# Forward masking as a function of frequency, masker level, and signal delay

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The forward masking of a sinusoidal signal by a sinusoid of the same frequency was investigated for frequencies ranging from 125 to 4000 Hz. Forward masking in dB is proportional to both masker level and log signal delay at each frequency. More forward masking occurs at very low frequencies than at high frequencies, given equal-sensation-level maskers, and masked thresholds are greater at low frequencies than at high frequencies given equal-SPL maskers. The data can be described equally well by assuming that the difference in forward masking as a function of frequency is due to a change in the time course of recovery from masking or to a change in the growth of masking at each signal delay. The frequency effect is not large enough to change the interpretation of forward-masking data in studies of suppression or psychophysical tuning curves.

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## INTRODUCTION

The amount of forward masking is determined by the interaction of a number of factors including masker level, the temporal separation of masker and signal, masker and signal frequency, and masker and signal duration. The details of these interactions are poorly understood because there are so many factors that they cannot all be varied in a single experiment. Most studies have reported data for several values of one or two factors, with all of the remaining factors held constant. The specific values of the remaining factors may have a strong influence on the results, but that influence cannot be determined from the data in any given experiment. Differences in stimuli, test procedures, and listeners make comparisons across studies difficult.

In the present study and in subsequent studies in this series, we explore the relations among factors that govern forward masking, with emphasis on the range of values for each factor where the greatest change in amount of masking occurs. Our goal is to describe the interaction of several factors to a first approximation rather than to map the effect of any one in great detail. Because we are particularly interested in the use of forward masking in measures of frequency analysis, we have obtained data for sinusoidal stimuli rather than noise bursts and clicks. This facilitates comparisons with recent physiological data concerning forward masking (Harris and Dallos, 1979; Smith, 1977, 1979; Smith and Zwislocki, 1975). In the present study, we are primarily concerned with the time course of forward masking when both the masker and signal are the same frequency, and this frequency is varied from 125 to 4000 Hz. Because quiet thresholds for the signal and masker vary significantly over this frequency range, it is important to distinguish at the outset between intensities expressed in terms of sound pressure level (SPL) such as masked thresholds or equal-SPL maskers, and those that are referenced to quiet thresholds, such as amounts of masking or equal-sensation level (SL) maskers. For reasons discussed below, we prefer the latter approach and will summarize results whenever possible in terms of amount of masking for equal-SL maskers.

A number of studies have reported forward-masking data obtained at different frequencies (Bronstein and Churilova, 1936; Ehmer and Ehmer, 1969; Elliott, 1962; Harris and Rawnsley, 1953; Harris *et al.*, 1951; Luscher and Zwislocki, 1949; Rawdon-Smith, 1934, 1936; Rawnsley and Harris, 1952). The majority of these studies have concluded that there is greater forward masking at higher frequencies (2000 to 8000 Hz), particularly at relatively long signal delays. A strong frequency effect could add to or cancel differences in suppression (e.g., Shannon, 1976) or other aspects of masking (e.g., Moore, 1978) as a function of frequency. If the amount of forward masking does vary as a function of test frequency, it is important to know whether the effect is due to a change in the slope of forward masking as a function of frequency or a change in the time required to recover from a given amount of masking. To understand the possibilities, we must know more about forward masking as a function of these two major factors.

In studies using sinusoidal maskers and signals, masker level has been varied by Ehmer and Ehmer (1969), Fastl (1979), Gardner (1947), Harris and Rawnsley (1953), Harris *et al.* (1951), Munson and Gardner (1950), Rawnsley and Harris (1952), Widen and Viemeister (1979), and Zwislocki *et al.* (1959). In almost all cases, the data describing amount of masking in dB as a function of masker level are well fitted by straight lines, with slopes less than the value of about 0.9 typically obtained in studies of simultaneous tonal masking or intensity discrimination (e.g., Jesteadt *et al.*, 1977; McGill and Goldberg, 1968). These linear functions intersect the abscissa at a masker level several dB above the quiet threshold for the masker, although when low-SL maskers are used (Widin and Viemeister, 1979), the masking function appears to curve toward the origin just as it does in simultaneous masking (e.g., Hawkins and Stevens, 1950).

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The interval separating masker and signal has been varied by Fastl (1979), Rawnsley and Harris (1952), Widin and Viemeister (1979), and Zwislocki *et al.* (1959). All four studies reported that the amount of masking decreased linearly in log time. Similar functions have been reported in studies using broader bandwidth maskers or signals (Fastl, 1976, 1977; Smiarowski and Carhart, 1975; Weber and Moore, 1981) and in related studies of temporal decay measured in terms of gap detection (Penner, 1977; Plomp, 1964). Plomp's (1964) summary of the data is of particular interest because he concludes that forward-masking and gap-detection data should have the same time course, and that functions describing this time course for maskers of different levels should all have a common x-axis intercept. The data from Smiarowski and Carhart (1975), Penner (1977), and Widin and Viemeister (1979) are in general agreement with this summary, which reduces the number of parameters required to describe forward masking as a function of signal delay and masker level.

Duifhuis (1973) has argued that two temporal processes are reflected in forward-masking data, one with a short time constant (< 10 ms) determined by the mechanics of the basilar membrane and one with a longer time constant (~75 ms) determined by short-term neural adaptation (Smith, 1977; Smith and Zwislocki, 1975). Because the shorter of the two temporal processes is difficult to measure with sinusoidal maskers and signals that cannot be switched on and off abruptly, we have concentrated our efforts on measuring the longer temporal process, and have used signal delays in the range from 4 to 40 ms. We will see below that for signal delays within this range, the pattern of results is actually simpler than that described by Plomp (1964) in that just three parameters are required to describe all of the data at any given frequency. One must know all of these parameters, however, in order to compare results for different frequencies.

## I. METHOD

### A. Subjects

A different group of four adults served as paid listeners in each of the three experiments to be described. All had thresholds within normal limits over the frequency range from 125 to 4000 Hz.

### B. Apparatus and signal generation

The signal tone was generated digitally in all experiments and the intensity was controlled by a Charybdis programmable attenuator. The output of the attenuator was combined with the masker in an active op-amp mixer and the mixer output was fed to a Crown D-60 amplifier used to drive a TDH-39 headphone mounted in an MX-41/AR cushion. Separate programmable attenuators, mixers, and Crown amplifier channels allowed us to test four listeners simultaneously. The masker in experiment 1 was produced by a Tektronix (FG-501) function generator and gated in random phase by a Grason Stadler (Model 1287 B) electronic switch which produced 10-ms linear ramps. In experiments 2 and 3, the masker was generated by a second D-A converter. Digitally generated waveforms were produced using 10-bit D-A converters available as part of an AR-11 interface module in the PDP-11/34 computer and low-pass filtered at half the sampling rate. A 20-kHz sampling rate was used in experiments 1 and 3 and a 5-kHz rate was used in experiment 2 (where the only frequency required was 125 Hz). A cosine-squared function (Hanning window) was used for all digitally generated ramps. Subjects were tested in separate sections of a double-walled IAC sound-treated room that had single walls between sections.

### C. Conditions

In all conditions, we measured the threshold for detection of a brief sinusoidal signal following the presentation of a sinusoidal masker of the same frequency. The masker-signal frequency, masker intensity, and signal delay were varied parametrically. We also measured quiet thresholds for both the signal and the masker in each experiment. All durations, including signal delays, were measured from the 0-voltage points of the onset and offset ramps.

In experiment 1, the frequencies tested initially were 250, 1000, and 4000 Hz. When preliminary analyses indicated a difference between 250 Hz and the higher frequencies, an additional lower frequency, 125 Hz, was added to the experiment. The masker was 300 ms and the signal 20 ms, with 10-ms ramps in both cases except at 125 Hz, where it was necessary to use a 24-ms signal with 12-ms ramps in order to present an integral number of cycles. The masker intensities were 60, 70, 80, and 90 dB SPL at 125 Hz; 40, 60, and 80 dB SPL at 250 Hz; and 20, 40, 60, and 80 dB SPL at 1000 and 4000 Hz. The signal delays were 5, 10, 20, and 40 ms.

In experiment 2, all testing was at 125 Hz. The masker was 296 ms and the signal 24 ms, with 12-ms ramps in both cases. The masker intensities were again 60, 70, 80, and 90 dB SPL. The signal delays were 4, 8, 16, 32, 64, 128, 256, and 512 ms. Thresholds were obtained for signals both in phase and 180° out of phase with the masker, where phase is defined as the phase relation that would exist if the masker were extended in time so that it overlapped with the signal.

In experiment 3, 125, 250, 500, and 1000 Hz were tested initially, and 4000 Hz was added at the end of the experiment when it was clear that there was sufficient time available. The masker was 296 ms and the signal 24 ms, with 12-ms ramps in both cases. The masker intensities were the same as those in experiment 1, with the exception of 250 Hz and the additional test frequency, 500 Hz, where the intensities were 50, 60, 70, and 80 dB SPL. The signal delays were 4, 8, 16, and 32 ms. The signal was always in phase with the masker.

### D. Procedure

All thresholds were obtained using a two-interval forced-choice adaptive procedure (Levitt, 1971) with a decision rule that estimated the signal intensity required for 70.7% correct performance.

A trial consisted of a 200-ms warning interval, two observation intervals separated by 400 ms, and an answer interval terminated by the listeners' responses. Each interval was marked by a separate light on the listener's response box. Correct-answer feedback was presented immediately after each listener's response and remained on until 400 ms after the last listener responded. In quiet-threshold trials where the signal and observation interval were brief, the intersignal interval was lengthened from 400 to 600 ms.

Each condition was replicated two to four times. In each replication, two threshold determinations were obtained in 50-trial blocks separated by an interval of approximately 30 sec. In rare cases where the threshold estimates from the two 50-trial blocks differed by more than 8 dB, the data were discarded and two additional 50-trial blocks were obtained for that listener. In experiments 1 and 3, all conditions of masker level and signal delay were tested in random order for a given frequency. Frequencies were tested in succession from low to high, then high to low, with the exceptions of 125 Hz in experiment 1 and 4000 Hz in experiment 3, where all replications were completed in consecutive sessions.

Shaw (1966) has demonstrated that the actual level of a low-frequency tone at the tympanic membrane varies widely from one listener to the next and from one earphone placement to the next when standard calibration procedures are used. The differences in level, which can be as much as 15 dB, are due to differences in the degree of leakage around the earphone cushion. To control this source of variability, Knowles Electret microphones were placed on the inner edge of the earphone cushions, and the microphone outputs were amplified and brought back to the equipment rack where they were read with a Hewlett-Packard 3581A wave analyzer and set to standard levels after each earphone placement (see Domnitz, 1975, for a description of this system). This acoustic-calibration procedure was used in obtaining the data at 125 Hz in experiments 1 and 2 and in obtaining all data except those at 4000 Hz in experiment 3.

## II. RESULTS

### A. Forward masking as a function of masker level and signal delay

We will begin by describing the general pattern of results as a function of masker level and signal delay using data from experiment 1 as an example. We will then consider effects of frequency in experiment 1.

We were particularly interested in estimating the amount of masking and the masked threshold for both constant-SPL and constant-SL maskers and in separating the effects of changes in growth of masking as a function of masker level from the effects of changes in the time course of the recovery process. We began by plotting the data for experiment 1 as a function of log signal delay, with masker level as the parameter, and as a function of masker level with signal delay as the parameter. Plots of this kind for means across listeners are shown in Fig. 1. The data are well fit by straight lines in both coordinate systems, a result consistent with almost all previous studies that have varied masker level, signal delay, or both.

The straight lines in the left half of Fig. 1 indicate that the separation between the functions in the right half must be proportional, within an additive constant, to log signal delay. Likewise, the straight lines in the right half indicate that the separation between the functions in the left half of Fig. 1 must be proportional to masker level, above some base level. All of the functions in the left half of Fig. 1 must therefore intersect their respective x axes at a common point, in agreement with the model proposed by Plomp (1964). Furthermore, all of the functions in the right half must also intersect their x axes at a common point.

A straightforward description of the data is provided by the equation

$$M = \mathrm{a}(\mathrm{b} - \log \Delta t)(L_m - c)\,, \qquad (1)$$

where $M$ is the amount of masking, $\Delta t$ is signal delay in ms, $L_m$ is the masker level in dB SL, and a, b, and c are parameters whose values are established by fitting the equation to the data. The parameter a is related to the slope of the time course of masking for a given masker level in Fig. 1 and the slope of the masking function for a given signal delay. The parameter b is the log of the signal-delay intercept of the functions in Fig. 1. The parameter c is equivalent to the masker-level intercept of the functions in Fig. 1, when masker level is expressed in dB SL.

Changes in the recovery process imply changes in the slopes of masking, but the reverse is not necessarily true. The slope of masking at a given signal delay is given by $\mathrm{a}(\mathrm{b} - \log \Delta t)$. Thus any change in the time course of recovery, specified by b, will also change the slopes of masking at all signal delays, unless we compensate for the change in b by using a different value of a for each delay. It is possible to change the slopes of masking while holding the time course of recovery constant, however, by simply changing a. The exponential equation used by Duifhuis (1973) and Widin and Viemeister (1979), which will be discussed in greater detail below, has this same property.

Optimum values of a, b, and c for each frequency were used to generate the functions shown in Fig. 1. These values were obtained by an iterative procedure that maximized variance-accounted-for.[1] The functions in Fig. 1 account for 98% of the variance in the mean data. In fitting Eq. (1) to the data for individual listeners at each frequency in the three experiments, 40 sets of data in all, the median variance accounted for was 96%.

The three parameters, plus quiet thresholds for the signal and masker, allow us to estimate the amount of masking that would be produced by any combination of masker level and signal delay within the ranges we have used or to estimate the masker level required for a con-

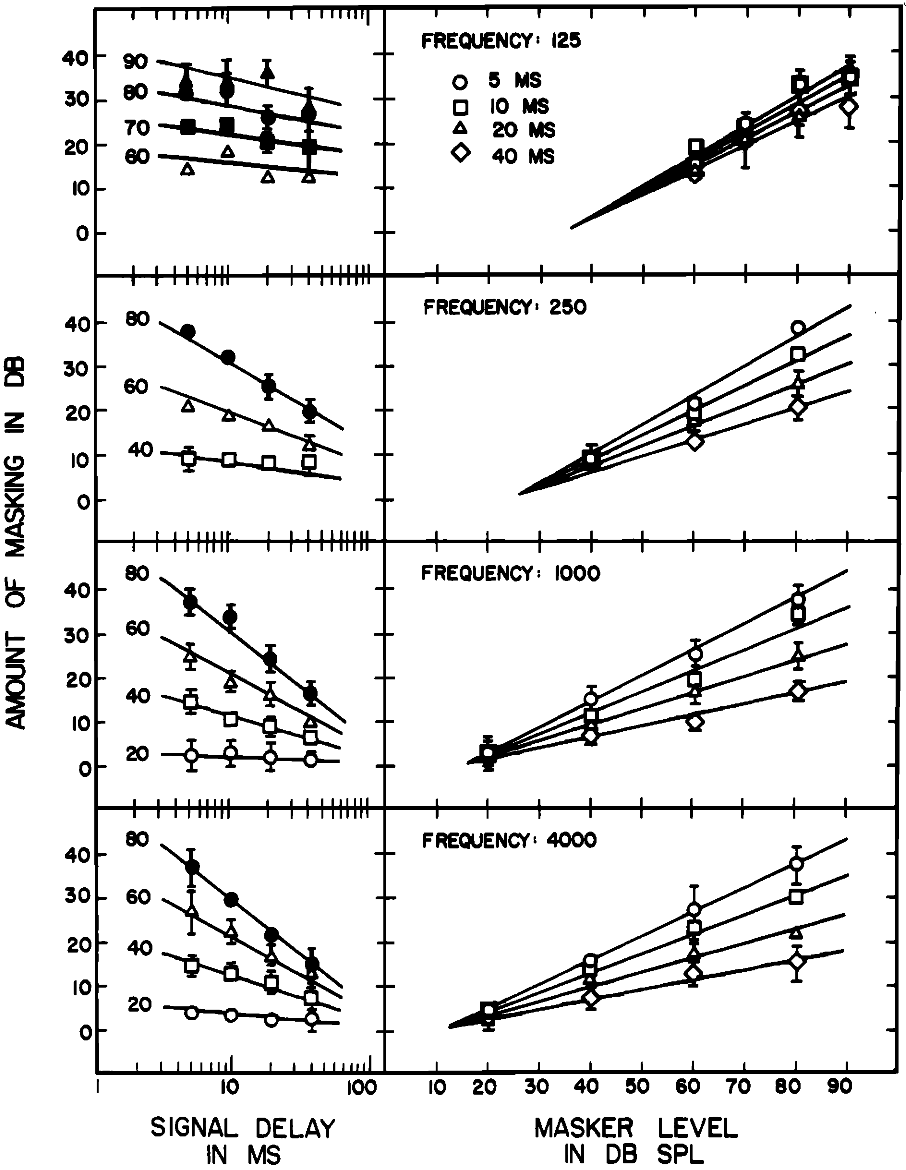


FIG. 1. Mean amount of forward masking observed at each test frequency, signal delay, and masker level in experiment 1. Each point is based on approximately 300 trials for each of four listeners. The error bars indicate one standard deviation around the mean, showing variability across listeners. The same data have been plotted as a function of signal delay and masker level in the left and right halves of the figure, respectively.

stant amount of masking at a given signal delay. As a test of the latter capability, we obtained forward-masking data for another group of four listeners, using a 320-ms, 1000-Hz masker and 10-ms, 1000-Hz signal, with 5-ms ramps. The masker levels were 30, 50, 70, and 90 dB SPL and the signal delays were 4, 8, 16, and 32 ms. We fitted Eq. (1) to the data for each listener and used the resulting parameter values to estimate the masker levels required for 5, 10, and 20 dB of masking. We then tested the same listeners with the signal level fixed at 5, 10, or 20 dB SL and determined the level of the masker required to mask the signal at each of the four signal delays. The mean predicted and obtained masker levels are shown in Fig. 2. The predictions account for 92.7% of the variance in the obtained masker levels for individual listeners, and there is no bias in the predictions as a function of signal level, signal delay, or listeners.

Equation (1) does not provide a general description of forward masking. It would predict too little masking for masker levels greater than those used here and negative amounts of masking for both long signal delays

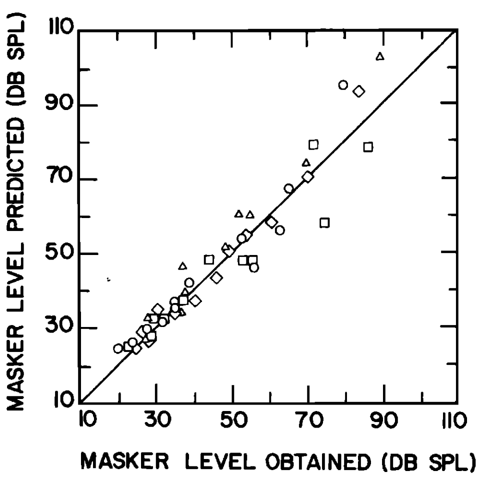


FIG. 2. Masker levels required for 5, 10, and 20 dB of masking at signal delays of 4, 8, 16, and 32 ms for four listeners plotted against estimates of these masker levels based on an independent set of data for conditions with fixed masker level and variable signal level. The four symbols indicate different listeners. All data were obtained for signals and maskers at 1000 Hz.

($\Delta t > 10^b$) and low-level maskers ($L_m < c$). It does, however, provide an excellent summary of the data at any one frequency for the range of signal delays and masker levels we have used and is particularly useful as a tool for data reduction. All comparisons across frequencies in the following sections will be made in terms of estimates obtained using Eq. (1). Some of these comparisons will involve single estimates based on mean data while others will involve means of the estimates for individual subjects, so that we can preserve information about individual differences. The correlations of mean estimates with estimates based on mean data for the conditions used in experiment 1 range from 0.997 to 1.000 for the four test frequencies.

### B. Effects of frequency in experiment 1

Table I contains quiet thresholds, optimum values of a, b, and c, and variance-accounted-for for each frequency in experiment 1 for the individual listeners as well as for the means across listeners. The parameters at the bottom of the table were used to generate the functions in Fig. 1. The most striking result in experiment 1 is the very gradual recovery from forward masking observed for all four listeners at 125 Hz. As we noted above, these data were collected after the data at the higher frequencies, and it was necessary to use a more gradual ramp and longer duration probe. Thus listeners had more experience and the effective separation between masker and signal was longer at 125 Hz than at the higher frequencies for the same nominal values of signal delay. Both of these factors, however, should have resulted in less forward masking, not more.

Two comparisons of forward masking as a function of frequency are shown in Fig. 3. Figure 3(a) shows means and standard deviations of the estimated amount of masking that would be obtained using 30- and 60-dB SL maskers combined with 5- and 20-ms signal delays. Figure 3(b) shows a similar comparison in terms of estimated masked thresholds for 39- and 69-dB SPL maskers, the levels corresponding to 30 and 60 dB SL at 1000 Hz. Both the amount of masking and masked thresholds are greater at low frequencies for maskers at comparable levels. This result holds for a wide

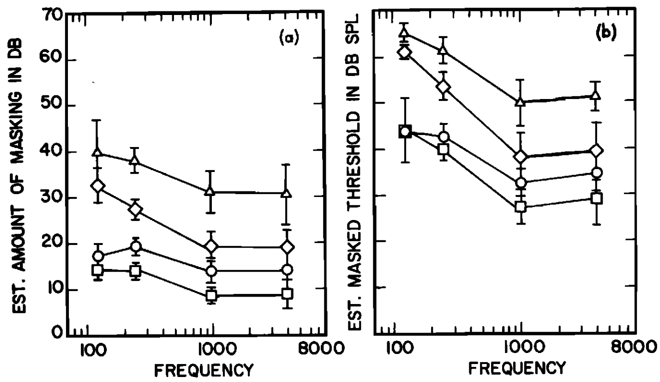


FIG. 3. Estimates of amount of masking and masked thresholds in dB SPL that would be obtained at two masker levels and two signal delays for the four listeners in experiment 1. The estimates were obtained by using the parameters for individual listeners in Table I, then computing a mean and standard deviation across listeners for the estimated values. The four functions in (a) show amounts of masking for 60-dB SL maskers at signal delays of 5 and 20 ms (triangles and diamonds) and 30-dB SL maskers at signal delays of 5 and 20 ms (circles and squares). The functions in (b) show masked thresholds for 69- and 39-dB SPL maskers, the average SPL levels of the corresponding functions in (a) at 1000 Hz.

TABLE I. Parameters for best fits of the equation $M = a(b - \log \Delta t)(L_m - c)$ to data at each frequency in experiment 1.

| Subject | Frequency | Parameter values a | b | c | Slope of masking ($\Delta t$ = 5 ms) | Variance-accounted-for | Quiet thresholds (dB SPL) Signal | Masker |
|---|---|---|---|---|---|---|---|---|
| JA | 125 | 0.180 | 5.200 | 10.84 | 0.810 | 0.817 | 38.49 | 27.41 |
| | 250 | 0.200 | 3.225 | −9.25 | 0.505 | 0.919 | 31.47 | 23.50 |
| | 1000 | 0.360 | 2.215 | 9.97 | 0.546 | 0.984 | 17.83 | 5.18 |
| | 4000 | 0.401 | 2.165 | 7.84 | 0.588 | 0.983 | 20.19 | 7.41 |
| SF | 125 | 0.040 | 2.845 | −1.87 | 0.486 | 0.830 | 43.14 | 28.47 |
| | 250 | 0.296 | 2.890 | −1.41 | 0.649 | 0.942 | 33.61 | 27.16 |
| | 1000 | 0.296 | 2.295 | 2.77 | 0.472 | 0.938 | 14.16 | 1.23 |
| | 4000 | 0.105 | 4.350 | −1.51 | 0.383 | 0.960 | 25.71 | 7.01 |
| BC | 125 | 0.393 | 2.858 | 9.74 | 0.848 | 0.927 | 42.49 | 30.71 |
| | 250 | 0.357 | 2.550 | 4.70 | 0.661 | 0.981 | 30.98 | 21.80 |
| | 1000 | 0.357 | 2.425 | 4.41 | 0.616 | 0.987 | 16.37 | 8.59 |
| | 4000 | 0.493 | 1.923 | 12.61 | 0.603 | 0.991 | 14.70 | 1.79 |
| TC | 125 | 0.293 | 3.608 | 5.08 | 0.852 | 0.830 | 42.18 | 34.07 |
| | 250 | 0.303 | 2.908 | −0.36 | 0.669 | 0.965 | 36.45 | 26.06 |
| | 1000 | 0.421 | 2.243 | 4.77 | 0.650 | 0.979 | 27.45 | 19.73 |
| | 4000 | 0.398 | 2.263 | −3.10 | 0.622 | 0.962 | 18.79 | 13.25 |
| Mean data | 125 | 0.140 | 5.583 | 5.36 | 0.684 | 0.992 | 41.58 | 30.16 |
| | 250 | 0.334 | 2.697 | 1.02 | 0.667 | 0.984 | 33.13 | 24.63 |
| | 1000 | 0.372 | 2.278 | 7.20 | 0.587 | 0.988 | 18.95 | 8.68 |
| | 4000 | 0.351 | 2.252 | 4.19 | 0.545 | 0.993 | 19.85 | 7.36 |

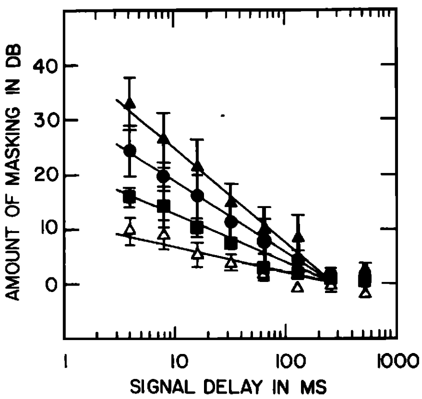

FIG. 4. Mean amount of forward masking observed at each signal delay and masker level at 125 Hz in experiment 2. Each point is based on 400 trials for each of four listeners, 200 trials at 0° and 200 trials at 180°. The error bars indicate one standard deviation around the mean, showing variability across listeners. The four functions are for 90, 80, 70, and 60 dB SPL maskers.

range of masker levels and signal delays. Although the greatest difference occurs at 125 Hz, the estimates for 250 Hz are consistent with this pattern. The frequency effect summarized in Fig. 3 is in the opposite direction of that reported in most of the studies reviewed above.

### C. Experiment 2

The extended time course of forward masking at 125 Hz observed in experiment 1 was further investigated for a new group of listeners. Mean data across listeners and signal phase angles for experiment 2 are shown in Fig. 4. Equation (1) has been fitted to the data for signal delays from 4 to 256 ms. Quiet thresholds, optimum parameter values, and variance-accounted-for are given in Table II. Because Eq. (1) cannot fit the slope-zero regions associated with longer signal delays, inclusion of longer signal delays in the analysis of the data for experiment 2 tends to make the recovery functions appear more gradual than they really are. This is illustrated by the second set of parameters in Table II for an analysis that includes only signal delays from 4 to 64 ms, closer to the 5–40-ms range of delays used in experiment 1. We were clearly unable to replicate the very gradual recovery functions obtained in experiment 1, even with longer delays in the analysis.

When the mean data in Fig. 4 were separated into conditions in which the signal was in phase with the "image" of the masker and those in which signal and masker were 180° out of phase, we generally found more masking in the in-phase conditions, although all of these differences were small. When such comparisons were made for each of the 32 conditions for each of the four listeners, there were 88 cases of greater masking for the 0° phase angle and only 40 cases in the other direction. A repeated-treatment analysis of variance also showed a significant overall effect of phase ($F=11.48$; $df=1, 3$; $p=0.043$), as well as a marginally significant interaction of phase, masker level, and signal delay ($F=1.57$; $df=21, 63$; $p=0.085$), indicating a greater phase effect at higher masker levels and shorter signal delays. A convenient summary of the magnitude of the phase effect can be obtained by fitting Eq. (1) to the data for each phase angle. The resulting parameter values indicate that the differences in masking are equivalent to a 3.5-dB change in the level of the masker. The individual phase effects observed for various combinations of masker level and signal delay are not sufficiently orderly, however, to be predicted from the two sets of parameter values.

TABLE II. Parameters for best fits of the equation $M=a(b-\log \Delta t)(L_m-c)$ to data for signal delays from 4 to 256 ms and 4 to 64 ms in experiment 2.

Signal delays from 4 to 256 ms

| Subject | Parameter values a | b | c | Slope of masking ($\Delta t=4$ ms) | Variance-accounted-for | Quiet thresholds (dB SPL) Signal | Masker |
|---|---|---|---|---|---|---|---|
| MB | 0.474 | 2.352 | 20.40 | 0.829 | 0.960 | 40.98 | 24.52 |
| MT | 0.484 | 2.471 | 21.59 | 0.904 | 0.968 | 47.62 | 29.69 |
| DI | 0.251 | 2.309 | 4.65 | 0.428 | 0.932 | 43.91 | 30.97 |
| JR | 0.411 | 2.709 | 24.53 | 0.866 | 0.925 | 46.99 | 30.09 |
| Mean data | 0.421 | 2.434 | 19.65 | 0.771 | 0.982 | 44.88 | 28.97 |

Signal delays from 4 to 64 ms

| Subject | Parameter values a | b | c | Slope of masking ($\Delta t=4$ ms) | Variance-accounted-for |
|---|---|---|---|---|---|
| MB | 0.564 | 2.152 | 20.40 | 0.874 | 0.971 |
| MT | 0.484 | 2.371 | 19.59 | 0.856 | 0.977 |
| DI | 0.321 | 2.034 | 4.65 | 0.460 | 0.966 |
| JR | 0.346 | 2.984 | 24.03 | 0.824 | 0.942 |
| Mean data | 0.456 | 2.284 | 18.65 | 0.767 | 0.991 |

## D. Experiment 3

The recovery from forward masking at 125 Hz observed in experiment 2 was not much different than that observed at the higher frequencies in experiment 1. We therefore replicated experiment 1 for a new group of listeners under conditions that would provide better control of the phase of the signal with respect to the masker and that would allow us to use the same probe duration for all frequencies.

Mean data across listeners for experiment 3 are shown in Fig. 5. Quiet thresholds, optimum parameter values, and variance-accounted-for are given in Table III. Figure 6 shows comparisons of forward masking as a function of frequency like those shown for experiment 1 in Fig. 3. Once again, the amount of masking and masked thresholds are greatest at 125 Hz. Masked thresholds for equal-SPL maskers are greater at 4000 than at 1000 Hz, unlike those obtained in experiment 1. Although the thresholds for listener SS at 4000 Hz are within normal limits, they are clearly higher than those of the other listeners and may have contributed to the higher masked thresholds at that frequency. The pattern is similar, however, when SS is not included in the

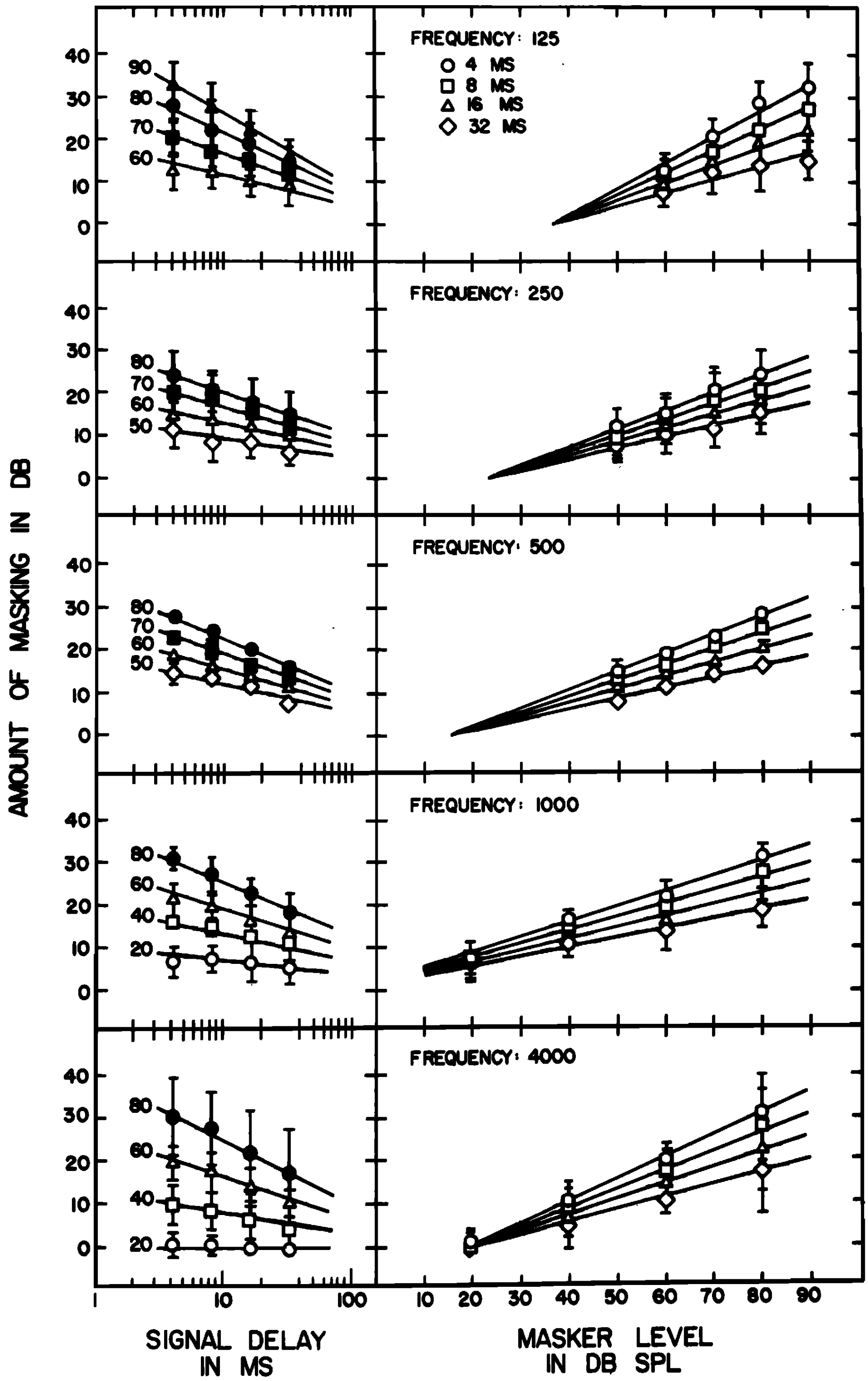


FIG. 5. Mean amount of forward masking observed at each test frequency, signal delay, and masker level in experiment 2. Additional information is given in the text and in the caption of Fig. 1.

TABLE III. Parameters for best fits of the equation $M = a(b - \log \Delta t)(L_m - c)$ to data at each frequency in experiment 3.

| Subject | Frequency | Parameter values a | b | c | Slope of masking ($\Delta t$=4 ms) | Variance-accounted-for | Quiet threshold (dB SPL) Signal | Masker |
|---|---|---|---|---|---|---|---|---|
| SS | 125 | 0.400 | 2.029 | 7.50 | 0.571 | 0.974 | 42.24 | 34.27 |
| | 250 | 0.187 | 2.590 | 6.48 | 0.372 | 0.961 | 29.53 | 13.60 |
| | 500 | 0.218 | 2.771 | 12.76 | 0.473 | 0.957 | 17.20 | 4.27 |
| | 1000 | 0.162 | 3.054 | −3.40 | 0.397 | 0.987 | 12.74 | 2.82 |
| | 4000 | 0.207 | 2.553 | 4.19 | 0.404 | 0.958 | 35.63 | 24.26 |
| WR | 125 | 0.408 | 2.534 | 5.16 | 0.788 | 0.964 | 41.82 | 30.02 |
| | 250 | 0.229 | 2.799 | −1.26 | 0.503 | 0.958 | 25.89 | 13.03 |
| | 500 | 0.162 | 2.778 | −6.62 | 0.352 | 0.952 | 19.53 | 7.89 |
| | 1000 | 0.180 | 2.594 | −1.61 | 0.358 | 0.910 | 10.22 | −4.94 |
| | 4000 | 0.277 | 2.639 | 10.50 | 0.564 | 0.985 | 18.26 | 4.17 |
| MV | 125 | 0.132 | 3.933 | −17.02 | 0.440 | 0.916 | 45.46 | 38.44 |
| | 250 | 0.086 | 5.686 | 4.94 | 0.437 | 0.925 | 33.23 | 21.58 |
| | 500 | 0.174 | 3.258 | 19.00 | 0.462 | 0.978 | 22.57 | 4.97 |
| | 1000 | 0.091 | 4.283 | −21.40 | 0.335 | 0.982 | 10.13 | 1.83 |
| | 4000 | 0.196 | 3.920 | 7.63 | 0.650 | 0.958 | 21.31 | 9.62 |
| YW | 125 | 0.466 | 2.125 | 6.96 | 0.710 | 0.941 | 40.33 | 37.86 |
| | 250 | 0.278 | 2.238 | 19.78 | 0.455 | 0.955 | 32.46 | 17.60 |
| | 500 | 0.217 | 2.602 | 9.74 | 0.434 | 0.986 | 19.93 | 4.58 |
| | 1000 | 0.212 | 2.447 | 11.48 | 0.391 | 0.936 | 16.12 | −0.85 |
| | 4000 | 0.352 | 1.876 | 16.34 | 0.448 | 0.959 | 21.92 | 2.78 |
| Mean data | 125 | 0.332 | 2.479 | 1.52 | 0.623 | 0.974 | 42.46 | 35.15 |
| | 250 | 0.182 | 2.975 | 6.52 | 0.432 | 0.983 | 30.28 | 16.45 |
| | 500 | 0.198 | 2.812 | 10.24 | 0.438 | 0.994 | 19.81 | 5.43 |
| | 1000 | 0.151 | 3.009 | −4.32 | 0.363 | 0.985 | 12.30 | −0.28 |
| | 4000 | 0.253 | 2.650 | 9.09 | 0.518 | 0.995 | 24.28 | 10.21 |

means. The difference between 1000 and 4000 Hz is greatly reduced when the comparison is made in terms of amounts of masking for equal-SL maskers. Some of these differences may be related to the fact that all of the data for 4000 Hz were obtained at the end of experiment 3. Comparisons between experiments 1 and 3, however, indicate that the two sets of data at 4000 Hz are in very good agreement. The data at lower frequencies show less masking and shallower slopes of masking in experiment 3 than in experiment 1. Although Fig. 6 shows some evidence of a frequency effect at high frequencies, in agreement with earlier studies, both Figs. 3 and 6 show a larger effect at low frequencies.

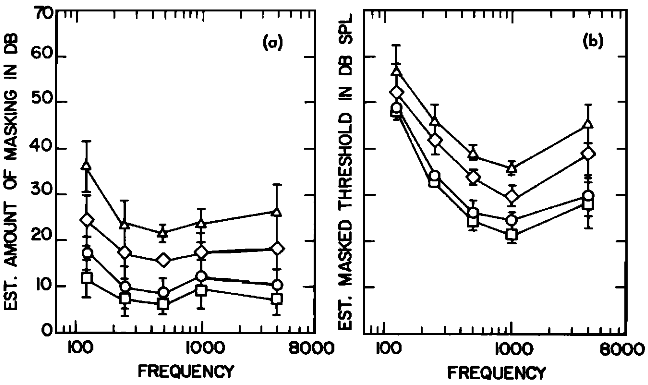


FIG. 6. Estimates of amount of masking and masked thresholds that would be obtained at two masker levels and two signal delays for the four listeners in experiment 3. The masker levels were 30 and 60 dB SL in (a) and 30 and 60 dB SPL in (b), the average SPL levels of the corresponding functions in (a) at 1000 Hz. The signal delays were 4 and 16 ms. Triangles and diamonds indicate estimates for the higher masker level and short and long signal delays, respectively. Circles and squares indicate corresponding estimates for the lower masker level. Other details are given in the caption of Fig. 3.

### E. Analyses with fewer parameters

The parameters shown in Tables I and III provide a good account of the data at each individual frequency, but there is no clear pattern in the parameters across frequencies. Because there were often broad ranges of parameter values that were almost as good as the best combinations, the differences in some of the parameters in Tables I and III might not be meaningful. To test this hypothesis, we reanalyzed mean data across listeners for all frequencies simultaneously holding various combinations of parameters constant as a function of frequency.

Alternative fits to the data for experiments 1 and 3 are described in Table IV. If we assume no real variability in any of these parameters as a function of frequency, i.e., that equal-SL maskers produce equal amounts of masking regardless of frequency, we can account for only 81% to 83% of the variance in the mean data. The resulting functions provide a very poor description of the data, particularly at low frequencies. If we allow any one of the parameters to vary as a function of frequency and select optimum common values for the remaining two parameters, the fits are very good, with the exception of some of the aberrant data at 125

TABLE IV. Parameter values for best fits to mean data from experiment 1 and experiment 3 when certain parameters are held constant for all test frequencies. Quiet thresholds are given in the mean data rows of Tables I and III.

| | | Experiment 1 | | | | | Experiment 3 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Parameter values | | | Slope of masking | Variance- | Parameter values | | | Slope of masking | Variance- |
| Parameters held constant | Frequency | a | b | c | ($\Delta t$=4 ms) | accounted-for | a | b | c | ($\Delta t$=4 ms) | accounted-for |
| **a, b, c** | | | | | | | | | | | |
| (Assume that constant SL | 125 | 0.290 | 2.741 | 3.38 | 0.620 | 0.284 | 0.190 | 2.735 | −1.53 | 0.405 | 0.344 |
| maskers produce constant | 250 | 0.290 | 2.741 | 3.38 | 0.620 | 0.868 | 0.190 | 2.735 | −1.53 | 0.405 | 0.888 |
| masking at all signal de- | 500 | ... | ... | ... | ... | ... | 0.190 | 2.735 | −1.53 | 0.405 | 0.796 |
| lays, at all frequencies) | 1000 | 0.290 | 2.741 | 3.38 | 0.620 | 0.886 | 0.190 | 2.735 | −1.53 | 0.405 | 0.972 |
| | 4000 | 0.290 | 2.741 | 3.38 | 0.620 | 0.854 | 0.190 | 2.735 | −1.53 | 0.405 | 0.948 |
| | Total | | | | | 0.809 | | | | | 0.826 |
| **a, b** | 125 | 0.290 | 2.707 | −7.79 | 0.610 | 0.661 | 0.190 | 2.861 | −13.12 | 0.429 | 0.911 |
| (Assume that slope of mas- | 250 | 0.290 | 2.707 | −0.29 | 0.610 | 0.971 | 0.190 | 2.861 | 5.65 | 0.429 | 0.982 |
| king and recovery from mas- | 500 | ... | ... | ... | ... | ... | 0.190 | 2.861 | 9.49 | 0.429 | 0.994 |
| king are constant at all | 1000 | 0.290 | 2.707 | 9.06 | 0.610 | 0.971 | 0.190 | 2.861 | 1.89 | 0.429 | 0.960 |
| frequencies, but that the | 4000 | 0.290 | 2.707 | 5.84 | 0.610 | 0.931 | 0.190 | 2.861 | 7.09 | 0.429 | 0.956 |
| masker level intercept | Total | | | | | 0.922 | | | | | 0.958 |
| changes) | | | | | | | | | | | |
| **a, c** | 125 | 0.290 | 4.108 | 13.41 | 1.017 | 0.655 | 0.190 | 3.645 | 3.35 | 0.578 | 0.888 |
| (Assume that all differ- | 250 | 0.290 | 3.570 | 13.41 | 0.861 | 0.778 | 0.190 | 2.772 | 3.35 | 0.412 | 0.976 |
| ences in time course of | 500 | ... | ... | ... | ... | ... | 0.190 | 2.672 | 3.35 | 0.393 | 0.983 |
| recovery and slope of mas- | 1000 | 0.290 | 2.802 | 13.41 | 0.638 | 0.944 | 0.190 | 2.815 | 3.35 | 0.420 | 0.971 |
| king are due to changes in | 4000 | 0.290 | 2.672 | 13.41 | 0.600 | 0.908 | 0.190 | 2.935 | 3.35 | 0.443 | 0.975 |
| recovery intercept) | Total | | | | | 0.876 | | | | | 0.961 |
| **b, c** | 125 | 0.297 | 3.166 | 4.66 | 0.761 | 0.833 | 0.290 | 2.776 | 3.67 | 0.630 | 0.960 |
| (Assume that all differ- | 250 | 0.297 | 3.166 | 4.66 | 0.761 | 0.949 | 0.190 | 2.776 | 3.67 | 0.413 | 0.976 |
| ences are due to differ- | 500 | ... | ... | ... | ... | ... | 0.180 | 2.776 | 3.67 | 0.391 | 0.986 |
| ences in the slope of | 1000 | 0.196 | 3.166 | 4.66 | 0.503 | 0.942 | 0.195 | 2.776 | 3.67 | 0.424 | 0.968 |
| masking) | 4000 | 0.196 | 3.166 | 4.66 | 0.503 | 0.937 | 0.210 | 2.776 | 3.67 | 0.457 | 0.979 |
| | Total | | | | | 0.936 | | | | | 0.976 |

Hz in experiment 1. As we might expect, the corresponding plots of forward masking as a function of frequency are all very similar to those in Figs. 3 and 6. Forward masking clearly varies as a function of frequency by as much as 15 dB under some conditions, but we cannot determine from these data whether the difference is in the growth of masking as a function of masker level, in the intercept of these functions, or in the rate of recovery from masking, which would influence both the signal-delay intercept and the slope of masking at different signal delays. In theory, we should be able to determine whether the frequency effect is due to a difference in the slope of masking or a difference in the time course of recovery. But given a relatively small effect and a high correlation between predictions based on alternative assumptions, the issue cannot be resolved on the basis of variance-accounted-for.

## III. DISCUSSION

### A. The effect of frequency on forward masking

The primary goal of the experiments reported here was to determine whether forward masking varies as a function of frequency, and if so, whether the differences reflect only changes in growth of masking as a function of masker level or changes in the recovery process as well. The analyses summarized in Figs. 3 and 6 demonstrate that forward masking is greater at low frequencies, regardless of how masker levels are equated (SL versus SPL) or how the data are compared (amount of masking versus masked thresholds). This result is in disagreement with previous studies (e.g., Harris *et al.*, 1951; Luscher and Zwislocki, 1949; Rawnsley and Harris, 1952) which have shown greater forward masking at high frequencies for equal-SL maskers. The difference could be due to the use of forced-choice procedures in the current study compared to use of the method of constant stimuli or method of limits in the earlier work. This may have resulted in lower quiet thresholds for the lower frequencies in the current study (e.g., Watson *et al.*, 1972) and hence, greater amounts of masking. Quiet thresholds were not published in the earlier studies, so no comparisons are possible.

Data obtained in recent physiological studies of forward masking (Abbas, 1979; Harris and Dallos, 1979; Smith, 1977, 1979) suggest that the physiological mechanism underlying forward masking is an adaptation process in the hair cells or at the synapses between the hair cells and neurons in the eighth nerve (Abbas, 1979; Smith, 1979). Harris and Dallos (1979) reported uniform time constants for three groups of chinchilla eighth-nerve fibers with CFs of 2500 or less, 3000 to 6000 Hz, and 9000 Hz and above. Unfortunately, their low-frequency group covers a much wider range of frequencies than the low-frequency effect we have observed.

Because adaptation is proportional to the total response of the eighth-nerve fiber to the adaptor tone, we might expect a relation between the steepness of rate-intensity functions and the amount of masking. The slopes of rate-intensity functions do not vary, however, as a function of frequency (e.g., Sachs and Abbas, 1974; McGee *et al.*, 1979). Thus there is no clear support in the physiological literature for either longer time constants or steeper slopes of masking at low frequencies. Responses recorded from single fibers in the eighth nerve do not show a frequency effect. There are, of course, many ways in which psychophysical forward-masking data do not correspond to data from individual eighth-nerve fibers. The physiological data indicate, for example, that adaptation occurs after the saturating nonlinearity observed in rate-intensity functions. Yet we see no corresponding reduction in the growth of forward masking at high intensities, just as we see no reduction in intensity discrimination at high intensities.

Although both Harris and Dallos (1979) and Smith (1979) noted the problems in equating physiological adaptation with psychophysical forward masking, neither could resist discussing the obvious parallels. If these two phenomena are closely related and reflect changes at the hair cell synapses, then it is more likely that the origin of the frequency effect is in more rapid growth of masking at low frequencies than in longer time constants. There is no reason to believe that the recovery from adaptation should be different for low-frequency hair cells, but the combination of rate-intensity functions across fibers may be different due to differences in basilar membrane mechanics, in spread of excitation, or in the relative CFs of the neurons involved. On the basis of a number of related studies (Jesteadt, 1980; Jesteadt and Bacon, 1980; Jesteadt and Lehman, 1980, 1981; Neff and Jesteadt, 1980), we believe that most changes in forward masking have their origin in changes in growth of masking or in the effective level of the masker, not in changes in the recovery process. We are inclined to attribute the frequency effect to a change in growth of masking as well.

### B. Sensation level versus sound pressure level

The summaries of experiments 1 and 3, presented in Figs. 3 and 6, demonstrate greater forward masking at low frequencies regardless of whether the comparison across frequencies is made in terms of amounts of masking for equal-SL maskers [Figs. 3(a) and 6(a)] or masked thresholds for equal-SPL maskers [Figs. 3(b) and 6(b)]. This consistency is fortunate because there is no consensus on a format for presentation of forward-masking data. Because quiet thresholds vary by 30 dB over the range of frequencies we have used, the choices between masked thresholds or amounts of masking and between equal-SPL or equal-SL maskers have greater impact on the interpretation of the data than in studies where quiet thresholds for masker and signal are relatively constant across conditions. The interpretation of the difference between the left- and right-hand panels of Figs. 3 and 6 is rather straightforward and may provide a framework for consideration of more difficult cases, such as comparisons of normal-hearing and hearing-impaired listeners.

The elevation in quiet thresholds at low frequencies is primarily the result of increased attenuation of these frequencies by the middle ear. An earplug could be used to produce the same conductive loss at 1000 Hz. If the earplug attenuated both the signal and a 60-dB SPL masker by 30 dB, then the parameters for means across subjects in experiment 3 (bottom of Table III) predict that there would be 12.9 dB less forward masking for a 4-ms signal delay. This reduction in masking is equivalent to the difference between the circle and triangle at 1000 Hz in Fig. 6(a). It occurs simply because less masker energy reaches the cochlea. The earplug will still cause a net increase of 19.1 dB in signal threshold in the presence of the 60-dB SPL masker, however, because the 10.9-dB decrease in amount of masking is more than compensated for by the 30-dB increase in quiet threshold for the signal. This will always be the case when the slope of forward masking is less than 1.0, as it typically is for sinusoidal maskers and signals. The equal-SPL comparisons in Figs. 3(b) and 6(b) represent a combination of linear attenuation and nonlinear forward masking, as in the earplug example. Equal-SL comparisons provide a clearer picture of the forward-masking process itself.

### C. Effect of signal phase

We did not expect to find an effect of signal phase in experiment 2 and did not realize that the small differences were consistent and significant until after experiment 3 had been completed. We do not know, therefore, whether the effect is limited to very low frequencies. Both Vogten (1978) and Gorga *et al.* (1980) failed to find a phase effect for a nonoverlapping masker and signal at 1000 Hz but they collected less data for such conditions than we did in experiment 2, and may not have been able to detect the small effect we observed.

We can account for the phase effect in terms of the temporal properties of the auditory filter (e.g., Duifhuis, 1973) if we are willing to assume that the filter "rings" for several cycles at 125 Hz. A second possibility is that the auditory system uses the temporal information present in phase-locked responses of auditory nerve fibers. When the signal is in phase with the masker, responses to the signal would resemble a continuation of the masker. When the signal is out of phase, the responses would shift slightly on an absolute time scale and the interspike intervals between masker offset and signal onset would be unique, making the out-of-phase signal more detectable. A third possibility is that the difference in detectability is due to a difference in pitch cues of the type described by Green *et al.* (1975).

### D. Alternative approaches

Several recent studies of forward masking have reached different conclusions about the relation between masker level, signal delay, and forward masking than those presented here. These discrepancies are a result of different methods of data analysis, not different procedures of data collection. The data themselves are all in good agreement.

Some of the recent studies report data obtained with a tuning-curve paradigm, where signal level is fixed and masker level is varied, with signal delay as an independent variable (e.g., Nelson and Turner, 1980; Vogten, 1978). As Fig. 2 demonstrates, there is consistency between data obtained with a tuning-curve paradigm and those obtained with fixed masker level and variable signal level. Neither approach allows us to separate changes in growth of masking from changes in the time course of recovery unless several masker levels are sampled at a given signal delay. In the case of the tuning-curve paradigm, this would require us to use several probe levels (e.g., Nelson and Turner, 1980) and to rewrite Eq. (1) (or some analogous equation) in a form with masker level as the independent variable. The algebra is straightforward, but the resulting equation is more complicated than the form we have used. It is not surprising, therefore, that previous analyses of tuning-curve data have focused on the time course of recovery rather than possible differences in the slope of masking.

We have chosen to fit the data reported here with an equation that generates intersecting straight lines as a function of log signal delay, in agreement with Plomp's (1964) summary of forward masking, while Widin and Viemeister (1979) have used a variation of an exponential model developed by Duifhuis (1973). They begin with an equation of the form

$$L_p = K(e^{-t/\lambda_1} + e^{-t/\lambda_2})L_m, \tag{2}$$

where $L_p$ is the threshold level of the signal in dB SPL, $L_m$ is the masker level in dB SPL, $t$ is the signal delay, and $\lambda_1$ and $\lambda_2$ are time constants. Widin and Viemeister (1979) note that some combinations of time constants will generate recovery functions that are essentially linear on masked threshold by log-signal-delay coordinates and Eq. (2) describes growth of masking as a function of masker level in terms of a family of straight lines that intersect at a common point. The major difference between Eqs. (1) and (2) is not in the use of logs or exponentials, but in the definitions of masker and signal level. Because Eq. (2) deals with masked thresholds and masker SPLs, it predicts that functions describing the slope of masking will intersect when masked threshold and masker level are both 0 dB SPL and that masked thresholds will decay to 0 dB SPL for long signal delays. Because masked thresholds can never be less than the quiet thresholds (11 and 14 dB at 1000 Hz for Widin and Viemeister's two listeners), the equation always underestimates the data. In an effort to correct for this, Widin and Viemeister added an internal noise parameter to the equation, which adds linearly in power, rather than in dB, to the masker, and is then multiplied by the proportionality constant, $K$. Even with this correction, they still underestimated masked thresholds at low masker levels and concluded that different time constants would be required for each masker.

We have corrected for our quiet thresholds by simply analyzing the data in terms of amount of masking as Duifhuis (1973) did, and by adding a correction term for the masker as well. To retain $L_p$ and $L_m$ as quantities expressed in dB SPL, we would rewrite Eq. (2) as

$$L_p = K(e^{-t/\lambda_1} + e^{-t/\lambda_2})(L_m - C') + L_{pt}, \tag{3}$$

where $C'$ is equal to the quiet threshold for the masker and $L_{pt}$ is the quiet threshold for the probe. Note that $C'$ is operated on by both the proportionality constant, $K$, and the exponential recovery process. The present study makes it clear that neither $L_{pt}$ nor $C'$ can be considered an internal noise since they are both largely determined by differences in quiet thresholds as a function of test frequency, presumably due to the middle-ear transfer function. Equation (3), of course, simplifies to Eq. (2) if the signal and masker levels in Eq. (2) are assumed to be in dB SL rather than dB SPL. When the exponential equation is rewritten in terms of amount of masking and masker SL, we can fit the data for at least one of Widin and Viemeister's subjects using the same time constant at all masker levels. It may be possible to improve the fit further by assuming an internal noise in addition to the SL corrections. Our c intercept is generally a few dB greater than 0 dB SL for the masker and an additive internal noise would generate more reasonable estimates of amount of masking in this region. The effect of additive internal noise is small, however, compared to the SL correction.

## IV. SUMMARY

Forward masking varies as a function of test frequency. The data reported here indicate greater forward masking at low frequencies for equal-SL maskers, while the previous literature suggests greater forward masking at high frequencies. This difference in results may be due to the use of forced-choice procedures in the current experiments.

Changes in forward masking as a function of masker level and signal delay are extremely orderly, and there is good agreement across studies concerning the general pattern of the results. The combined effect of signal delay and masker level on forward masking can be summarized conveniently in terms of two multiplicative factors that are proportional, within an additive constant, to log signal delay and masker level in dB SL. This pattern of results makes it difficult to separate changes in growth of masking from changes in the recovery process, and the frequency effect described here can be accounted for equally well by assuming either type of change as a function of frequency. Given existing physiological data and data from other studies of forward masking, we are inclined to attribute the frequency effect to a change in growth of masking as a function of frequency.

A small but consistent phase effect is apparent in the results of experiment 2. There have been no previous reports of phase effects for conditions with no temporal overlap between signal and masker, but there have been no previous tests at very low frequencies where such effects would be most observable.

Neither the frequency effect nor the phase effect reported here is sufficiently large to interfere with the use of forward masking in measuring two-tone suppression.

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[1]There does not appear to be a closed-form solution to the parameter estimation problem and we encountered a number of local minima in the iterations. We therefore considered all possible combinations of a, b, and c within a reasonable range. We first computed independent least-squares fits for each masker level for amount of masking versus log signal delay and then used the smallest and largest x-axis intercepts as the limits of the b range. We reasoned that the best x-axis intercept for all masker levels combined would be somewhere in the range of the individual intercepts. We used the same procedure to obtain a range of possible c values. We then stepped through all possible combinations of b and c. For a given b and c, we solved Eq. (1) for the value of a that would predict the observed amount of masking for each data point, then stepped through the range from the smallest to the largest of the individual optimum a values. We typically used steps of 0.005 on a, 0.025 on b, and 0.50 on c.

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