Suppression and the upward spread of masking

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The purpose of this study is to clarify the role of suppression in the growth of masking when a signal is well above the masker in frequency (upward spread of masking). Classical psychophysical models assume that masking is primarily due to the spread of masker excitation, and that the nonlinear upward spread of masking reflects a differential growth in excitation between the masker and the signal at the signal frequency. In contrast, recent physiological studies have indicated that upward spread of masking in the auditory nerve is due to the increasing effect of suppression with increasing masker level. This study compares thresholds for signals between 2.4 and 5.6 kHz in simultaneous and nonsimultaneous masking for conditions in which the masker is either at or well below the signal frequency. Maximum differences between simultaneous and nonsimultaneous masking were small (<6 dB) for the on-frequency conditions but larger for the off-frequency conditions (15–32 dB). The results suggest that suppression plays a major role in determining thresholds at high masker levels, when the masker is well below the signal in frequency. This is consistent with the conclusions of physiological studies. However, for signal levels higher than about 40 dB SPL, the growth of masking for signals above the masker frequency is nonlinear even in the nonsimultaneous-masking conditions, where suppression is not expected. This is consistent with an explanation based on the compressive response of the basilar membrane, and confirms that suppression is not necessary for nonlinear upward spread of masking. [S0001-4966(98)03812-0]

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INTRODUCTION

For tonal signals presented in a band-limited masker, thresholds increase roughly linearly with increasing masker level for signal frequencies around the masker frequency region. In contrast, thresholds increase more rapidly for signal frequencies well above the masker frequency region (Wegel and Lane, 1924; Egan and Hake, 1950). This leads to the well-known ''upward spread of masking.'' Frequency selectivity, and hence masking as a function of frequency separation, is generally believed to be established at the level of the cochlea. This assumption has support from studies that have compared behavioral and physiological frequency selectivity in the same species (e.g., Evans *et al.*, 1992). Traditionally, it has been assumed in psychophysics that masking is excitatory. That is, the masker is assumed to produce sufficient activity to make the additional activity due to the signal inaudible. Consequently, with the additional assumption that a constant ''internal'' signal-to-masker ratio is required for detection, the threshold of a sinusoidal signal is thought to reflect the excitation produced by a masker at the signal frequency. This assumption is used in most psychophysical models of masking (Zwicker, 1970; Glasberg and Moore, 1990; Rosen and Baker, 1994), intensity discrimination (Florentine and Buus, 1981), and loudness perception (Zwicker, 1960; Moore *et al.*, 1997). An alternative mechanism that could account for masking is suppression. Suppression refers to the reduction in the response to one stimulus by the introduction of a second. Masking by suppression alone implies that the neural activity due to the signal is reduced by the masker to a level indistinguishable from spontaneous activity. Suppression has been observed physiologically at the level of the auditory nerve (Sachs and Kiang, 1968) and the basilar membrane (Ruggero *et al.*, 1992a) and it is thought to be an inherent property of nonlinear cochlear mechanics.

Delgutte (1990) has pointed out that the two masking mechanisms, excitation and suppression, are not necessarily mutually exclusive; a masker may partially suppress a signal to a level at which its excitation is not distinguishable from that produced by the masker. In his extensive study at the level of the auditory nerve, Delgutte sought to differentiate between these two mechanisms over a range of masker levels and for conditions where the signal frequency was either below, at, or above the masker frequency. For signals well above the masker frequency, the amount of suppressive masking was large, and increased with masker level more rapidly than did excitatory masking. This led Delgutte to suggest that ''the upward spread of masking is largely due to the growth of suppression rather than to that of excitation.'' This view has been supported by other physiological studies (e.g., Pang and Guinan, 1997). If this interpretation is correct, it has important consequences for psychoacoustic models. As pointed out by Moore and Vickers (1997), if suppression plays a dominant role in some simultaneous-masking

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conditions, then models that equate simultaneous-masking patterns with excitation patterns must be inaccurate.

Some psychoacoustic evidence suggests that suppression is not necessary to produce nonlinear growth of masking at frequencies above that of the masker. Oxenham and Plack (1997) found highly nonlinear growth of masking in a forward-masking condition, where suppression should presumably play no role (Arthur *et al.*, 1971). In fact, they found that the growth of masking was much steeper than previously found for any simultaneous-masking condition. The slope of the masking function at signal frequencies of 2 and 6 kHz, when the masker was an octave below the signal, was between 5 and 6 dB/dB, compared with typical values of around 2 dB/dB for simultaneous-masking conditions (Stelmachowicz *et al.*, 1987).[1] Oxenham and Plack argued that the large value is expected, based on the following known properties of basilar-membrane (BM) mechanics: the BM response to tones well below characteristic frequency (CF) is linear, while the response to tones at CF is highly compressive over a wide range of levels. Thus, for a masker well below the signal frequency, an increase in masker level by 1 dB will result in a 1-dB increase in excitation at the place on the BM corresponding to the CF of the signal. If the BM response to the signal grows at a rate of $1/x$ dB per dB increase in signal level, then, assuming a constant signal-to-masker ratio at threshold, the signal level will have to be increased by x dB to match the increase in excitation due to the masker. Rates of growth of 0.2 dB/dB and lower have been recorded from BM measurements (Ruggero, 1992; Murugasu and Russell, 1996). Thus, it is expected that the growth of masking slope could exceed 5 dB/dB in some cases. Note that this explanation of the nonlinear upward spread of masking does not rely on suppression. In fact, it has been argued that suppression may *reduce* the slope of the masking function, as the presence of a high-intensity, low-frequency stimulus can linearize the response to a tone at CF (Ruggero *et al.*, 1992b).

The psychoacoustic finding by Oxenham and Plack (1997) of strong upward spread of masking in nonsimultaneous masking seems inconsistent with the physiological results of Delgutte (1990), who found essentially linear growth of masking for his ''nonsimultaneous masking'' conditions. Oxenham and Plack suggested that this apparent discrepancy may be due to the different range of signal levels used in the two studies. In Delgutte's study, in the frequency regions where most suppression was observed, signal levels in the nonsimultaneous conditions rarely exceeded 40 dB SPL; in Oxenham and Plack's study, measurements were concentrated on signal levels between 40 and 90 dB SPL. According to physiological measurements, the BM response to CF tones is nearly linear at low levels and becomes highly compressive only at levels above about 30–40 dB SPL (Yates *et al.*, 1990; Murugasu and Russell, 1995; Ruggero *et al.*, 1997). Thus, the finding by Delgutte of linear growth in his nonsimultaneous-masking condition may be due to the fact that high signal levels were not tested.

This study has two main aims. The first is to use psychophysical methods to investigate whether the upward spread of masking is due primarily to suppression or excitation, or a combination of both. This has important implications for most psychoacoustic models. As mentioned above, if it were found that suppression is dominant in producing the upward spread of masking, then models that equate simultaneous-masking patterns with excitation patterns (Florentine and Buus, 1981; Glasberg and Moore, 1990; Rosen and Baker, 1994; Moore *et al.*, 1997) may require some revision. The second aim is to test the hypothesis that the apparent discrepancy between the physiological results of Delgutte and the psychophysical results of Oxenham and Plack can be ascribed to the different ranges of signal levels tested. This is important in resolving apparent differences between physiological and psychophysical data. If the data from the two studies are found to be comparable when similar signal levels are used, this will provide further support for the idea that psychophysical suppression reflects processes already apparent at the level of the BM and auditory nerve. If not, it will be more likely that other effects, such as lateral inhibition at higher levels of the auditory pathways, play a significant role in basic masking experiments.

Experiment 1 compares thresholds for simultaneous and nonsimultaneous maskers in an on-frequency condition and in a condition where the masker is centered at a frequency well below that of the signal (off-frequency condition). In line with physiological studies, it is assumed that the effects of suppression on the signal can only be observed in the off-frequency, simultaneous-masking condition. Thus, by comparing the results from the off-frequency simultaneous- and nonsimultaneous-masking conditions, it should be possible to draw conclusions about the role of suppression in the upward spread of masking.

I. EXPERIMENT 1: GROWTH OF SIMULTANEOUS AND NONSIMULTANEOUS MASKING IN ON- AND OFF-FREQUENCY CONDITIONS

A. Stimuli

Thresholds were measured for a brief 4-kHz sinusoidal signal in the presence of a 500-Hz-wide Gaussian-noise masker that was either centered at the signal frequency (on-frequency condition) or centered at a lower frequency of 2.4 kHz (off-frequency condition). The signal had a total duration of 10 ms and was gated with 5-ms raised-cosine ramps (no steady state). The masker was gated with 2-ms ramps. In the simultaneous-masking condition, the signal was presented in the temporal center of a 400-ms (half-amplitude duration) masker. In the nonsimultaneous-masking condition, the signal was presented in a temporal gap between two 200-ms masker bursts. The silent interval between the end of the first masker (forward masker) and the beginning of the signal was 2 ms (defined as the time between the 0-voltage points in the electrical envelope); the interval between the end of the signal and beginning of the second masker (backward masker) was 5 ms. The backward masker was added to reduce the possibility of ''off-time listening'' at high signal levels (see Robinson and Pollack, 1973; Oxenham and Moore, 1994).[2] A high signal frequency was chosen to reduce the possibility that nominally nonsimultaneous stimuli overlapped in the auditory periphery, due to ''ringing'' in the

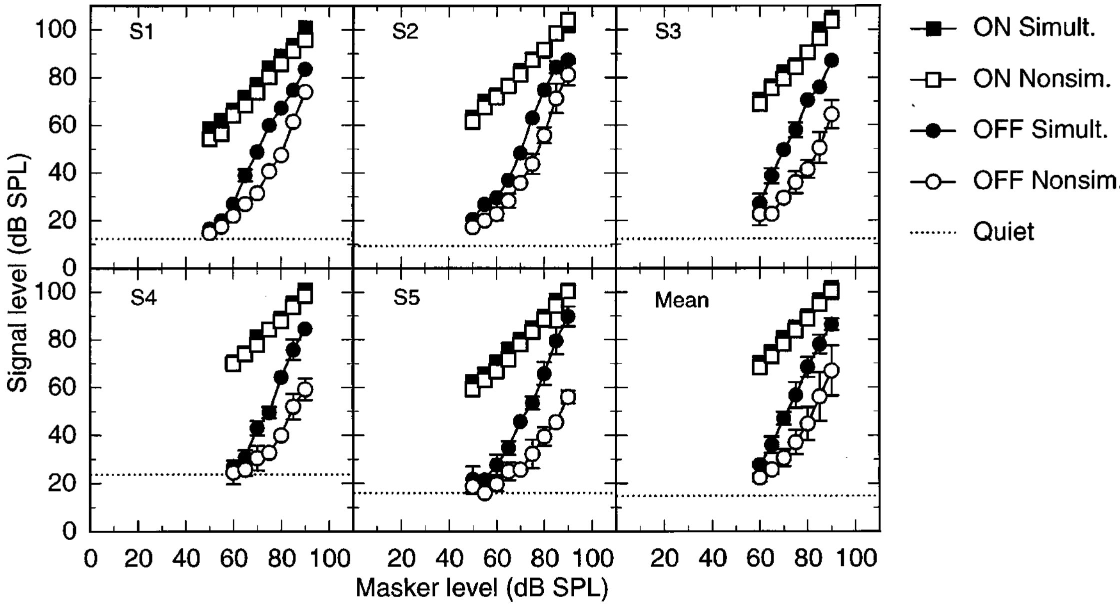

FIG. 1. Thresholds for a brief 4-kHz signal as a function of masker level. Filled and open symbols represent simultaneous- and nonsimultaneous-masking conditions, respectively. Circles represent off-frequency conditions, where the masker center frequency was 2.4 kHz; squares represent on-frequency conditions, where the masker center frequency was 4 kHz. Thresholds in quiet are shown as dotted lines. Error bars represent ±1 s.d. of the mean and are omitted if smaller than the symbol.

auditory filters. To reduce the possibility that ''confusion'' effects (Moore and Glasberg, 1982; Neff, 1986) were playing a role in the on-frequency nonsimultaneous conditions, an independently generated contralateral noise with the same spectral properties and level as the masker was always gated with the masker. Contralateral noise has been shown to have little or no effect on thresholds in simultaneous noise masking (e.g., Kohlrausch and Langhans, 1992), but may lower thresholds in some forward-masking situations in which confusion could play a role (see the Appendix). Signal thresholds were measured in quiet and for masker levels between 50 and 90 dB SPL (between 60 and 90 dB SPL for two listeners), in steps of 5 dB.

Bandpass noise was created at the beginning of each run by generating a 2-s circular buffer of wideband Gaussian noise, performing a discrete Fourier transform, setting the amplitude of the components outside the desired passband to zero, and applying an inverse Fourier transform. A random starting point within the resulting noise buffers was selected on each presentation interval. Thus, only the gating of the noise produced spectral components beyond the specified passband. All stimuli were generated digitally at a 32-kHz sampling rate, and were played out using the built-in 16-bit D/A converter and reconstruction (anti-aliasing) filter of a Silicon Graphics workstation. Stimuli were passed through a programmable attenuator (TDT PA4) and a headphone buffer (TDT HB6) before being presented to listeners via a Beyer DT990 headset. The signal was always presented to the listener's left ear.

B. Procedure

Thresholds were measured using a three-interval forced-choice method with a two-down, one-up adaptive procedure that tracks the 70.7%-correct point of the psychometric function. Each trial consisted of three intervals containing the masker and the contralateral noise. The interstimulus interval was 300 ms. The signal occurred randomly in one of the three intervals and listeners were required to select the signal interval. The signal level was initially adjusted in steps of 8 dB. After every two reversals, the step size was halved until a minimum step size of 2 dB was reached. The run terminated after a further eight reversals. Threshold was defined as the median level at the last eight reversals. For every listener, four such threshold estimates were made for each condition, and the mean and standard deviation of the four estimates were recorded. Listeners were tested in 2-h sessions, including short breaks. The four estimates for each data point were generally collected on four separate days. Responses were made via a computer keyboard, and feedback was provided via a computer monitor placed outside the listening booth. Listeners were tested in a single-walled sound-attenuating booth, which was situated in a sound-attenuating room.

C. Listeners

Five listeners were tested. Listener 1 was the author A.O.; the others were students who were paid for their participation. The listeners were between 19 and 28 years of age and had absolute thresholds of less than 15 dB HL at octave frequencies between 250 and 8000 Hz. Listeners S1 and S3 were male; listeners S2, S4, and S5 were female. None reported histories of hearing disorders or difficulties. The listeners were given at least three hours practice before data were collected. No consistent improvements in performance were noted during the course of the experiment.

D. Results

The individual and mean results for the five listeners are shown in Fig. 1. The dotted lines represent thresholds for the signal in quiet. Filled and open symbols represent simultaneous- and nonsimultaneous-masking conditions, respectively. Squares represent on-frequency conditions, where the masker center frequency is 4 kHz (labeled ON in Fig. 1), and circles represent off-frequency conditions, where the masker center frequency is 2.4 kHz (labeled OFF in Fig. 1). Error bars represent ± 1 s.d. and are shown if they exceed the size of the symbol. Standard deviations for thresholds in quiet were less than 2 dB for all listeners.

Consider first the results from the simultaneous-masking conditions (filled symbols). In line with many previous studies, the growth of masking for the on-frequency condition (filled squares) is approximately linear. Linear regression analysis of the individual data resulted in slope estimates of between 0.94 and 1.14 (slope of mean data: 1.01; percent of variance accounted for, $R^2 = 99.7\%$). Again consistent with many previous studies, the growth of masking for the off-frequency condition (filled circles) is steeper than linear. Taking into account only data points that lie 5 dB or more above threshold in quiet, a linear regression analysis produced individual slope estimates between 1.80 and 2.18 (slope of mean data: 2.01; $R^2 = 99.8\%$). The slope of the mean data is in good agreement with a survey of previous growth-of-masking studies carried out by Stelmachowicz *et al.* (1987).

Consider next the results from the nonsimultaneous-masking conditions (open symbols). Results from the on-frequency condition (open squares) are very similar to those from the on-frequency simultaneous condition. There is a tendency for thresholds to be somewhat lower in the nonsimultaneous than in the simultaneous condition, but the difference is always less than 6 dB. The mean difference between the on-frequency simultaneous and nonsimultaneous conditions, pooled across listeners and conditions, is 2.1 dB. A small difference in thresholds between a simultaneous-masked signal and a signal presented in a brief gap has been reported before: Oxenham and Moore (1994) found that thresholds in very brief gaps were either similar to or, in some cases, even higher than thresholds in a simultaneous masker. As this was found using a broadband masker with a 6-kHz sinusoidal signal, it is unlikely that the present results are due to the confusion of the signal with the 500-Hz-wide masker. A linear regression analysis produced individual slopes of between 0.96 and 1.12 (slope of mean data: 1.06; $R^2 = 99.9\%$). Thus, there appears to be no difference in the slope of the growth of masking between the two on-frequency conditions. Linear growth of nonsimultaneous masking is unusual, but has also been reported for a very brief signal in forward masking alone (Oxenham and Plack, 1997). Furthermore, linear growth is expected when the masker and signal levels are nearly equal, based on a recent theory of forward masking that links the nonlinear growth of forward masking to the nonlinear response of the BM (Oxenham and Moore, 1995; Oxenham and Moore, 1997; Plack and Oxenham, 1998). In contrast to the small difference between the two on-frequency conditions, the differences between the two off-frequency conditions are considerable, especially at medium to high levels.

If the difference between the two on-frequency conditions reflects the difference in effectiveness between simultaneous and nonsimultaneous masking *per se*, any further differences between the two off-frequency conditions may be due to suppression. In this way, the nonsimultaneous thresholds may reflect masker excitation at or near the signal frequency, while the simultaneous thresholds reflect masker excitation *plus* the increase in signal level required to compensate for the effects of suppression.

It can be seen that, at least at higher masker levels, the growth of masking of the nonsimultaneous off-frequency condition is steeper than linear. This suggests that suppression is not necessary for nonlinear upward spread of masking. However, at lower levels the function appears shallower for the nonsimultaneous than for the simultaneous condition. According to the hypothesis stated in the Introduction, we might expect the off-frequency growth of masking to be linear up to a certain signal level, and then to become nonlinear. The breakpoint between these two regions should reflect the level at which the on-frequency BM response becomes compressive. For the purposes of this analysis, we assume that the breakpoint occurs at 40 dB SPL.[3] A linear regression performed using data from the off-frequency nonsimultaneous condition for signal levels between 5 dB SL and 40 dB SPL resulted in individual slopes ranging from 0.90 to 1.0 (slope of pooled data: 0.94; $R^2 = 93.6\%$).[4] For the same condition, linear regression using only data points where thresholds were above 40 dB SPL resulted in slopes between 1.93 and 2.56 (slope of pooled data: 2.32; $R^2 = 97.9\%$). Thus, if only signal levels at or below 40 dB SPL are taken into account, the off-frequency growth of masking in the nonsimultaneous condition is essentially linear. This is consistent with the finding of Delgutte (1990) that, at low signal levels, there was no nonlinear upward spread of masking in the nonsimultaneous-masking condition. It is also consistent with the hypothesis that BM nonlinearity governs the upward spread of nonsimultaneous masking: at low levels, where the BM is thought to respond linearly, linear growth of masking is observed; at higher levels, where the BM response is compressive, nonlinear growth of masking is observed.

The difference between the off-frequency simultaneous and nonsimultaneous conditions may provide us with an estimate of the amount of suppression found for a given masker–signal combination. Once differences in effectiveness between on-frequency simultaneous and nonsimultaneous masking are accounted for, the difference in dB between the two off-frequency conditions can be interpreted as the gain required to restore the simultaneous-masked signal to its unsuppressed internal representation. Note that in this interpretation, also made by many others (Houtgast, 1973; Shannon, 1976; Duifhuis, 1980; Moore and Glasberg, 1981), the nonsimultaneous threshold provides a better estimate of the masker excitation at or near the signal frequency than the simultaneous threshold. In estimating the amount of suppression, the difference between the on-frequency conditions was accounted for individually by taking the mean difference for each listener between the two on-frequency conditions and subtracting it from the difference between the two off-frequency conditions at each masker level. The mean difference between the on-frequency conditions ranged from 0.4

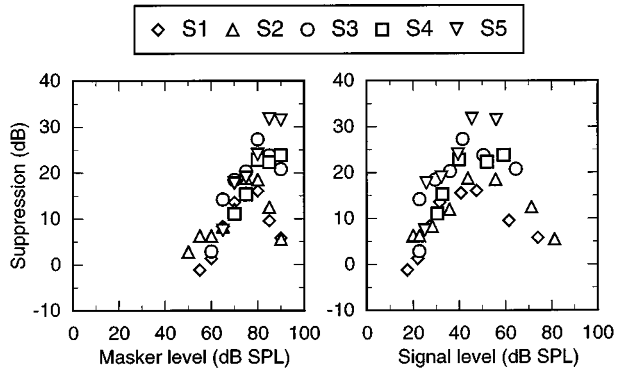

FIG. 2. Amount of suppression, estimated as described in the text, as a function of masker level (left panel) and as a function of nonsimultaneous-masked signal level (right panel). Different symbols represent results from the different listeners.

(S2) to 3.7 dB (S1). The estimated amounts of suppression for the individual listeners are shown in Fig. 2.

The amount of suppression estimated in this way is substantial for all listeners. However, there are also large differences between individual listeners, especially at the highest masker levels, as can be seen in the left panel of Fig. 2. For listeners S1, S2, and S3, suppression seems to reach a maximum at masker levels of around 80 dB SPL and then decrease somewhat at higher levels. For listeners S4 and S5, suppression remains high at the highest masker levels. An alternative way of plotting the results is shown in the right panel. Here, suppression is plotted as a function of nonsimultaneous signal level. This measure could also be thought of as reflecting the *effective* masker level at the signal CF. Generally, maximum suppression seems to occur for signal levels between about 40 and 60 dB SPL and to decline below and above that. Listeners exhibit a maximum amount of suppression of between 15 (S1) and 32 dB (S5). The amounts of suppression observed here are in line with those observed at similar masker–signal frequency ratios by previous investigators. Duifhuis (1980) showed that suppression using the pulsation-threshold method could be very large when the suppressor was well below the frequency of the suppressee. The maximum amounts of suppression measured by him with frequencies of 600 Hz and 1 kHz for the suppressor and suppressee, respectively, ranged from about 12 to 35 dB, depending on the listener. Similarly, Shannon (1986), also using the pulsation-threshold method, found that the suppression of a 1-kHz 60-dB SPL tone produced by a 400-Hz 80-dB SPL tone lay between 20 and 30 dB for all three of his listeners. Moore and Vickers (1997), using an on-frequency forward masker at 2200 Hz and a higher-level suppressor at 500 Hz, also found that the effective level of the on-frequency masker was reduced by between 12 and 20 dB for all four listeners.

Returning to Fig. 1, the growth-of-masking slope in the nonsimultaneous off-frequency condition generally does not exceed about 2.5, even when only signal levels above 40 dB SPL are taken into account. The slope of 2.3 for the data pooled across listeners is only marginally greater than the slope of 2.0 for signal levels above 40 dB SPL in the simultaneous off-frequency condition. A repeated-measures analysis of covariance (ANCOVA) allowing two-way interactions, with masker level, simultaneity, and listener as factors showed that this difference in slope was significant ($F_{1,146} = 13.13$; $p < 0.001$), although the difference in slopes for listeners 4 and 5 did not fit this trend. Given that suppression should reduce the apparent compression (Ruggero *et al.*, 1992a), we expected a larger difference in slope between the simultaneous and nonsimultaneous off-frequency conditions at these higher signal levels. Also, the slope of 2.3 contrasts with the growth of masking found by Oxenham and Plack (1997) using a sinusoidal forward masker and signal. In that study, a slope of about 6 was observed for signal levels between 50 and 80 dB SPL, which is more in line with the slope expected based on BM measurements. It is possible that the difference may in part be due to ''off-frequency'' listening at high signal levels (Johnson-Davies and Patterson, 1979; O'Loughlin and Moore, 1981). In the previous study a highpass noise was added to restrict the listening band. However, other differences in the present experiment may also play a role. These include the use of a noise, rather than a tonal, masker and the different frequency ratio between masker and signal used (1:1.67, as opposed to 1:2). Further experiments are required to clarify the difference.

In summary, experiment 1 supports the hypothesis that suppression plays a major role in the upward spread of masking. This can been seen by the amount by which the off-frequency simultaneous-masked thresholds exceed the nonsimultaneous-masked thresholds. Also, no evidence for nonlinear growth of masking is found for the nonsimultaneous condition at signal levels below 40 dB SPL. However, at higher signal levels, nonlinear growth of masking is also observed in the off-frequency nonsimultaneous condition. Thus, it seems that the apparent discrepancy between the physiological findings of Delgutte and psychophysical findings of Oxenham and Plack may be due to the different ranges of signal levels studied.

The second experiment investigates how the growth of masking and the amount of suppression changes with increasing masker–signal frequency ratio.

II. EXPERIMENT 2. EFFECT OF INCREASING MASKER–SIGNAL FREQUENCY RATIO

A. Method

In this experiment, the 500-Hz-wide masker had a fixed center frequency of 2.4 kHz. The signal frequency was either 2.4, 4, 4.8, or 5.6 kHz. In order to produce reasonably high signal thresholds, even at the largest masker–signal frequency interval, the duration of the signal was reduced to a total duration of 4 ms, gated with 2-ms raised-cosine ramps (no steady state). For the 2.4-kHz signal frequency (on-frequency condition), thresholds were measured at masker levels from 25 to 85 dB SPL in 10-dB steps. For the other three (off-frequency) conditions, thresholds were measured at masker levels of 40, 50, 55, 60, and 65 dB SP, and then at 2.5-dB steps up to 90 dB SP. The smaller steps at the higher levels were designed to trace the growth of masking in more

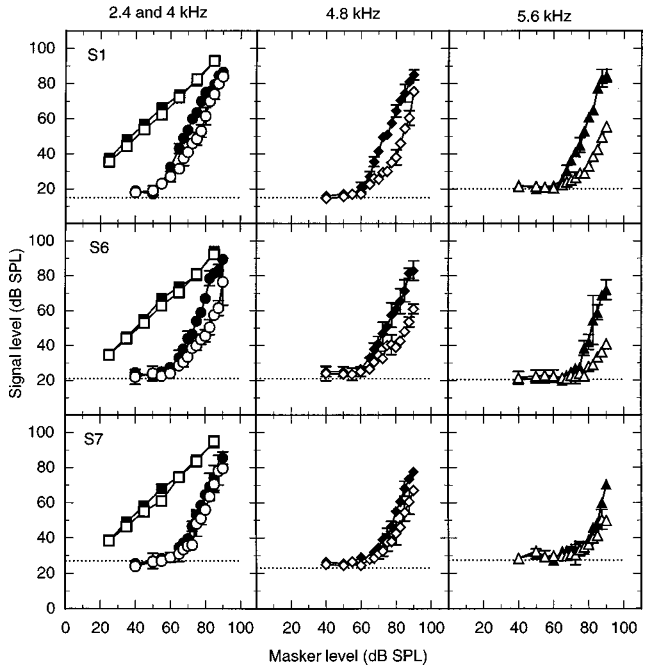

FIG. 3. Growth of masking using a noise masker with a center frequency of 2.4 kHz. Different symbols represent different signal frequencies. Data from the three listeners are shown in the three rows. See Fig. 1 for further details.

detail than was done in experiment 1. All other parameters, including masker durations and masker-signal time intervals, were the same as in experiment 1.

Thresholds were measured using a similar adaptive procedure to that used in experiment 1. Due to the larger number of conditions, and the finer level steps, the measurement procedure was shortened by terminating each run after six reversals at a step size of 2 dB and taking the median value of the last six reversals, and by measuring only two estimates for each data point. All other aspects were the same as in experiment 1.

Three listeners participated in experiment 2. Listener S1 (author A.O.) was joined by two new listeners (S6 and S7), both students 20 years old, who were given at least 4 h training on the task. Listener S6 was male; listener S7 was female. Both had absolute thresholds of less than 15 dB HL at octave frequencies between 250 and 8000 Hz and reported no history of hearing difficulties or disorders.

B. Results

The individual results from experiment 2 are shown in Fig. 3. The left panels show data for signal frequencies of 2.4 kHz (on-frequency; squares) and 4 kHz (circles). The middle and right panels show data for signal frequencies of 4.8 and 5.6 kHz, respectively. Filled symbols represent the simultaneous-masking conditions and open symbols represent the nonsimultaneous-masking conditions. Dotted lines represent signal thresholds in quiet. Error bars represent ± 1 s.d. and are shown if they exceed the size of the symbol.

The results for the on-frequency conditions (left panels; squares) are very similar to those found in experiment 1 at 4 kHz. There is very little difference between the simultaneous and the nonsimultaneous conditions for all three listeners. Linear regression analysis resulted in individual slopes between 0.89 and 0.95 with no systematic differences between listeners or conditions. The fact that the slopes are somewhat less than unity may be due to listeners being able to detect some off-frequency ''spectral splatter'' at the higher levels. The use of a shorter signal and a lower center frequency than in experiment 1 may have made such a cue more salient. Again, the fact that there was very little difference between the two on-frequency conditions suggests that the large differences between the simultaneous and nonsimultaneous conditions at other frequency intervals may be primarily due to suppression.

Linear regression on the three off-frequency simultaneous conditions, taking into account data points 5 dB or more above threshold in quiet, resulted in individual slopes ranging from 1.9 to 2.8. There was a slight tendency for the simultaneous-masked slopes to become steeper with increasing frequency interval: slopes from the data pooled across listeners (see footnote 4) were 2.04 at 4 kHz ($R^2=98\%$), 2.09 at 4.8 kHz ($R^2=98.5\%$), and 2.50 at 5.6 kHz ($R^2=96\%$). This finding is consistent with some previous studies (e.g., Smits and Duifhuis, 1982; Stelmachowicz *et al.*, 1987; Murnane and Turner, 1991; Nelson and Schroder, 1997), although data from Schöne (1977), using tonal maskers, suggest little or no change with increasing masker–signal frequency interval.

Linear regression on the three off-frequency nonsimultaneous conditions, taking only signal levels between 5 dB SL and 40 dB SPL into account, again provides no evidence for nonlinear growth of masking. The slopes for the data pooled across the three listeners are 1.02 ($R^2=94.6\%$), 1.01 ($R^2=87.4\%$), and 0.91 ($R^2=91.5\%$) for the 4-, 4.8-, and 5.6-kHz conditions, respectively. Taking only signal levels above 40 dB SPL into account resulted in slopes for the pooled data of 2.4 ($R^2=95.6\%$), 2.5 ($R^2=93.7\%$), and 2.47 ($R^2=98.1$) for the 4-, 4.8-, and 5.6- kHz conditions, respectively. Thus, there seems to be no effect of signal frequency on the nonsimultaneous growth of masking for the off-frequency conditions tested. As in experiment 1, the slope of around 2.5 is less than that expected based on BM measurements and on the psychophysical data of Oxenham and Plack (1997). Kidd and Feth (1981) measured growth-of-masking functions for off-frequency forward-masked signals for masker–signal frequency ratios up to 2.0. However, because of their more typical stimulus conditions (i.e., longer signal duration and no backward masker), the amount of masking measured by them at the large frequency ratios never exceeded 25 dB, making a direct comparison with our data difficult.

The amount of suppression, estimated as in experiment 1 by subtracting the mean difference for each listener between the two on-frequency conditions from the differences between each pair of off-frequency conditions, is shown in Fig. 4. The differences are plotted as a function of the signal level in the nonsimultaneous conditions, as in the right panel of Fig. 2. Generally, suppression seems to increase with increasing masker–signal frequency interval over the range tested here. Reassuringly, S1's pattern of suppression in experiment 2 for the 4-kHz signal is very similar to that in

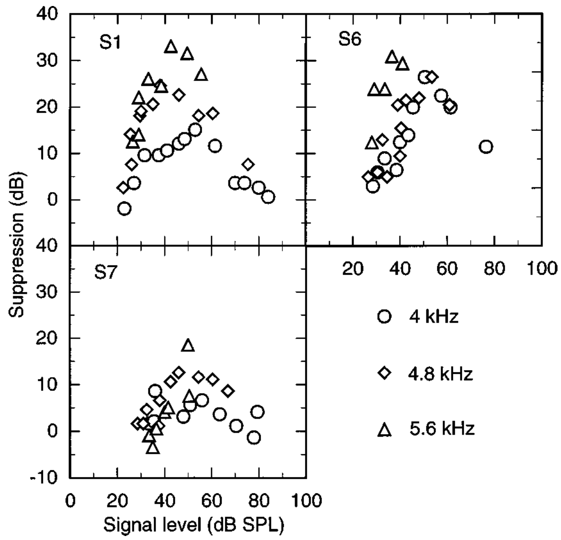

FIG. 4. Amount of suppression, estimated as described in the text, as a function of nonsimultaneous-masked signal level. Different symbols represent different signal frequencies. Data from three listeners are shown individually in the three panels.

experiment 1, despite the slightly different stimulus conditions, with suppression maxima of 16 dB and 15 dB in experiments 1 and 2, respectively. S7 generally shows less suppression at all frequency intervals. Again, for all three listeners at all three frequency intervals, suppression seems to be maximal at signal levels between about 40 and 60 dB SPL.

III. GENERAL DISCUSSION

A. The role of suppression in masking

Both experiments 1 and 2 indicate that suppression plays a major role in the psychophysical upward spread of masking. This is consistent with physiological studies of masking in the auditory nerve (Delgutte, 1990; Pang and Guinan, 1997). Experiment 2 suggests that the relative contribution of suppression continues to increase with increasing signal–masker frequency ratio at least up to the highest ratio of 2.33 measured here (signal frequency of 5.6 kHz). However, even at this ratio, excitation seems to produce some masking, as evidenced by the nonsimultaneous-masked thresholds. Therefore, for the conditions tested here, it can in some sense be argued that the masking process *per se* is entirely excitatory. In other words, the (suppressed) signal is only rendered undetectable because it is obscured by masker excitation. Except in cases where the signal is suppressed below absolute threshold, suppression *alone* will not produce any masking. It is possible that such situations are encountered at larger signal–masker frequency ratios than were measured here. However, Moore and Vickers (1997) measured the effect of a 500-Hz suppressor at a signal frequency of 2200 Hz. Even at this frequency ratio of 4.4, evidence for excitatory masking was found. Similarly, auditory-nerve rate-level functions for a pure-tone signal at CF in the presence of a lower frequency-masking noise show both a shift to the right, i.e., to higher signal levels (suppression), and an increase in the background firing rate (due to excitation from the noise) as noise level is increased (Delgutte, 1990; Pang and Guinan, 1997). Only for very low signal levels could it be argued, on the basis of these physiological measurements, that signal threshold would be determined entirely by suppressive processes.

Both the present experiments showed that suppression seems to be maximal for signal levels between about 40 and 60 dB SPL. It is important to note, however, that this measure of suppression does not necessarily reflect the decrease in signal excitation produced by the simultaneous masker. If the signal is compressed, then a given decrease in signal *level* reflects a smaller decrease in signal *excitation*. Thus, the apparently greater suppression between 40 and 60 dB SPL may in part reflect the greater compression of the BM in that level region.

The assumption of this study has been that psychophysical suppression primarily reflects the suppression measured at the level of the BM and the auditory nerve. This assumption is supported by the similarity in the form of our data with those of Delgutte (1990). In contrast, some investigators have argued that psychophysical suppression probably also reflects mechanisms such as neural inhibition occurring at higher stages of the auditory pathways (Champlin and Wright, 1993). This claim was based on results showing a relatively slow ($>$10 ms) build-up for some effects ascribed to suppression. However, the main effect found by Champlin and Wright (1993) has since been shown to be compatible with an instantaneous (and hence peripheral) suppression mechanism (Bacon, 1996). Furthermore, in line with previous studies, the results from the present study indicate a very rapid release from suppression; the gap between the beginning of the masker offset and the peak of the signal in our experiment 2 is only 6 ms. Thus, the assumption that psychophysical suppression is mediated primarily by peripheral processes remains reasonable.

B. Possible implications for comodulation masking release (CMR) and thresholds in fluctuating maskers

While we have ascribed the threshold differences in our off-frequency conditions to suppression, at least one alternative explanation is possible. It may be that the off-frequency masker, by exciting many frequency channels that are not excited by the signal, allows an across-channel comparison of ''internal'' stimulus level within the noise gap that is not possible in the on-frequency condition. This cue may also be used in conditions eliciting comodulation masking release (CMR) (Hall *et al.*, 1984). However, we think that a CMR-like mechanism is not likely to account for our data for the following reasons. First, the contralateral masker should have provided a CMR-like cue, even in the on-frequency condition. Second, similar amounts of suppression have been found in pulsation-threshold studies (Duifhuis, 1980; Shannon, 1986) where CMR should not play a role.

Conversely, it may be that some effects previously ascribed to CMR may in part be due to suppression. For instance, Buus (1985) found a large release from masking by introducing level fluctuations in a masker well below the signal in frequency. He argued that the release may be due to the auditory system comparing the fluctuations across different frequency channels—something not possible with an on-frequency masker. However, a release from masking would also be predicted based on the effects of suppression, as follows: suppression would generally reduce the effective level of the signal more at a masker peak than in a masker valley, due to the nonlinear growth of suppression. Thus, the release from masking introduced by brief reductions in masker level will be greater for off-frequency maskers than for on-frequency maskers, where suppression plays no role.

A similar argument can be applied to the findings reported by Zwicker (1976), Nelson and Swain (1996), and Gregan *et al.* (1998) that the peak-to-valley difference in thresholds for a brief signal in a modulated masker is greater for signal frequencies well above the masker frequency than for those at or below the masker frequency. It has been argued that this difference is due in part to the upward spread of masking found for stationary maskers; the difference is thought to reflect the internal difference in excitation between the peak and the valley of a masker at the signal frequency (Zwicker, 1976). However, at rapid modulation rates and large modulation depths, thresholds in masker valleys have been found to be determined by forward masking from the masker peak, rather than by simultaneous masking from the masker valley (Gregan *et al.*, 1998). In such cases, the explanation in terms of stationary maskers does not hold. It seems possible that the differences in such cases can be accounted for by suppression: consider a 100% amplitude-modulated sinusoidal masker and a brief sinusoidal signal well above the masker in frequency. When the signal is presented at a time corresponding to a peak in the masker envelope, thresholds will be determined by the excitation *and* suppression produced by the peak. When the signal is presented in a masker valley, the signal is no longer suppressed by the masker peak. Thus, the peak-to-valley difference in thresholds represents the combined decay of forward masking and release from suppression. When the signal is at the same frequency as the masker, the peak-to-valley difference reflects only the decay of forward masking. Therefore, the peak-to-valley threshold difference is expected to be smaller for on-frequency maskers than for maskers well below the signal frequency, as has been found.

For these reasons, caution should be used in interpreting CMR purely in terms of across-channel comparisons in situations where masker energy below the signal is sufficiently high to potentially produce suppression effects.

C. An alternative theory

The psychophysical effects of suppression on masking have been controversial. Although early measures of suppression found large effects, later studies showed that some of these effects may have been due to factors other than suppression, such as confusion. Lutfi (1984, 1988) proposed that it may not even be necessary to consider the effects of suppression when explaining the difference between tuning curves measured in forward and simultaneous masking. While this theory is controversial (Lutfi, 1985; Moore, 1985), it has been endorsed in a review article (Jesteadt and Norton, 1985) and seems not to have been totally disproved even now (Sommers and Gehr, 1998). A stated, and fundamental, assumption of Lutfi's model is that masking patterns in forward masking are identical to those in simultaneous masking, but shifted down in level by a fixed dB amount. It is clear from the present data that this assumption is not tenable, at least for the frequency intervals tested here; differences between simultaneous and nonsimultaneous conditions are much greater for the off-frequency conditions than for the on-frequency conditions. Thus, Lutfi's model does not hold at least for masker–signal frequency ratios between 1.67 and 2.33. This somewhat restricts the applicability and attractiveness of the model.

IV. SUMMARY

Suppression seems to play a major role in the nonlinear upward spread of masking, especially at signal levels below 40 dB SPL. However, it seems that masking is rarely, if ever, purely suppressive. At signal levels higher than 40 dB SPL, suppression is substantial, but not necessary for the nonlinear upward spread of masking. The results suggest that the theoretical underpinnings of psychoacoustic models that equate simultaneous-masking patterns with excitation patterns may require reconsideration. In particular, the assumption that the upward spread of masking is due solely to a broadening of auditory filters at high levels (Glasberg and Moore, 1990; Rosen and Baker, 1994) seems questionable. As many stimuli in the natural environment are masked by simultaneous sounds, these assumptions may still provide a useful model of *effective* processing. Nevertheless, it should be remembered that the amount of excitation may be considerably less than that estimated in simultaneous-masking tasks. This may have some implications for the underlying theory in models of loudness or intensity discrimination, which assume a summation of excitation across frequency (Zwicker and Scharf, 1965; Florentine and Buus, 1981; Moore *et al.*, 1997).

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APPENDIX: AVOIDING POSSIBLE CONFOUNDING FACTORS

1. Effects of ''confusion''

Differences between simultaneous and nonsimultaneous masking have been interpreted as evidence for suppression in the past (Houtgast, 1972, 1973, 1974; Shannon, 1976; Weber and Green, 1978; Moore, 1980b). However, in certain stimulus conditions other effects have also been shown to play a role. For instance, when the signal is at the same frequency as the masker, the signal may be confused with a continuation of the forward masker, resulting in elevated thresholds. The addition of a second stimulus, gated with the masker but at a different frequency, may provide a cue for the detection of the signal and thus reduce thresholds without actually producing any suppression. Similarly, a reduction in threshold as the signal moves away from the masker in frequency may reflect an increase in perceptual dissimilarity between the masker and signal as well as the effects of frequency selectivity. The role of confusion and its alleviation have been studied in considerable depth (Moore, 1980a; Moore and Glasberg, 1982, 1985; Neff, 1985, 1986). Briefly, ''confusion'' can occur if the masker and signal are in the same frequency region and (1) both masker and signal have the same bandwidth (e.g., a sinusoidal masker and signal), or (2) the masker is a narrow-band noise and the signal can be confused with the inherent fluctuations of the masker. Thresholds affected by confusion are generally less stable, are more susceptible to practice effects, and can depend strongly on the starting level of an adaptive threshold-tracking procedure (Neff, 1985, 1986). Confusion can generally be alleviated by introducing a temporal ''cue'' to demarcate the masker. This cue can be either ipsi- or contralateral (Moore and Glasberg, 1982).

The stimulus configuration used in the present experiment was designed to avoid confusion effects. The masker bandwidth of 500 Hz was sufficiently wide to avoid slow, audible fluctuations in the envelope, and the percept of the 10-ms sinusoidal signal was rather different from that of the noise. Furthermore, a contralateral noise was gated with the masker in all conditions to further cue the temporal boundaries of the masker. Pilot studies using a range of different starting levels in the adaptive tracking procedure showed no effect of starting level. Also, no long-term practice effects were observed for any of the listeners. Thus, we conclude that confusion probably did not play a major role in our experiment.

2. Physical overlap of nonsimultaneous stimuli in the auditory periphery

The underlying assumption of this study is that, since suppression is thought to be the result of nonlinear interactions on the BM, suppression only occurs when the stimuli physically overlap in time on the BM. Due to the filtering action of the cochlear partition, it is possible that acoustic stimuli that are separated in time may in fact overlap temporally in the cochlea. This has been termed ''ringing in the auditory filters.'' A number of studies have investigated the possible effects of peripheral stimulus interactions. Carlyon (1988), by measuring thresholds as a function of masker duration, found that forward-masked thresholds behaved like simultaneous-masked thresholds at a center frequency of 250 Hz when the signal was placed very close to the masker. He ascribed this effect to continued ringing in the auditory filters, effectively producing simultaneous masking, even though the acoustic signals did not physically overlap. At a signal frequency of 2 kHz, no such effects were found. His masker and signal were both gated with 2-ms ramps, the signal had a half-amplitude duration of 5 ms, and the shortest masker–signal interval tested was 1 ms (0–V points in the envelope). Even in this situation, no evidence for interaction was found at 2 kHz, suggesting that filter ringing did not limit performance to any significant degree.

Vogten (1978) studied peripheral interactions by manipulating the phase relationship between a sinusoidal masker and signal, both at 1 kHz. Vogten used ramps of 10 ms and a signal with no steady state. He found no evidence for interaction at 1 kHz even when the masker and signal overlapped at the -6-dB points in their envelopes. In this condition, the delay between the beginning of the masker offset and the peak of the signal is 10 ms, which is comparable to the 9 ms used in experiment 1 of the present study. In a gap-detection study, Shailer and Moore (1987) found that the phase relationship between the stimulus portions preceding and following the gap could influence performance at short gap durations (up to 8 ms) for signal frequencies up to and including 1 kHz. They interpreted this in part as being due to cancellation and/or addition in the auditory filters. No such effect was found at 2 kHz.

In summary, there is no evidence suggesting that ringing in the auditory filters affects performance at frequencies of 2 kHz or higher. As the lowest center frequency tested here is 2.4 kHz, we can conclude that peripheral interactions probably play no role in our experiments.

[1]Oxenham and Plack (1997) plotted masker level as a function of signal level. Thus, the slopes in their graphs are the reciprocal of the typical growth-of-masking functions discussed here.

[2]Off-time listening refers to the possibility that listeners can attend to the decay of an ''internal representation'' of the signal, after the offset of the physical stimulus, thereby enhancing detection. The addition of a backward masker should reduce the availability of this cue.

[3]The value of 40 dB SPL is based on the physiological findings and accompanying model of Yates *et al.* (1990) and Yates (1990). The assumption also corresponds reasonably well with the psychophysical data of Oxenham and Plack (1997), who found a breakpoint of around 45 dB SPL, and Plack and Oxenham (1998), who in a different set of tasks found a breakpoint of around 35 dB SPL. It should be noted, however, that the exact level of this breakpoint is still a matter of debate. Direct physiological measurements of BM response have resulted in estimates ranging from 20 dB (Ruggero *et al.*, 1997) to 65 dB SPL (Murugasu and Russell, 1995). These differences may result in part from differences in calibration procedures, but may also reflect real differences within and across species.

[4]Due to the partitioning of the data from the off-frequency conditions into ranges below and above 40 dB SPL, different masker levels were included for different individuals. In order to pool the data to obtain summary slopes, the individual data were first swept to eliminate differences in means on both axes.

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