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Effect of masker level on overshoot in running- and frozen-noise maskers

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Masked thresholds were measured with running- and frozen-noise maskers. The 5-kHz signal was 2 ms in duration. The masker was low-pass noise (20 Hz–10 kHz); its total duration was 300 ms. The overall level of the masker was 30, 50, or 70 dB SPL. The onset of the signal was delayed by 0, 3, 8, 18, 198, or 278 ms relative to the onset of the masker. In all frozen-noise measurements, the signal was added to the same fine structure of the noise. Overshoot in frozen noise was measured for two starting phases of the signal that led to a 10-dB difference for large signal-onset delays. In all three configurations (running noise and frozen noise with two different signal phases) masker level had a similar influence on overshoot. At the intermediate masker level (50 dB SPL), a significant amount of overshoot (up to 15 dB) was observed in all three conditions. At the low and the high masker levels, overshoot was very much reduced, and even became negative in most conditions for the 30-dB-SPL masker. For the 50-dB frozen-noise masker, the total variation of thresholds with signal phase was 8 to 11 dB for long signal-onset delays, but only 3 to 6 dB for short delays. For the low- and high-level maskers, where only a small overshoot was observed, the threshold variation with phase for a signal at masker onset was the same as that for the long-delay condition. An explanation for the variation of signal detectability with masker level is proposed that refers explicitly to the compressive input-output characteristic of the basilar membrane at intermediate levels.

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INTRODUCTION

The term *overshoot* refers to the fact that a brief signal is sometimes harder to detect if it is presented at the onset of a masker than if it is presented with a long onset delay. About 30 years ago the first experiments to investigate this phenomenon were conducted (Samoilova, 1959; Scholl, 1962; Zwicker, 1965a,b; Elliott, 1965). In the last decade overshoot has received renewed attention which can partly be attributed to the fact that no satisfactory explanation has been offered so far (e.g., Bacon and Viemeister, 1985; Bacon and Moore, 1986; Carlyon, 1987, 1989; Carlyon and Sloan, 1987; Champlin and McFadden, 1989; McFadden, 1989; Bacon, 1990; McFadden and Champlin, 1990; Bacon and Smith, 1991; Schmidt and Zwicker, 1991; Carlyon and White, 1992; Bacon and Takahashi, 1992).

It is known that overshoot is influenced by many parameters like frequency and duration of the signal, spectral composition and level of the masker, prior stimulation, hearing impairment, and even consumption of aspirin by subjects. Since these effects and the possible relation to neural short-term adaptation have been reviewed in several recent publications (e.g., Bacon and Smith, 1991; Carlyon and White, 1992; Bacon and Takahashi, 1992), we will concentrate on the influence of masker level on overshoot.

Zwicker (1965a) measured overshoot of a 5-kHz 2-ms signal in a broadband noise at spectrum levels between

–15 and 45 dB. He found an increase of overshoot from 0 to about 10 dB for an increase in the masker spectrum level up to +5 dB. For all higher masker levels, up to a spectrum level of 45 dB, overshoot remained constant at this value. Fastl (1976) used a uniform masking noise of 16-kHz bandwidth and an 8-kHz signal of 2-ms duration. The spectrum level in the 8-kHz region ranged from –15 to +25 dB. Similar to Zwicker's results, overshoot increased for spectrum levels up to 5 dB and remained constant for all higher levels. The amount of overshoot, however, was much larger than reported by Zwicker, being as much as 30 dB.

The results of more recent measurements revealed a different dependence of overshoot on masker level. Bacon (1990) measured overshoot for a 10-ms 4-kHz signal. The noise had a bandwidth of 8 kHz and was presented at spectrum levels between –10 and 50 dB. Overshoot grew nonmonotonically with level, reaching an asymptote of 10 to 15 dB at spectrum levels of 20 to 30 dB, before decreasing at higher levels. For a majority of the subjects, overshoot at a 50-dB spectrum level was as small as it was at –10 dB.

Carlyon and White (1992) measured overshoot with broadband maskers for signal frequencies of 2.5 and 6.5 kHz. At 2.5 kHz, overshoot values were independent of the masker level. At 6.5 kHz, overshoot for most subjects was larger at a masker spectrum level of 25 dB than at either 5 or 45 dB. However, two of the subjects showed either no

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level dependence or an inverse behavior, with the smallest overshoot occurring at the intermediate masker level.

Bacon and Takahashi (1992) collected data for masker spectrum levels between 20 and 40 dB. Their signal was a 10-ms 4-kHz sinusoid. For the majority of their subjects, overshoot decreased monotonically with increasing masker level. The range of individual overshoot values at the lowest masker level was 7 to 26 dB, while at the highest level it was 2 to 14 dB.

The present study is concerned with level effects in overshoot conditions for running- and frozen-noise maskers. There are two reasons to investigate overshoot effects for frozen-noise maskers. We know from recent experiments that thresholds of short signals in frozen noise can be much lower than those in running noise and that they vary strongly with the temporal position of the signal in the noise and with the signal starting phase (Langhans, 1991; Langhans and Kohlrausch, 1992). These results for frozen-noise maskers indicate that with the lack of statistical variability in the masker waveform, additional cues like slight timbre differences caused by the addition of the signal can be evaluated by the subjects. It is unclear whether the use of such subtle cues could help to detect a signal placed close to the onset of a frozen noise and thus lead to smaller overshoot values than for a running-noise masker.

A second motivation for the use of frozen noise stemmed from theoretical predictions derived from a model for temporal processing. This model has been applied to nonsimultaneous-masking data and other temporal effects and is described in detail elsewhere (Püschel, 1988; Kohlrausch *et al.*, 1992; Dau *et al.*, 1994). The relevant elements of the model are a (linear) basilar-membrane stage followed by a series of adaptive-gain-control stages with time constants between 5 and 500 ms that result in a loglike compression for signals with a *stationary* envelope. Fast fluctuations in the envelope of an input signal like in amplitude modulation or the fluctuations of a noise envelope are, however, transformed more linearly and lead to larger variations in the internal representation of the stimulus. The detection criterion used to predict thresholds is derived from the stationary behavior in such a way that, for a stationary signal, the just-noticeable change in level is 1 dB at all levels.

For a signal placed at the onset of a frozen-noise masker, the model predicts a somewhat *lower* threshold than for a signal with a long onset delay. The reason for this lower threshold is that both the signal and the masker are less compressed at the onset of the masker than at a later point. The addition of the signal at the onset of the masker thus leads to a greater change in the internal representation than for one positioned later in the masker, and thus the signal is detected more easily.

A negative overshoot (or undershoot) for noise maskers has been observed only in some listeners under a limited set of conditions (e.g., Osman and Raab, 1963; Wilson and Carhart, 1971; Bacon, 1990, Figs. 2 and 3; Bacon and Smith, 1991, Fig. 1; Bacon and Takahashi, 1992, Fig. 2), and little emphasis has been given to these findings. When

we started the experiments described in this paper, we were interested in checking whether this discrepancy between the model prediction and the majority of data is a consequence of using frozen noise in the simulation and running noise in the measurements, or whether the model is incorrect in this respect.¹

I. METHOD

A. Stimuli and apparatus

All stimuli were generated digitally, converted to analog voltages with a two-channel, 16-bit D/A converter at a sampling rate of 30 kHz, and low-pass filtered at 10 kHz.

To obtain the noise masker, a complex spectrum of frequency components between 20 Hz and 10 kHz was constructed. All frequency components had a constant amplitude, the phase values were randomly distributed between 0 and 2π . The inverse FFT of this spectrum results in a cyclic noise signal consisting of 2^{15} samples with a period of 1.1 s. In experiments with frozen noise, a *fixed* 300-ms part of this time waveform was used. This fixed noise sample was presented in all intervals of all runs for a given signal delay (for more details, see Sec. I C below).

In contrast, in experiments with running noise, *different* 300-ms sections of this 1.1-s noise were presented to the listener in every interval of a run. These noise bursts were copied from the long noise waveform by randomly choosing one of the 2^{15} values as starting point. For every run, a new 1.1-s noise waveform was calculated by using a new set of phase values.

The noise maskers were presented at three different levels: 30, 50, and 70 dB SPL, corresponding to spectrum levels of -10, 10, and 30 dB. All noise bursts had a rectangular temporal envelope, i.e., the duration of the onset ramp was only influenced by the analog low-pass filter at 10 kHz.

The signal was a 5-kHz sinusoid with a total duration of 2 ms. It was gated with 1-ms raised-cosine on and off ramps. The signal was added to the masker with one of the following onset delays: 0, 3, 8, 18, 198, or 278 ms. The onset delay of the signal was defined as the time between masker onset and the onset of the signal's ramp. In the running-noise measurements, the starting phase of the signal, defined with respect to its envelope, was always zero. In the frozen-noise measurements, the starting phase was an additional parameter.

At each masker level, the following three measurements were performed:

(1) Thresholds of a signal placed with a 278-ms delay in the noise bursts. This measurement was performed for nine values of the starting phase between 0 and 2π in frozen noise (signal phase increased in steps of $\pi/4$), and in addition for the signal in running noise. The values for the starting phases 0 and 2π , although physically identical, were measured separately to test the reliability of the data.

(2) Measurement of the thresholds for six temporal positions of the signal, with onset delays between 0 and 278 ms. This measurement was performed for frozen noise for those two signal-phase values which gave the highest and

the lowest thresholds in the first measurement.

(3) Thresholds of a signal placed close to the onset of the masker burst at that temporal position for which the highest thresholds had been found in the second measurement. The onset delay was chosen for each subject separately and was either 0 or 3 ms. This measurement again was performed for nine values of the starting phase in frozen noise and in addition for the signal in running noise.

All measurements reported in this paper were performed diotically, i.e., masker and signal were presented identically to both ears of the subjects.

B. Subjects and procedure

The experiments were performed by three subjects, who had experience in psychoacoustic experiments and had several hours of training in overshoot conditions. The subjects ranged in age from 24–28 years. The subjects were seated in a sound-insulated booth and listened to the stimuli via headphones (Beyer DT 880M with diffuse-field equalizer). The computer controlled the experiments and read the answers of the subjects.

The masked thresholds were measured using a standard three-interval forced-choice (3IFC) procedure with adaptive level adjustment. The three noise intervals had a duration of 300 ms each and were separated by interstimulus intervals of 500 ms. In one randomly chosen interval, the signal was added to the noise masker. The task of the subject was to specify the interval containing the signal. The signal level was varied according to a two-down one-up procedure (Levitt, 1971). A run began with the signal level well above the expected threshold. The initial step size for the level change was 10 dB and was halved (dB measure) after each second turnaround point of the signal level. When the step size became smaller than 1 dB, it was set to the constant value of 1 dB and the run was extended over 20 more trials. The threshold levels were calculated as median signal level within these last 20 trials of each run. Typically, 4 to 6 reversals of the signal level occurred during the 20 trials. For each condition this procedure was repeated four times in different sessions. Data in the figures are calculated as the median values from these four runs and are shown together with the corresponding interquartile ranges.

C. Construction of the frozen-noise measurements

For different temporal positions of a short signal in frozen noise, thresholds can vary by more than 10 dB (Langhans, 1991). This value corresponds to the order of overshoot in running noise. If the signal was added to a fixed frozen-noise sample with a variable onset delay, a possible overshoot effect could become invisible due to this fine-structure effect. Hence, it is very important that the signal is always added to the same fine structure in all frozen-noise measurements.

To meet this requirement a noise sample of 1 s was generated. Within this noise a fixed temporal position for the signal was chosen where the phase dependence of the threshold was maximal (i.e., about 10 dB).² According to

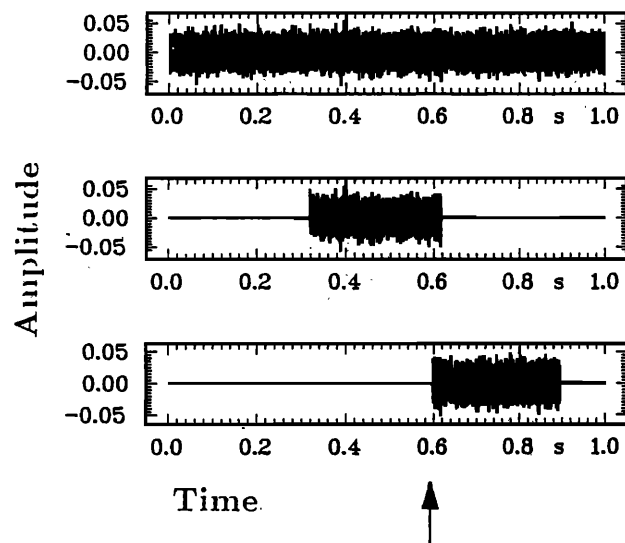


FIG. 1. Illustration of the generation of the frozen-noise masker bursts. The top row shows the 1-s frozen noise. The signal onset (marked by the arrow at the bottom) occurred at 0.6 s. The middle trace shows the 300-ms masker burst which was used in the measurement with a 278-ms delay between masker and signal onset. The bottom row shows the masker for the delay of 0 ms between masker and signal.

the desired masker-signal onset delay, a 300-ms section surrounding this time point was cut out of the long noise signal with a rectangular window. This procedure is illustrated in Fig. 1. The top row shows the 1-s noise where the arrow (bottom) marks the position of the signal. The situation for a 278-ms delay between masker and signal is shown in the middle trace and the masker used for the 0-ms delay is shown in the bottom trace.

II. RESULTS

A. Signal detectability as a function of masker level

In Fig. 2, the influence of signal phase on masked thresholds in a frozen-noise masker of 50 dB SPL is shown for a short-delay (a) and a long-delay condition (b) by the open symbols. The closed symbols to the left in both panels indicate the thresholds in running noise for the same signal delay. The different symbols indicate individual data from the three subjects.

The results for frozen noise always show a maximum at phase $\pi/2$ and a minimum at phase $3\pi/2$. In the long-delay condition, the threshold difference between these two phases is 8 to 11 dB. The signal thresholds for running noise at this delay are higher than the arithmetic average of those for frozen noise, but they do not form an upper limit for the frozen-noise thresholds as we found in recent experiments at 1 kHz (Langhans and Kohlrausch, 1992).

The measurements in the short-delay condition were performed for that signal position close to the masker onset that led to the highest threshold (cf. Fig. 3). This time point was 0 ms for subjects AS and SM and 3 ms for subject RK. The phase dependence of the thresholds in frozen noise is much smaller than in the long-delay condition and amounts for two of the subjects to no more than 3 dB. The variation of threshold with phase is largest for

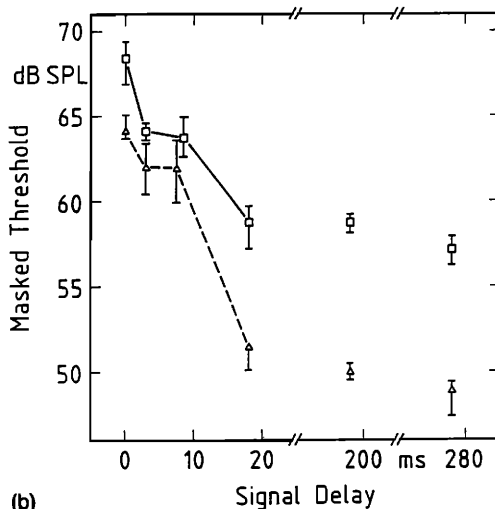
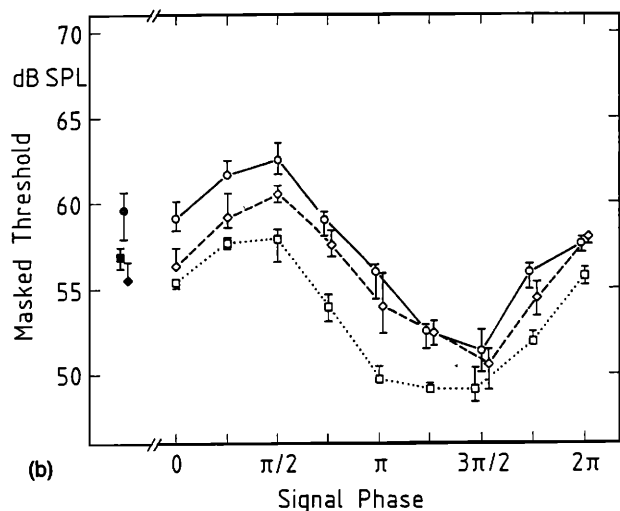
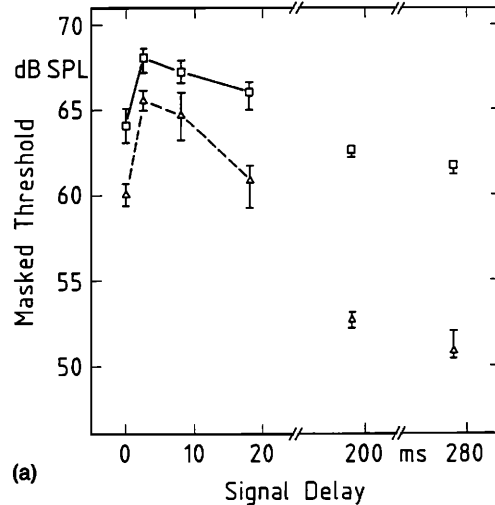
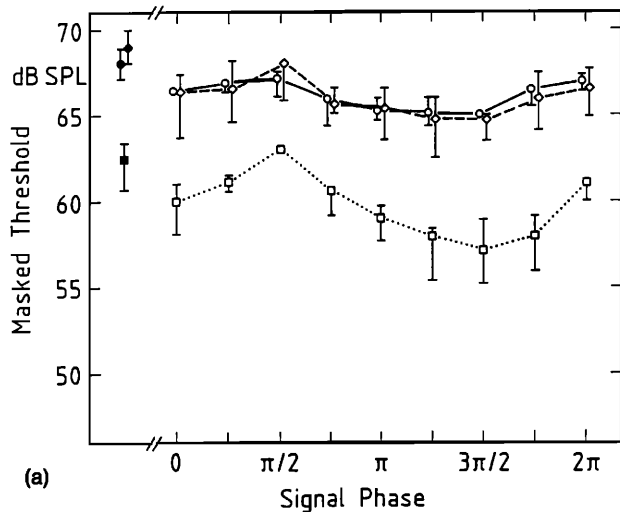


FIG. 2. Thresholds of a 2-ms 5-kHz signal in 300-ms bursts of running and frozen noise. The flat-spectrum noise had a bandwidth of 10 kHz and a level of 50 dB SPL. Open symbols indicate the results in frozen noise, filled symbols indicate running-noise data. The abscissa denotes the starting phase of the signal for the frozen-noise results. Circles are used for subject RK, diamonds for subject AS and squares for subject SM. Median and interquartiles of four runs for each parameter value and subject are shown. (a) Data for a short-delay condition (onset delay of 0 ms for AS and SM and of 3 ms for RK) and the (b) the data for a long-delay conditions (onset delay of 278 ms).

that subject (SM) who is most sensitive in the short-delay condition. In this condition, the running-noise thresholds form an upper limit for the frozen-noise values.

The amount of overshoot for the frozen noise was determined by placing the signal at various delays relative to the masker onset. The results are shown for each subject in a separate panel of Fig. 3. The measurements were performed for the phase values $\pi/2$ (squares) and $3\pi/2$ (triangles) which corresponded to the maximum and the minimum signal thresholds, respectively. Experiments at the phase $3\pi/2$ show an overshoot of up to 15 dB. At $\pi/2$ all subjects measured a smaller overshoot of 3 to 10 dB. The maximum in threshold did not always occur for the 0-ms delay [see Fig. 3(a)].

The same measurements were repeated at two other masker levels, namely 30 dB SPL and 70 dB SPL. The

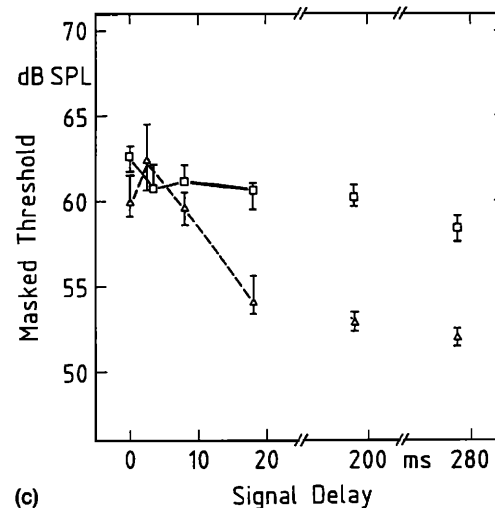


FIG. 3. Masked thresholds of the 2-ms signal in frozen noise as a function of the signal delay. The masker level was 50 dB SPL. Squares indicate the results for the signal phase $\pi/2$ and triangles the data for the phase $3\pi/2$. Median and interquartiles of four runs for each parameter value and subject are shown. (a) Results for subject RK. (b) Results for subject AS. (c) Results for subject SM.

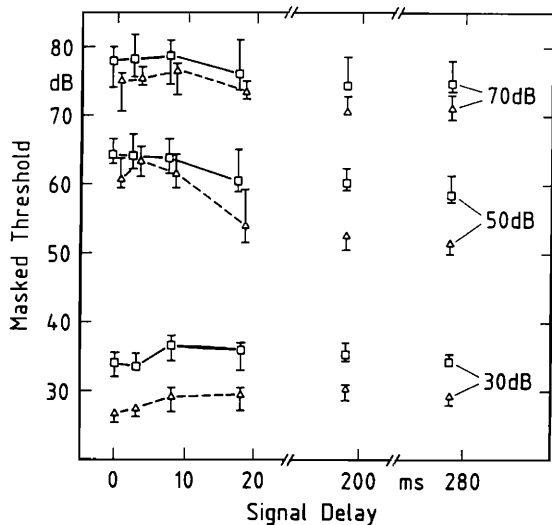


FIG. 4. Masked thresholds of the 2-ms signal in frozen noise as a function of the masker-signal delay for the masker levels 30, 50, and 70 dB SPL. Squares indicate the results for the signal phase $\pi/2$ and triangles the data for the phase $3\pi/2$. The data show the median and the corresponding interquartile ranges of the 12 individual threshold values.

same three subjects as before participated in the measurements determining overshoot, while the influence of signal phase on the threshold was studied with two of these subjects (AS and RK). The effect of signal phase on the thresholds at these two levels can be summarized as follows: (1) As at 50 dB SPL, the frozen-noise thresholds resemble one period of a sinusoid. (2) The minimum of this pattern occurs for the 70-dB masker at a phase value of $3\pi/2$ (as for the 50-dB masker), but for the 30-dB masker at a phase value of $5\pi/4$. (3) The total variation of thresholds with phase is about 8 dB at 30 dB and about 5 dB at 70 dB and is the same in the short- and the long-delay positions. (4) Running-noise thresholds are generally in the upper-half range of the corresponding frozen-noise thresholds.

Overshoot in frozen noise was again determined for two different phase values of the signal. The results for all three masker levels are summarized in Fig. 4. Data in this figure are calculated as median values from the 12 individual runs of the three subjects and are shown together with the corresponding interquartile ranges. Squares indicate results for a signal phase of $\pi/2$ and triangles indicate results for a signal phase of $3\pi/2$.

Compared to the results at 50-dB masker level, the curves at 30- and 70-dB masker level are flatter. At 30 dB, the signal is even easier to detect for a position at the masker onset than at the end. For the signal phase of $3\pi/2$ (triangles), such a negative overshoot occurs not only in the median values, but also in the individual data of each subject.

The figure also indicates a strong level nonlinearity in signal detectability, in particular at short signal delays. This nonlinear aspect of overshoot measurements is emphasized in Fig. 5, where signal thresholds [$10 \log(E/N_0)$] in *running noise* have been plotted as a function of masker level. These measurements were performed by one subject

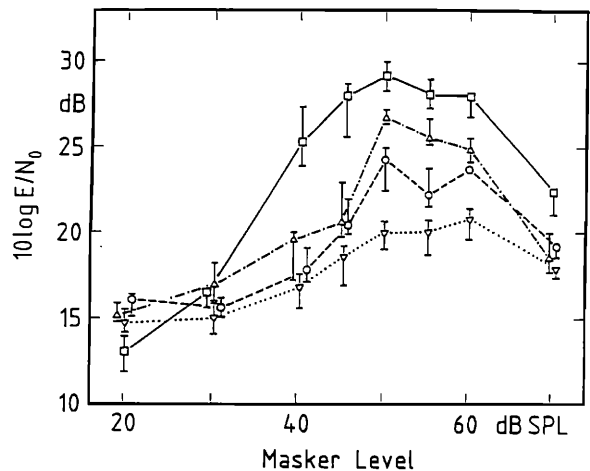


FIG. 5. Masked thresholds of the 2-ms signal in running noise as a function of the masker level. Signal thresholds are expressed as $10 \log(E/N_0)$. The parameter is the signal delay. Squares: short delay condition (median of values for 0, 3, and 8 ms delay); triangles: 18-ms delay; circles: 48-ms delay; inverted triangles: long-delay position (median of values for 198- and 278-ms delay). Median and interquartiles of four runs for each parameter value are shown for one subject (RK).

(RK) and included more masker levels and signal delays than the main experiments. The parameter in the figure is the onset delay of the signal. At all signal delays, thresholds vary nonmonotonically with masker level. The variation is largest for the short-delay condition (squares), but even at delays of more than 200 ms (inverted triangles), the relative detectability varies by 6 dB with masker level. All three curves representing a signal position within the first 50 ms after masker onset reach their maximum at a masker level of 50 dB. In the long-delay condition, thresholds increase up to a masker level of 60 dB.

B. Overshoot as a function of masker level

The experiments in frozen noise have shown that both the masker level and the starting phase of the signal affect overshoot. In Fig. 6, the amount of overshoot is represented as a function of the masker level for both phases $\pi/2$ (squares) and $3\pi/2$ (triangles) in frozen noise and for running noise (circles). Individual overshoot values were calculated in the following way: The reference value was the median threshold value of the eight single measurements for the two longest delays 198 and 278 ms. The value of overshoot resulted from the difference between this reference and the highest threshold within the first 10 ms after masker onset. If thresholds were lower in the onset region than the reference value, the lowest value was chosen to indicate the maximal undershoot. The data points in Fig. 6 represent the averages of these individual overshoot values.

In all three conditions, overshoot is maximal at the intermediate masker level. In frozen noise, the maximum overshoot was obtained with a signal phase of $3\pi/2$ and the minimum overshoot was obtained with a signal phase of $\pi/2$. The overshoot for running noise fell between these two extremes. At the lower masker level of 30 dB SPL, the

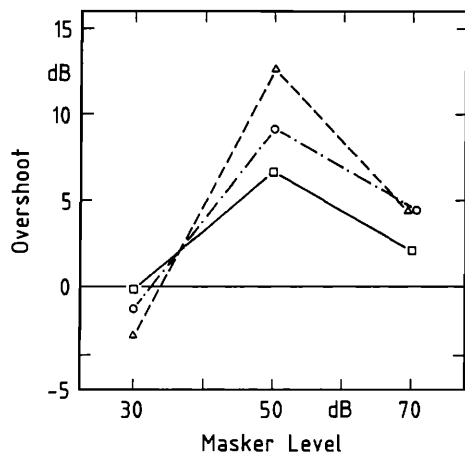


FIG. 6. Overshoot as a function of the masker level. Circles indicate the magnitude of overshoot in running noise. Squares indicate the frozen-noise data for the signal phase $\pi/2$ and triangles indicate the results in frozen noise for the phase $3\pi/2$. Average values of the three listeners.

average overshoot values are always negative. From the nine individual values at this level, only those in running noise and in frozen noise for phase $\pi/2$ of subject RK are positive with a maximum of 3 dB. Small overshoot values are also found at 70 dB SPL, although the values are on average a few dB higher than at 30 dB SPL and they are negative in only one individual case (subject AS for signal phase $\pi/2$). While at the intermediate masker level of 50 dB SPL, the amount of overshoot for the three conditions is systematically ordered for all subjects, this is not the case at the two extreme masker levels.

III. DISCUSSION

A. Effects of signal phase

The results presented in this paper demonstrate that overshoot values of more than 10 dB can be obtained for a frozen-noise masker at an intermediate masker level. In addition, the nonmonotonic dependence of overshoot on masker level is similar for frozen- and running-noise maskers. A third result is that the amount of overshoot in frozen noise depends upon the starting phase of the signal, although the overall level dependence is similar.

Thresholds of a short signal in frozen noise are influenced by the deterministic interaction of masker and signal and thus depend on the signal's starting phase. The phase dependence can be illustrated by using a vector diagram (Fig. 7). The masker and the signal are both represented by a vector and the angle between the two corresponds to the (relative) phase of the two fine structures. The masked threshold is reached if the sum of the two vectors matches a certain threshold criterion (circle in Fig. 7). If the masker and the signal are in phase, this criterion is reached with a minimal length of the signal vector. Since a decrease in the vector length cannot be detected for frozen-noise maskers and short signals, thresholds are highest for a signal added in antiphase to the masker (cf. Langhans and Kohlrausch, 1992).

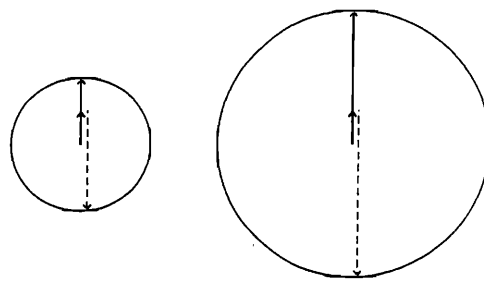


FIG. 7. Vector diagrams illustrating the addition of a masker and a signal of the same frequency. The solid vector in both diagrams represents the masker, and the thin vectors represent the signals for relative phase values of 0 (continuous) and of π (dashed). The circles around the origin of the masker vector indicate the just noticeable change in vector length. In the left panel this criterion is a change by a factor two (the diameter has twice the length of the masker vector). The length of the two signal vectors differs by a factor of 3 (9.5 dB). In the right panel the threshold criterion is a change by a factor of 4. The length of the two signal vectors now differs by a factor $\frac{5}{3}$ (4.4 dB).

An important additional parameter in the vector diagram is the relative length between the masker and the signal vector for a signal at threshold. If the criterion corresponds a doubling of the length of the masker vector (left panel in Fig. 7), the amplitude relation between the in-phase and the out-of-phase signal at threshold is a factor of three or 9.5 dB. The right half of Fig. 7 shows the situation for a threshold criterion that is equivalent to quadrupling the length of the masker vector. In such a situation, the amplitude relation between the in-phase and the out-of-phase signal is only $\frac{5}{3}$, which corresponds to a level difference of 4.4 dB. Because higher thresholds occur, for instance, for a signal placed at the onset of the masker, the right half of Fig. 7 might represent a short-delay condition, whereas the left half might represent a long-delay condition.

Thus with increasing signal-to-noise ratio at threshold, the variation of threshold with the starting phase decreases. Another consequence of this reasoning is a difference in overshoot for the in-phase and the out-of-phase signal. The threshold amplitude for the in-phase signal differs by a factor of 3 between the two vector diagrams which corresponds to a threshold change of 9.5 dB. The threshold of the antiphase signal changes only by $\frac{5}{3}$ which corresponds to 4.4 dB.

Such an idealized picture is in line with our results for the 50-dB-SPL frozen-noise masker (Figs. 2 and 3). For the large onset delay, the thresholds of the individual subjects vary with the signal phase by 8 to 11 dB [Fig. 2(b)]. For signals placed at the onset, where thresholds in general are much higher, the variation with phase is much smaller [2 to 6 dB, cf. Fig. 2(a)]. The variation at the onset position is largest for subject SM whose thresholds are lowest. Finally, the amount of overshoot is on average 6 dB smaller for a starting phase of $\pi/2$ (higher signal-to-noise ratio at threshold) than for a starting phase of $3\pi/2$ (lower signal-to-noise ratio), a value in agreement with the above example.

At the masker levels of 30 and 70 dB SPL, the influence of the signal phase is similar for the onset and the

long-delay position. Such a result is expected from the reasoning with the vector diagram, if the threshold criterion is not strongly elevated for the signal at the masker onset. And indeed, overshoot in all conditions, for frozen noise as well as for running noise, is smaller than at 50 dB (with one exception in the results of subject SM for frozen noise and phase $\pi/2$). This result agrees with other recent studies showing a relative maximum of the overshoot in running noise for spectrum levels between 20 to 30 dB (Bacon, 1990; Carlyon and White, 1992; Bacon and Takahashi, 1992), although the maximum for our subjects seems to occur closer to a spectrum level of 10 dB (cf. Fig. 6). The different level dependence in the results reported by Zwicker (1965a) and Fastl (1976) might be a consequence of applying a different experimental procedure (method of adjustment), as was pointed out by Bacon (1990).

For the 30-dB-SPL masker, we observe a negative overshoot for the signal with starting phase $3\pi/2$ in frozen noise. The effect is not very large, but it is the kind of behavior that we expected from our model predictions mentioned in the Introduction. In contrast to our recent simulations mentioned in footnote 1, however, the results with running noise also indicate a negative overshoot for two of the subjects. Thus it appears that a negative overshoot at low levels is not a particular consequence of using a deterministic masker, as our model predictions suggested.

B. Adaptation in auditory-nerve fibers and overshoot

Overshoot and especially the nonmonotonic level effects have been related by several authors to peripheral adaptation in the two populations of auditory nerve fibers (e.g., Champlin and McFadden, 1989; Bacon, 1990; McFadden and Champlin, 1990). In simplified terms, this argument is as follows. Fibers in the eighth nerve can be subdivided in two groups according to their physiological properties (e.g., Liberman and Simons, 1985). About 75% of the fibers have a low threshold and a high spontaneous activity, while the remainder have high thresholds and a low spontaneous activity. These two groups of fibers also differ in their onset response. Low-threshold fibers exhibit a large onset response that decreases over time due to adaptation. High-threshold fibers, on the other hand, show only a small onset response and thus much less adaptation (Rhode and Smith, 1985, but see below). For low to moderate masker levels, the response of the low-threshold fibers is dominant. These fibers respond to a short increment (corresponding to the "signal" in an overshoot measurements) in the level of a pulsed stimulus (the "masker") with a constant increment in firing rate, independent of the temporal position of the increment relative to the "masker" onset (e.g., Smith and Zwislocki, 1975). Since the response to the masker adapts over time, the neural signal-to-masker ratio (Bacon, 1990) increases with increasing onset delay, corresponding to a decrease in masked threshold. At high masker levels, the low-threshold fibers are saturated and the response is domi-

nated by the high-threshold fibers. Since these fibers exhibit only a small onset response, overshoot decreases for higher levels.

Although it is generally believed that peripheral adaptation is involved in overshoot, the above scheme is certainly not sufficient to explain all or even a major part of the observed effects (for a thorough discussion, see McFadden and Champlin, 1990). Probably most puzzling are the changes in overshoot due to aspirin consumption, prior noise exposure or with sensory-hearing impaired subjects (Bacon and Takahashi, 1992; Champlin and McFadden, 1989; McFadden and Champlin, 1990). In all these conditions, overshoot is reduced or disappears, because subjects become more sensitive in the *short-delay* condition. McFadden and Champlin (1990) discussed the idea that in aspirin as well as in TTS overshoot experiments, an unusual rebalancing effect between low- and high-threshold auditory nerve fibers could take place. If, at intermediate masker levels, subjects could use information supplied by high-threshold fibers (instead of information supplied by low-threshold fibers as in "normal" overshoot experiments), overshoot would disappear.

However, this idea as well as the above argument for the decrease of overshoot at high levels have to be questioned in the light of recent physiological results by Relkin and Doucet (1991). They showed that with a sufficient interstimulus time of at least 500 ms (a typical interval in psychophysical overshoot measurements), high-threshold fibers show a similar onset response as low-threshold fibers.

In the next section we present an alternative, probably related, idea, which links signal detectability directly to the nonlinear input-output characteristic of the basilar membrane. Although we have to admit that our consideration is not an explanation of overshoot per se, it seems to offer a different view on some of the above-mentioned puzzling effects in the short-delay conditions.

C. Basilar-membrane nonlinearities and signal detectability

In the input-output characteristic of the basilar membrane (BM), we can roughly discriminate three level regions (e.g., Johnstone *et al.*, 1986; Yates, 1990; Ruggero and Rich, 1991). At low levels up to about 40 dB above absolute threshold, the response is rather linear. At intermediate levels between about 40 and 80 dB, the function becomes strongly compressive. This compressive behavior is assumed to be a consequence of the saturation of the active processes and to work instantaneously. At the highest levels above about 80 dB, the function again tends to be more linear. This compressive characteristic is only observed for signal frequencies close to the resonant frequency of a particular place on the BM. For frequencies of about half an octave (or more) below the resonant frequency, the input-output characteristic becomes linear (e.g., Sellick *et al.*, 1982; Johnstone *et al.*, 1986). This frequency-dependent function of the mechanics is also reflected in the rate-intensity functions of auditory nerve fibers (Yates *et al.*, 1990).

Such a compressive characteristic should be reflected in a reduced differential sensitivity for levels in the midlevel range (midlevel "hump"). This *change* in sensitivity will, however, only be substantial (in terms of changes in the measured thresholds), if the detection task requires a large change in amplitude, as for short stimulus durations. Only then the differential effect of compression will be large compared to the limited resolution of psychoacoustic measurements.

Such an increased threshold at intermediate levels has been observed in intensity discrimination experiments for clicks (Raab and Taub, 1969). Here, a maximal value for $\Delta I/I$ of 1.2 was observed for a click level of 40 dB SL. This value was larger by a factor 3 than the results at click levels of either 20 or 80 dB SL. Carlyon and Moore (1984) reported a much larger midlevel deterioration in intensity discrimination for 30-ms signals than for 225-ms signals. A similar result is mentioned by Plack and Viemeister (1992) who observed in preliminary experiments that the "mid-level elevation in the Weber fraction is also larger for brief signals" (p. 1909).

This reasoning is also of relevance for masking experiments using short signals. The peak amplitude of a 5-kHz signal of 2-ms duration, placed with a large onset delay in running noise with a spectrum level of -10 dB, is about 38 dB compared to the typical peak amplitude of the noise within the 5-kHz auditory filter of 30 dB (cf. the very instructive waveform picture in Zwicker, 1965a, Fig. 12). At a 20-dB higher noise level the BM becomes compressive. Assuming, for simplicity, a linear characteristic for input amplitudes up to 50 dB and a compression ratio of 1:3 for peak amplitudes above 50 dB, the difference between noise peaks and signal peak at the BM output is no longer 8 dB (as at the lower level), but only 2.7 dB. This difference occurs because the noise amplitudes are still in the range of linear transformation, while the higher signal amplitude undergoes compression. In order to reach an 8-dB difference *after* compression, the signal level would have to be increased by another 16 dB.

As we have shown in Fig. 6, the threshold signal-to-noise ratio of a 2-ms signal varies nonlinearly with masker level for *all* onset delays and is highest in the level region of strong BM compression. However, the amount of nonlinearity decreases with increasing onset delay. If one wants to explain this result purely with the input-output characteristic of the BM one has to assume that the amplification caused by the active processes is reduced in the course of a longer noise masker and that the input-output characteristic becomes more linear. Such an idea has been discussed by Schmidt and Zwicker (1991) who mention the time constants of the outer hair cells of several milliseconds and the delayed activation of the efferent system as possible source for such a change. In our opinion, however, the current experimental data seem insufficient to state a change of BM mechanics within a few ten milliseconds.

Nevertheless, the influence of the various manipulations on signal detectability in the short-delay condition shows many parallels with what would be predicted from BM properties. If the cochlear amplifier is disrupted as in

the case of sensorineural hearing loss, the input-output characteristic of the BM will be more linear than in a healthy ear (Yates, 1990) and (ideally) no midlevel deterioration should occur. Overshoot measurements for subjects with permanent sensorineural hearing loss by Bacon and Takahashi (1992) revealed maximum overshoot values of only 5 dB, while a control group of normal-hearing subjects reached overshoot values between 7 and 26 dB. The difference was primarily due to *lower* thresholds in the short-delay condition for the hearing impaired subjects. In addition, the short-delay thresholds varied much more linearly with masker level for these subjects (cf. Fig. 1 in Bacon and Takahashi, 1992).

McFadden and Champlin (1990) observed that after aspirin administration, the absolute threshold for tonal signals was increased and the sensitivity in the short-delay overshoot condition was *improved*, i.e., thresholds were lowered. As the authors discuss thoroughly, aspirin is known to affect the active micromechanical processes on the BM in a similar way as does TTS and permanent hearing loss, i.e., it makes the input-output characteristic of the BM more linear.

BM mechanics also offers an explanation for the smaller level nonlinearities observed with longer signals. If the duration of a signal is increased, its threshold level decreases. As soon as the peak amplitude of the signal and the typical noise peaks are of similar magnitude, the compression will affect both the noise and the signal similarly and the nonlinear growth of the masked threshold—and thus overshoot—at intermediate levels will disappear.

The last application of this argument is the specific influence of masker bandwidth on short-delay thresholds in overshoot conditions. Usually, no overshoot is observed for maskers with a bandwidth of two critical bands or less (e.g., Zwicker, 1965b; Fastl, 1976/77; Bacon and Smith, 1991). From experiments that combined on-frequency narrow-band maskers with flanking bands of higher and lower frequency it was concluded that the presence of masker components *above* the on-frequency band was crucial for a large overshoot (McFadden, 1989; Schmidt and Zwicker, 1989). On the other hand, Carlyon and White (1992) pointed out that at a frequency of 6.5 kHz, which is higher than those used in the other cited studies, a substantial overshoot was obtained for a relative masker bandwidth of only 0.3 times the center frequency.

A narrow-band signal produces main excitation on the BM at the place tuned to its center frequency as well as excitation at more basal places on the membrane that are tuned to higher frequencies (sometimes referred to as upward spread of excitation or as accessory excitation). Since the characteristic of the BM is *linear* for the accessory excitation, a short increment in a narrow-band noise of intermediate level can be detected more easily at a place tuned to a frequency above the noise, since there, no compression occurs. As long as the subjects can rely on information from off-frequency channels tuned above the signal frequency, signal thresholds should grow linearly with masker level.

In overshoot measurements, two conditions have been

used that reduce the availability of accessory excitation and that lead to large overshoot values: (a) Increasing the relative masker bandwidth beyond about 20% to 30% (Zwicker, 1965b; McFadden, 1989; Bacon and Smith, 1991; Carlyon and White, 1992); (b) choosing a very high frequency for the on-frequency band (Carlyon and White, 1992).

A third condition has been applied in intensity-discrimination experiments, where similar nonlinear level effects as for overshoot are observed for high-frequency signals. Surrounding the signal with a notched noise and thus masking spread of excitation, reduces the performance at intermediate levels markedly compared to the condition without a notched noise (Carlyon and Moore, 1984).

We would like to finish with the qualification that, in order to understand the overshoot phenomenon, it is certainly not sufficient to consider only BM properties. For example, overshoot with broadband on-frequency maskers as well as the probably related midlevel hump in intensity discrimination are largest at frequencies above 1 to 2 kHz. No BM measurements are known to us that show a different behavior of active processes below and above 1 kHz.

Neural adaptation processes or even more central parts of the hearing pathway must be taken into account in understanding overshoot. However, we think that on the basis of our above arguments the contribution of BM mechanics is of greater relevance for this phenomenon than argued in other recent articles (e.g., McFadden, 1989; Bacon and Smith, 1991; Carlyon and White, 1992).

Note added in proof. It was brought to our attention by Brian C. J. Moore that some recent publications conclude that active processes might be less involved in cochlear tuning at low frequencies (Rosen and Stock, 1992; Wilson, 1992). Rosen and Stock measured auditory filter bandwidths between 125 and 1000 Hz at various levels. Generally, filter bandwidths increased with level, with the strongest effect at 1000 Hz and little or no effect at 125 Hz. In the conclusion, they refer to a remark in a review article by Wilson that at low frequencies "there appears to be a much smaller involvement of the active process" (Wilson, 1992, p. 81). Unfortunately, this statement by Wilson is not supported by a reference. Nevertheless, such a difference would be consistent with our discussion of the role of basilar-membrane nonlinearities in overshoot situations, since overshoot seems to be absent at low frequencies.

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¹A recent extension of this model to running-noise maskers revealed that for such a masker no undershoot is predicted (Dau, 1992; Dau *et al.*, 1994). Thresholds remain constant for all (simultaneous) positions of the signal. We explain this behavior as follows. For a running-noise masker, the detection is limited by the statistical properties of the noise. The statistical variation in the internal representation is larger for the onset part and smaller for the later part of the noise. In a parallel manner, the increase in internal excitation caused by the addition of the signal varies with its temporal position. In summary, the relative detectability of the signal is not increased close to the masker onset.

²The choice of such a temporal position for the signal was inspired by our previous experience with frozen-noise maskers where the most interesting effects in frozen noise—like the monaural-diotic threshold difference—occurred at such positions (Langhans and Kohlrausch, 1992).

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