\Delta f$ from 15 dB at $\Delta f = 0$ to about 5 dB when probe and masker frequency are more than 100 Hz apart.

In case of equal frequencies the cross term is zero (energy increment equal to the probe energy) when probe and masker are added in quadrature. In case of unequal frequencies the increment equals the probe energy for

$$\Delta f = \pm (1, 2, 3, 4, \ldots) (1/2T) \text{ when } \phi = 0,$$

and for

$$\Delta f = \pm (2, 4, 6, \ldots) (1/2T) \text{ when } \phi = \frac{\pi}{2}.$$

In Fig. 1 the calculated ratio of increment energy to probe energy,

$$\frac{\Delta E_p}{E_p} = 1 + 2\frac{P}{2P + \Delta f} \left[ \sin \frac{\pi \Delta f}{T} \cos \left( \frac{\pi \Delta f}{T} + \varphi \right) \right],$$

is plotted as a function of frequency separation $\Delta f$ for the two phase conditions 0 and $\frac{\pi}{2}$. The plots hold for a rectangular probe of 50-ms duration under the assumption that the just noticeable probe to masker amplitude ratio amounts to 0.06 (corresponding to a difference limen of 0.5 dB). From these calculations one predicts that if the energy increment (integration time 50 ms or more) in the stimulus is the detection cue used by the subject, there will be no masking threshold difference between the two phases at $\Delta f = \pm (20, 40, 60, \ldots)$ Hz. But at $\Delta f = \pm (0, 10, 30, 50, \ldots)$ Hz one expects a very significant difference between the two phase conditions, decreasing from 15 dB at equal frequencies to about 5 dB when $f_m$ is more than 100 Hz apart from $f_p$.

Section II compares these calculated masking threshold differences with those found in the experiments.

**B. Experimental procedure**

The stimulus used in the experiments was the sum of a periodically repeated tone-burst probe and a stationary sinusoidal masker (Fig. 2). The probe started at a fixed phase $\varphi$ of the masker, independent of both the masker frequency $f_m$ and the probe frequency $f_p$. The probe carrier always started at zero phase. Unless otherwise stated, the probe frequency $f_p$ was 1 kHz, the probe duration $T = 50$ ms, the rise/decay time $\tau$ of the probe envelope was 3 ms with smoothed edges, the repetition time $T_0$ of the probe was 500 ms + 1 masker cycle, and the masker phase $\varphi$ at probe onset was 0 or $\frac{\pi}{2}$.

We kept the probe frequency fixed and took the masker frequency $f_m$ as the independent variable. One reason for keeping $f_p$ fixed was that the masking data of a fixed-frequency probe can be compared more readily with physiological tuning curves. We use the following terminology (Fig. 3):

1. The classical results for a fixed masker frequency and masker level, in which the probe threshold is

**FIG. 3.** Diagrammatic survey of the terminology on simultaneous masking used in the present paper. Some references are given with examples of these curves from psychophysical pure-tone masking literature.
II. RESULTS

In this section we first show the details of an iso-$L_p$ curve for the two phase conditions $0$ and $\frac{\pi}{2}$, illustrating how the masking depends on phase within a 200-Hz range around the probe frequency. The outcome is compared with the predicted effect of phase upon masking and implications are discussed with respect to amplitude changes or energy increment used as the detection cue by the observer. Next we give the probe threshold as a function of masker intensity for exactly equal frequencies (Weber function) under the two phase conditions. Then a full set of iso-$L_p$ and iso-$L_m$ curves is shown for various probe and masker levels, first for a 50-ms probe of 1 kHz, then for other probe frequencies and finally for other probe durations.

A. Details of an iso-$L_p$ curve for $\varphi = 0$ and $\frac{\pi}{2}$

Figure 1 shows that the theoretical effect of phase on the increment energy in the stimulus (based on an integration time of 50-ms or more) strongly depends on frequency separation between masker and probe. If indeed the energy increment plays a role in the masking process one might expect that the phase relation should affect the masking threshold at very specific frequencies of the masker. Figure 4(a) shows the results of masking experiments. The masker level $L_m$ required to mask a 1-kHz probe of 25 dB SPL, is plotted as a function of probe level $L_p$ and masker frequency $f_m$ as a function of phase 0 or $\frac{\pi}{2}$.

The results agree with our predictions for exactly equal frequencies. The calculated difference between phase 0 and $\frac{\pi}{2}$ is 15 dB (Fig. 1), the measured difference in Fig. 4(a) is $11 \pm 3$ dB.

The first unexpected result is that for $\Delta f = \pm (10, 30, 50, \ldots) \text{Hz}$ no significant difference occurs between the two phases. Even for $\Delta f = \pm 10 \text{Hz}$, where the predicted difference amounts to 13 dB, the two phase conditions yield almost equal masking threshold! Of course, in

FIG. 4. (a) Detail of an iso-$L_p$ curve for a 1-kHz probe of 25 dB SPL for subject LV. The onset of the probe was at masker phase zero (solid curve) and phase $\frac{\pi}{2}$ (dotted curve). Note that it is only at exactly 1 kHz that the difference between the two curves is significant. The probe duration was 50 ms. Vertical bars: 95% confidence intervals. (b) The waveform envelope of a 50-ms rectangular probe added to a stationary masker for several frequency separations under the $\varphi = 0$ (upper panel) and $\varphi = \frac{\pi}{2}$ (lower panel) condition. Note that only for $\Delta f = 0$ Hz and $\varphi = \frac{\pi}{2}$ the amplitude never reaches the value $M + P$ or $M - P$. plotted with $f_m$ as independent variable, will be referred to as "masking curves."

(2) Curves for a fixed probe frequency and with $f_m$ as the independent variable will be referred to as "iso-$L_m$ curves" when the masker level $L_m$ (at probe threshold) is plotted as a function of $f_m$. For plots of the probe level $L_p$ as a function of the masker frequency we will use the term "iso-$L_m$ curves."

Because we intended to collect extensive sets of data over a limited period of time the method of adjustment was adopted, with some modifications to be described below. Although the adjustment method has been subject to some criticism, we believe that the differences obtained between threshold values for different conditions are meaningful and reliable.

During the experiments the subject was seated in a sound-insulated booth. He listened to the stimulus monotonically through Sennheiser headphones (HD 414). For determining points on the iso-$L_p$ curves the subject adjusted either the masker level $L_m$ at a given masker frequency $f_m$ or, in the steep parts of the curves, the masker frequency $f_m$ at a given $L_m$. For the iso-$L_m$ curves the subject adjusted either the probe level $L_p$ or, in the steep parts, the masker frequency $f_m$. The threshold criterion for the probe was nothing audible with a repetition rate of 2 Hz. $L_m$ and $L_p$ could be adjusted in steps of 0.5 dB and $f_m$ was continuously adjustable. Frequency and attenuator positions could not be recognized by the subject; the adjusted values were printed outside the booth.

Each data point is the average of at least six adjustments, obtained in two sessions on different days, with at least three adjustments per data point per session. The standard deviation was estimated from the range divided by 2.53 (Mandel, 1967, p. 110). For clarity not all the 95% confidence intervals (length $4\sigma$) are drawn in the figures. The intervals selected are typical for the data. The results presented in this paper are of three observers, the author and two students who participated after a period of training, all with normal hearing.
the experiments a smoothed probe has been used and thus the measured phase effect might be somewhat smaller than displayed in Fig. 1. Nevertheless it is clear from Fig. 4(a) that if the energy increment plays a role in the masking process this can only be true within an extremely narrow frequency range of, at most, 5 Hz around \( f_p \). Outside that range changes in cross-term energy of the order of 10 dB do not have any effect upon the masking threshold.

A second unexpected finding illustrated in Fig. 4(a) is that for small frequency separation between probe and masker there exists a marked masking asymmetry. At a frequency of 1030 Hz the masker is about 6 dB more effective than at 970 Hz. Between 960 and 1040 Hz the general V shape of the iso-\( L_m \) curve is interrupted and a \( \Lambda \) shape occurs for both phases. Corresponding with the asymmetry there is not only a minimum at exactly 1 kHz for phase \( \pi/2 \) but also a local minimum (for both phases) at about 1040 Hz.

B. Interim discussion: Energy or amplitude detection?

The finding that phase does not affect the masking threshold makes it very doubtful whether the energy increment acts as the detection cue used by the observer when probe and masker have only slightly different frequencies. We can understand the results of Fig. 4(a) much better in terms of amplitude changes in the stimulus.

In Fig. 4(b) the stimulus envelope has been plotted for several values of \( \Delta f \). The only case where the waveform envelope does not reach the maximum \( M + P \) or the minimum \( M - P \) is at \( \Delta f = 0 \) for \( \varphi = \pi/2 \). This is precisely the only sharp discontinuity in the masking threshold in Fig. 4(a)!. In all other cases the duration of one cycle of the difference frequency \( \Delta f \) is small enough compared to the probe duration \( T \) for the envelope change to at least once reach the maximum \( M + P \). Provided the probe detection is based on amplitude changes, the sharp discontinuity in the \( \pi/2 \) threshold at exactly 1 kHz can therefore be explained by the physical properties of the stimulus. From this point of view the \( \varphi = \pi/2 \) point at 1 kHz is a singularity and cannot simply be compared to the \( \Delta f = 0 \) data.

This reasoning is of course diametrically opposed to the assumption that the energy increment determines detection. From energy considerations only the \( \pi/2 \) case at \( \Delta f = 0 \) can properly be compared with the disparate frequency data because only for \( \varphi = \pi/2 \) the energy increments equal and the cross terms zero.

The concept of amplitude detection may also be fruitful for a possible explanation of the \( \Lambda \) peak in the iso-\( L_m \) curve in Fig. 4(a) between 960 and 1040 Hz. If amplitude detection involves an integration time ["leaky integrator" or low-pass filter (Duifhuis, 1973)] it is plausible that increasing the difference frequency \( \Delta f \) will decrease the detector output and thus decrease the masker level required to mask the probe. In Sec. IID we show data for short and for long probe durations, in which we find that the \( \Lambda \) peak is much narrower for the longer probe. These data provide a support for detection on the basis of amplitude rather than of energy increments.

The implication of the amplitude detection point of view is that the maximum masking effect does not occur at equal frequencies of probe and masker, but at the local minimum at 1040 Hz in Fig. 4(a), because the minimum for \( \varphi = \pi/2 \) at 1 kHz must be rejected. The position of the maximum masking frequency thus depends on what kind of detection cue is assumed to be involved, energy increment or amplitude changes. In the present paper we define the maximum masking frequency (MMF) as that masker frequency for which the masking effect is maximum under the condition that probe detection is based on amplitude changes in the stimulus. Because Fig. 4(a) represents only one subject, one probe level, and one probe frequency it is somewhat premature to discard the energy detection cue completely. Anyway, our definition of MMF is restricted to data in which the \( \varphi = \pi/2 \) condition at equal frequencies of probe and masker is excluded. In order to avoid confusion about terminology we will separate the equal-frequency data from the disparate-frequency data. In the next sections we will first report the experiments for \( \Delta f = 0 \) and then those for \( \Delta f \neq 0 \).

C. Weber function at 1 kHz for \( \varphi = 0 \) and \( \pi/2 \)

We have seen that an interpretation of masking results at exactly equal frequencies of probe and masker requires special caution if one wants to make comparisons with off-frequency data. For exactly equal frequencies we have determined the probe threshold as a function of the masker intensity. The dots in Fig. 5 are the results for \( \varphi = 0 \), the circles for \( \varphi = \pi/2 \).

Below \( L_m = 30 \) dB SPL the probe threshold for \( \varphi = 0 \) is lower than the absolute threshold (without masker). This "negative masking" is well known (e.g., Raab et al., 1963; Leshowitz and Raab, 1967) and occurs in those cases where probe and masker are correlated. In terms of incremental energy detection this "negative masking" can be explained by the fact that the cross

\[ \text{energy level required to mask the probe. In Sec. IID we show data for short and for long probe durations, in which we find that the \( \Lambda \) peak is much narrower for the longer probe. These data provide a support for detection on the basis of amplitude rather than of energy increments.} \]
term also contributes to probe detection. In terms of amplitude detection “negative masking” is also plausible because just below the absolute threshold an in-phase addition of the masker causes the probe to exceed the threshold of audibility. With both interpretations it is clear that the “artifact” of negative masking vanishes for phase $\frac{\pi}{2}$, and this is confirmed by the $\frac{\pi}{2}$ data in Fig. 5.

Between $L_m = 30$ and about 75 dB SPL the slope is indistinguishable from unity for the in-phase condition (solid line in Fig. 5). Within this range of $L_m$ the probe amplitude increases proportionately with the masker amplitude and Weber’s law holds. Is this in contradiction with the well-known near miss to Weber’s law data (e.g., McGill and Goldberg, 1968; Moore and Raab, 1971; Viemeister, 1972)? The answer is no, because slope bending above 75 dB SPL affects the total slope and a fit of the data by one straight line between $L_m = 30$ and 100 dB SPL results in a slope of 0.90, the dotted line in Fig. 5. But we feel that such a “comparison in decimals” is of minor relevance because we can also fit the in-phase data with two straight lines, one with slope unity and one (above $L_m = 75$ dB SPL) with a slope considerably less than unity, the solid lines in Fig. 5.

For the $\frac{\pi}{2}$ condition there is no linear relationship between probe and masker amplitude and Weber’s law does not obtain. One possible explanation for this departure from Weber’s law is the fact that in the $\frac{\pi}{2}$ condition not only the amplitude but also the phase of the stimulus changes when the probe is added to the masker. Probably these phase transients are detected and are responsible for the slope bending.

Above $L_m = 75$ dB SPL and also for $\phi = 0$ the probe amplitude is no longer proportional to the masker amplitude and there is no significant difference between the two phase conditions. The possible candidate for this high-level deviation from Weber’s law will be discussed in Sec. III. First we will present more results for unequal frequencies of probe and masker at various intensities.

D. Iso-$L_p$ and iso-$L_m$ curves at 1 kHz

In Fig. 6 we plotted a set of iso-$L_p$ curves for two subjects and several probe levels. They show the masker level $L_m$ required to mask a fixed-level probe of 1-kHz frequency and 50-ms duration.

The slope of the steeper flank is about 220 dB/oct and almost independent of stimulus level, while the shallower slope depends on intensity. These data agree with those of Small (1959) and Zwicker (1974).

The masking asymmetry in the near-frequency region, shown in Fig. 4(a) for a 25-dB-SPL probe, appears to depend on intensity. For low probe levels the minimum is at about 1060 Hz, a positive MMF shift of 60 Hz. Increasing the probe level we find that the asymmetry decreases. For $L_p = 40-50$ dB SPL masking behaves symmetrical around $f_p$. At high levels the asymmetry has been reversed: A negative MMF shift occurs.

This can also be seen in the other set of curves, the iso-$L_m$ curves plotted in Fig. 7. Here the probe thresholds are plotted as a function of the masker frequency at various masker levels, for subject LV, Fig. 7(a) and subject CS, Fig. 7(b).

In crude contours we recognize the iso-$L_m$ curves as

![FIG. 6. Iso-$L_p$ curves: the masker level $L_m$ necessary to mask a 1-kHz probe as a function of the masker frequency $f_m$ for various probe levels $L_p$. (a) Subject LV and (b) subject RD, for whom only $f_m$ adjustments were performed. The probe duration was 50 ms. The 95% confidence intervals are indicated by bars.](image)

![FIG. 7. Iso-$L_m$ curves: the probe threshold level $L_p$ of a 1-kHz probe as a function of the masker frequency $f_m$ for various masker levels $L_m$. (a) Subject LV and (b) subject CS. The probe duration was 50 ms. Bars indicate the estimated 95% confidence intervals.](image)
The probe level was chosen in such a way that the sensation level of the probe (without masker) was 10 dB.

The absolute threshold of the masker is indicated by the dotted line. We can see that peaks and positive MMF shifts occur at almost every probe frequency. Above 0.5 kHz the MMF shift is roughly proportional to the probe frequency. Intersubject differences are considerable. The curves for subject CS are much sharper and steeper than those for subject LV.

The maximum slopes are 550 dB/oct for subject CS and 320 dB/oct for LV. Whether high-level negative MMF shifts can be found for other probe frequencies has not yet been investigated. As regards the probe duration, the MMF shift found for a 50-ms probe does not depend on probe duration. Figure 9 shows that a very short (6-ms) and a very long (200-ms) probe yield almost the same MMF shift.

For both curves the probe without masker had a sensation level of 15 dB. The two amplitude spectra are also shown in Fig. 9(b). We conclude that the low-level positive MMF shift is independent of probe duration. Two other facts emerge from Fig. 9: (a) The “A peak” at 1 kHz broadens as compared to a long probe, and (b) the spectrally wider probe is accompanied by a narrower iso-Lp curve when the two probes have identical sensation levels (both 15 dB). Figure 10 shows parts of iso-L curves at various levels for subject LV for a (short) 10-ms probe.

At low intensities the MMF is again 1060 Hz, whereas at high levels a masker of 870 Hz is most effective. For this 10-ms probe the negative MMF shift at the highest probe level is somewhat more than that for a 50-ms probe [Fig. 6(a)]. This does not necessarily imply that the negative MMF shift depends on the probe duration. We have to bear in mind that at these high levels a 5-

FIG. 8. Iso-Lp curves for various probe frequencies. The lozenges indicate the respective probe frequencies and probe levels. The latter were chosen in such a way that the probe sensation levels (without masker) were 10 dB at the corresponding fp. The dotted curves indicate the absolute threshold of audibility of the masker. (a) Subject LV and (b) subject CS, for whom the 1-kHz probe had a different level of 5 dB SL (without masker).

“mirrored” conventional masking curves. The slope on the high-frequency side does not change very much with Im and is roughly 110 dB/oct. On the low-frequency side the slope decreases with increasing Im from 60 dB/oct to about 15 dB/oct at high levels. In the conventional masking curves with fixed fp similar slopes have been found by Egan and Hake (1950), Ehmer (1959), Zwicker (1967), and Greenwood (1971).

Again we observe masking asymmetries in the near-frequency region.

For extremely low levels (Im below 20 dB SPL) the negative masking effect occurs when fp equals fp. This artifact has already been considered in Sec. II B. For a masker of 35 and fp dB SPL there is an asymmetry causing a positive MMF shift of about 60 Hz for subject LV and about 40 Hz for subject CS. Increasing the masker level further, we find that the MMF shifts downwards. At intermediate levels (Im about 70 dB SPL or more) maximum masking results at a frequency significantly lower than fp and a “negative MMF shift” occurs.

E. Iso-Lp curves for other probe frequencies and durations

Above we presented the results for a 1-kHz probe that had a duration of 50 ms. We were, of course, interested in discovering whether these MMF shifts could also be found for other frequencies of the probe.

Figure 8(a) shows iso-Lp curves for subject LV and 8(b) for subjects CS, fp varying from 0.1 up to 8 kHz.

FIG. 9. (a) Iso-Lp curves for a 1-kHz probe of 6-ms duration (dotted curve) and 200-ms duration (solid curves) for subject LV. Both probes have a sensation level (without masker) of 15 dB SL. (b) The amplitude spectrum of the 6-ms probe (dotted curve) and the spectral envelope of the 200-ms probe (solid curve).
dB difference in probe level causes a substantial shift of the MMF. From the iso-$L_p$ curves shown in Fig. 11 for subject CS we conclude that here, too, the negative MMF shift is not affected by the probe duration. For a 10-ms probe [Fig. 11(a)] and a 200-ms probe [Fig. 11(b)] the MMF at 90-dB-SPL probe level is 920 Hz, i.e., the same value as found for a 50-ms probe [Fig. 7(b)].

F. Data for other subjects

We have tested more than the three subjects from which the data are presented so far. Complete iso-$L_p$ and iso-$L_m$ curves for other five subjects will not be shown because they behaved almost the same. Only one observer showed no significant low-level positive MMF shift at 1 kHz. But for a 2-kHz probe he did. For the eight subjects the MMF at low probe levels is shown in Table I.

G. Summary of results

(1) Masking experiments with a 25-dB-SPL probe phase locked to a pure-tone masker, have shown that for near-equal frequencies, changes in the cross-term energy of the order of 10 dB do not have any effect upon the probe threshold.

(2) For exactly equal frequencies the probe threshold amplitude increases linearly with the masker amplitude only for $\varphi = 0$ within the intensity range between 30 and 80 dB SPL of the masker. Outside that range and also for $\varphi = \pi$, a nonlinear relation is found.

(3) Only at intermediate levels does the masking behave symmetrically around the probe frequency. In general there exists a marked masking asymmetry for small frequency separations between probe and masker.

(4) We defined the maximum masking frequency (MMF) as that masker frequency for which the masking effect is maximum under the assumption that probe detection is based on amplitude changes and not on energy increments in the stimulus.

At high stimulus levels the MMF is positioned significantly below the probe frequency. The magnitude of this negative MMF shift depends on stimulus level.

![FIG. 10. Parts of iso-$L_p$ curves for a 1-kHz probe of 10-ms duration. Subject LV. Bars indicate the 95% confidence intervals.](image1)

![FIG. 11. Iso-$L_m$ curves for a 1-kHz probe of (a) 10-ms duration and (b) 200-ms duration, for subject CS.](image2)

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**TABLE I. Maximum masking frequencies for several subjects.**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Probe frequency $f_p$ (Hz)</th>
<th>Probe level $L_p$ (dB SPL)</th>
<th>MMF (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>1000</td>
<td>20</td>
<td>1040</td>
</tr>
<tr>
<td>RD</td>
<td>1000</td>
<td>30</td>
<td>1060</td>
</tr>
<tr>
<td>LV</td>
<td>1000</td>
<td>15</td>
<td>1080</td>
</tr>
<tr>
<td>ML</td>
<td>1000</td>
<td>30</td>
<td>1080</td>
</tr>
<tr>
<td>HvL</td>
<td>1000</td>
<td>35</td>
<td>1080</td>
</tr>
<tr>
<td>HD</td>
<td>2000</td>
<td>30</td>
<td>2110</td>
</tr>
<tr>
<td>BLC</td>
<td>1000</td>
<td>25</td>
<td>1070</td>
</tr>
<tr>
<td>JvS</td>
<td>1000</td>
<td>35</td>
<td>1060</td>
</tr>
</tbody>
</table>

At low levels the MMF is above the probe frequency. For a 1-kHz, 50-ms probe of 20 dB SPL this positive MMF shift is about 60 Hz. Its magnitude depends to some extent on the subject. Both the positive and the negative MMF shift are independent of probe duration over a range between 10 and 200 ms at least.

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**III. DISCUSSION**

In this section we discuss the intensity dependence of the masking asymmetries (MMF shifts) as found in our experiments. First we make reference to some other psychoacoustical studies in which similar asymmetries can be discerned, followed by a brief reference to related data from cochlear and neural physiology. Then we discuss a possible relation between the high-level asymmetry and off-frequency listening, combination tones and two-tone suppression, all of which are well-known confounding problems inherent in the simultaneous-masking paradigm. The outcome of this discussion results in a suggestion for an interpretation of the high-level masking asymmetries in terms of changes with intensity of the excitation pattern on the basilar membrane.
A. Related studies

In the psychoacoustical literature it is often taken for granted that a pure-tone masker is most effective when its frequency is equal to that of the probe. But there are results which indicate that this is not generally valid. In recent simultaneous masking results an asymmetry leading to a low-level positive MMF shift is clearly present.

Houtgast (1974, Fig. 4.1) applied different masking paradigms (simultaneous-masking, forward-masking, and pulsation-threshold paradigms) to a pure-tone masker and a 1-kHz probe of 23 dB with an effective duration of 17-ms. Iso-\( L_a \) curves were determined with a two AFC up-down procedure. In the simultaneous-masking case the minimum of the curves occurred about 100 Hz above the probe frequency, a clear example of a positive MMF shift of 100 Hz.

A second example has been found in data of Zwicker (1974, Fig. 4). He determined iso-\( L_a \) curves with an automatic Beckesy tracking procedure at several levels and frequencies of a 600-ms duration. Although there were differences between individual observers a positive MMF shift of about 200 Hz can be discerned for a probe of 2 kHz.

A level dependence of the maximum masking frequency has also been reported by Zwillocki et al. (1968, Figs. 9 and 11) in experiments with contralateral ("central") masking. They found that, when the level of the masker on one ear increased, the frequency at which masking of the 200-ms probe on the other ear was maximum increased with intensity. For a 70-dB masker this shift is about 150 Hz, corresponding with our high-level negative MMF shift.

Using a forward-masking paradigm with a silent interval of about 30 ms, Munson and Gardner (1950, Fig. 8) found that the maximum masking of a 100-dB masker at 1 kHz was at a probe frequency of 1.5 kHz. This means a high-level negative MMF shift of about 500-Hz. Ehmer and Ehmer (1969) also found a shift of the MMF at high levels. They used a forward-masking paradigm in which a 100-ms masker preceded a 5-ms probe with a silent interval of 10 ms. The latter results, however, cannot easily be interpreted because of the very short (0.5 ms) rise and decay time of the probe.

Zwillocki et al. (1968) suggested that this high-level shift has the same underlying process as the pitch shifts reported in Steven's (1935) classical paper, later taken further by Walliser (1969), Terhardt (1974), and Verschueren and van Meeteren (1975). At 1 kHz, however, MMF shifts up to 15% are an order of magnitude greater than the observed pitch shifts, which do not exceed 2%.

Data from cochlear and neural physiology also display a high-level shift with intensity. We are thinking, for example, of the intensity dependence of the displacement pattern on the basilar membrane (BM), found by Rhode (1971) in the squirrel monkey. Using the M\( \text{ö} \)ssenbauer technique he found the maximum of the vibration to change, corresponding to a small shift towards the stapes with increasing stimulus intensity. Data on cochlear microphonics from Honrubia and Ward (1968, Figs. 5 and 6) and from Dallos (1973, Fig. 4; 1974, Fig. 5) show a shift of the same type; its direction corresponds to that of our negative MMF shift. The most effective frequency decreases for higher levels and the tuning broadens.

Another example of a high-level negative shift can be discerned in the "masking pattern" of the whole nerve action potential measured by Spoor and Eggermont (1971, Fig. 2). When the intensity of the masker increases, the probe frequency at which the masker is most effective increases. This corresponds to our negative MMF shift also.

B. Possible influence of off-frequency listening, combination tones, and two-tone suppression on our masking results

If a simultaneous-masking paradigm is used, one must realize that the results can be complicated by the possibility of off-frequency listening, combination-tone detection, and two-tone suppression. Thus before giving any interpretation of the data these issues are dealt with, point by point, in the next sections.

1. Off-frequency listening

Leshowitz and Wightman (1971) have demonstrated that masking results can be determined by details of the probe spectrum considerably remote from the probe frequency. Two unusual phenomena occurred in those cases where the probe was rectangularly shaped: (a) large deviations from Weber's law and (b) departure from the law of temporal integration. These phenomena were explained by the assumption that the observer's auditory filter was located at frequencies removed from the probe frequency, in order to maximize the output ("off-frequency listening"). On the other hand, the phenomena ceased to exist when the spectral difference between probe and masker was reduced by a proper filtering of the rectangular probe.

In our high-level masking experiments, the spectral width of the probe becomes considerable. If the observer's filter has the correct slope asymmetry, off-frequency listening may be possible, resulting in a high-level negative MMF shift. Examples of such a shift can be found in Ehmer and Ehmer (1969) and for forward masking in Shannon (1976).

We have indeed found a deviation from Weber's law for high masker levels. However, slope bending in the Weber function is no proof of off-frequency listening. On the contrary, we have three arguments against such a mechanism producing the high-level MMF shift.

First, for \( L_m \) of 75–80 dB SPL, where the Weber function just starts to deviate from the straight line with unity slope (Fig. 5, \( \varphi = 0 \)), the MMF shift amounts already to 50–80 Hz in Fig. 7.

Second, we note the presence of temporal integration. Comparing the threshold of a 10-ms probe with that of a 200-ms probe (Fig. 11) we observe a threshold difference of about 11 dB for a 80-dB-SPL masker. For a
90-dB-SPL masker this difference amounts to about 7 dB. Thus, although not perfect, a temporal integration is clearly present, true also for high levels.

Third, the MMF is independent of probe duration. Leshowitz and Wightman (1971) have demonstrated that narrowing the probe spectrum (e.g., by bandpass filtering) obstructs the off-frequency listening. Thus, if in our case off-frequency listening were involved, one should expect different MMF shifts for different probe spectra. In Fig. 11 we have used a 10-ms probe and a 200-ms probe, the latter with a much narrower spectrum than the first [see, e.g., Fig. 9(b)]. From these results it appears that the negative MMF shift is completely independent of the spectral shape of the probe. This finding makes off-frequency detection based on energy splatter highly questionable.

Thus the implications of off-frequency listening, no temporal integration, and a strong deviation of Weber's law are not satisfied in the present masking data. Though we cannot prove that off-frequency listening is not involved it cannot provide an adequate explanation for the present high-level negative MMF shifts.

2. Combination tones

The role of combination tones in simultaneous masking experiments is extensively treated by Greenwood (1971). He has demonstrated that the detection of combination products, such as $2f_1 - f_2$, rather than the probe can explain the characteristic notches in the masking curves which occur when $f_1/f_2$ is about 10.8. In our data notches are observed for subject CS, in Fig. 7(b) and in Fig. 11, for masker levels of 70 dB SPL and higher. These results are not at variance with Greenwood's data, where notches become significant at sensation levels of 50 dB. For subject LV, however, notches are only evident for a 90-dB-SPL masker level [Fig. 7(a)], which is rather unusual. Probably this can be explained by the fact that the generation of combination products is subject dependent or that observer LV has used a different detection criterion.

A seemingly significant finding in Fig. 11 is that the notches at $f_1 = 0.8$ kHz for a 200-ms probe are more distinct than for a 10-ms probe, indicating that "long" combination tones affect the masking threshold more than "short" ones. This finding could imply that the nonlinearity which generates the combination products is time dependent. Based on the present data such a conclusion is, we feel, rather premature because active listening in order to hear the combination product also might take some time. Clearly a more detailed study is required.

The main question with respect to combination tones is whether they can be responsible for the high-level masking asymmetry. There are two reasons for supposing this not to be the case.

First, near the probe frequency, say $f_1$, between $f_2$ and $0.9 f_2$, the significance of combination-tone detection is questionable. Greenwood (1971, Fig. 9–11) has shown that addition of low-pass noise in order to obstruct the detection of combination tones can eliminate the notches completely. However, this can be done without any effect of the noise upon the masking thresholds near the top. This would imply that in the frequency region where the negative MMF shift occurs the detection of combination tones is not significant.

But the second and we feel crucial argument is that any combination tone detection can only reduce the amount of masking for $f_1 < f_2$, never enhance it. Thus, if we assume the "original" iso-$I_0$ curve to be symmetrical, a reduction of the probe threshold caused by a detection of combination tones can only lead to a positive MMF shift, never to the negative MMF shift which has been found in our masking experiments.

3. Two-tone suppression

The third complicating factor in simultaneous masking is the mechanism of two-tone suppression. Houtgast (1974) and Shannon (1976) have demonstrated that the masking effect of a tone $M$ upon a probe $P$ can be reduced by the addition of a second tone $M_2$ provided that $M_2$ is simultaneously present with $M$ and $P$ is not. In general this suppression is asymmetrical. The maximum suppression occurs when the frequency of $M_2$ is about 1.2 times that of $M$ (and $P$). However, at high intensities the asymmetry vanishes (Houtgast, 1974, Fig. 5.3) or has a tendency to reverse (Shannon, 1976, Fig. 6). Houtgast interpreted the two-tone suppression as a reduction of the effectiveness in the frequency region of the first tone by a certain factor. In simultaneous masking experiments this would imply a reduction of the activity in the probe channels by the masker. Thus suppression by the masker can contribute to the masking of the probe, and it seems reasonable to assume that the ultimate threshold shift depicted in our iso-$I_0$ curves is, in some frequency ranges, at least partly composed of two-tone suppression.

The question now is whether two-tone suppression can account for the high-level masking asymmetries. Based on Houtgast's and Shannon's data, which show no suppression when the frequency of $M_2$ is between about 0.8 $f_2$ and $f_2$, one might question the contribution of suppression in that frequency range. Suppression, however, is an inherently nonlinear mechanism, strongly dependent on intensity. Duifhuis (1977, Fig. 7) provided psycho-physical data where the lower frequency suppression area, which was determined with a pulsation threshold paradigm, shows an upward spread for increasing probe levels. This means that the significance of suppression in the frequency range between 0.8 $f_2$ and $f_2$ increases with stimulus intensity. Thus a contribution in that frequency range, where we have observed the high-level MMF shifts, seems possible. Duifhuis' data, of course, are no proof that the high-level asymmetry is caused by two-tone suppression. Duifhuis (1977) related his own results and the corresponding neurophysiological results of Sachs and Abbas (1974) to a basalward shift of the basilar membrane excitation pattern (Geisler et al., 1974).

Presently we cannot give a clear answer to the question whether the high-level masking asymmetries can be interpreted in terms of two-tone suppression. We feel...
that both mechanisms are mutually dependent and related to cochlear nonlinearities, that is, to changes of the excitation pattern of the basilar membrane. In the next section we discuss this point in more detail.

C. Possible interpretations of the high-level masking asymmetry

In the previous section we have argued that there are arguments against an interpretation of the high-level masking asymmetry in terms of off-frequency listening and combination tones, while the possible relation with two-tone suppression is still unclear. Let us now consider two other possible reasons why the MMF should be positioned below the probe frequency.

A first and most obvious possibility seems to be that at higher levels the distribution of the vibration pattern along the basilar membrane (BM) changes in such a (nonlinear) way that the top shifts towards the stapes (cf. Munson and Gardner, 1950).

Let us assume that the top of the BM excitation shifts with intensity, say, 30–50 Hz per 10-dB level increment, this shift coming into operation at 50–70 dB SPL. We will assume further that in simultaneous pure-tone masking, maximum masking occurs when the peaks of probe and masker excitation on the BM coincide. Then, because of the nonlinear relation between the probe and masker amplitudes, we may expect a negative MMF shift, increasing with intensity, provided that the probe excitation is not affected by that of the masker. At maximum masking the ratio between probe and masker amplitude increases from 20 dB at \( L_m = 50 \) dB SPL to 30 dB at \( L_m = 90 \) dB SPL, as can be calculated from Fig. 7(a).

Thus a shift of the probe excitation towards the base, with 30–50 Hz per 10-dB level increment, falls behind that of the masker, resulting, for a 1-kHz probe, in a negative MMF shift of 60–150 Hz at high levels. Assuming a basalward shift of the excitation, a slope bending of the Weber function, as demonstrated in Fig. 5, can also be expected, without the necessity of supposing off-frequency listening.

This does not mean that a peak shift of the BM excitation is the only possible interpretation of the high-level pure-tone masking asymmetry. A saturation-type nonlinearity, without the involvement of a BM-peak shift, might possibly lead to the same psychophysical results. Furthermore, it is very questionable whether we can entertain the assumption that one "point" of the BM-excitation pattern is representative of the MMF.

A second possible interpretation might be given in terms of the increasing slope asymmetry of the excitation pattern. Let us assume that the probe threshold is determined by the amplitude ratio of probe + masker excitation \((P+M)\) to masker-alone excitation \((M)\). Let us assume, further, that detection of the probe involves a certain finite bandwidth, \( W \), and the \( P+M \) to \( M \) ratio is integrated over this bandwidth. The MMF is then determined by the masker frequency at which the integrated \( P+M \) to \( M \) ratio is minimum.

By way of an example we calculated the MMF shift for a 1-kHz probe. Let us take an excitation pattern simply represented by straight lines on a linear frequency scale and with slopes of \( \frac{1}{10} \) and \( \frac{1}{100} \) dB/Hz. Then the ratio \((P/M+1)\), integrated over a bandwidth \( W \) of 160 Hz, is minimum when the masker frequency is 55 Hz below that of the probe. The magnitude of this calculated negative MMF shift mainly depends on the bandwidth \( W \) and the slope asymmetry of the excitation. Quantitatively, negative MMF shifts of up to 200 Hz are possible.

Both interpretations presented above are in quantitative agreement with the masking results found at high levels for a 1-kHz probe.

Accordingly, high-level negative MMF shifts may be interpreted in terms of a peak shift and/or the increasing asymmetry of the cochlear vibration pattern with stimulus level.

D. Possible interpretations of the low-level masking asymmetry

The first possible cause for the positive MMF shift that can be seriously considered is the fact that simultaneous pure-tone masking the detection of the probe might be disturbed by the detection of combination products of the probe and masker. If the masker frequency is below that of the probe, the presence of the combination product \( 2f_m - f_p \) would require a higher level of the masker than when this frequency relation is reversed and this combination product is absent. In the iso-\( L_p \) curve this would cause an asymmetry leading to a positive MMF shift. In our case, however, we do not believe this to hold because of the following:

1) It was at low levels (20–30 dB SPL) that we found the most prominent MMF shift, and it decreased with increasing level. Combination products, on the contrary, are weak or absent at these levels and grow with increasing level of the primaries.

2) We carried out measurements with a bandpass noise of 50-Hz bandwidth, centered at the frequency of the combination product \( 2f_m - f_p \). The results showed that the low-level asymmetry remained, even when the combination product, possibly contributing to the detection of the probe, was masked completely by the bandpass noise. So the low-level positive MMF shift cannot be interpreted in terms of the detection of combination products.

A second possible cause of the positive MMF shift might be the asymmetry of two-tone suppression. This is a much more promising line of investigation, and in a second paper (Vogten, 1978) we shall elaborate the time and frequency effects of the low-level pure-tone masking and see whether the positive MMF shift can be interpreted in terms of two-tone suppression.

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