Vibrotacile masking of Pacinian and non-Pacinian channels[a)]

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Vibrotactile masking functions were determined using sinusoidal and noise maskers. Results were nearly identical within the Pacinian (P) and non-Pacinian (NP) channels. At low masker SLs there was a substantial amount of negative masking which proved not be an artifact of stimulus definition. The critical parameters for successful prediction of the data were a peripheral threshold and internal Gaussian noise. Threshold shifts in cross-channel stimulation can be attributed to the masker exceeding the detection threshold of the signal channel.

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INTRODUCTION

Although it has been long established that vibratory sensations on the skin are mediated by at least two distinct sensory channels (Verrillo, 1963, 1968; Talbot *et al.*, 1968; Gescheider, 1976a), few vibratory masking experiments have been performed with the duplex nature of the tactile modality in mind (Green, 1975; Hamer and Verrillo, 1975; Verrillo and Caparo, 1975; Craig, 1976; Zambelli *et al.*, 1976; Ferrington *et al.*, 1977; Hamer *et al.*, 1978; Labs, 1978). Much of the work has focused on the effects of masker locus (Sherrick, 1964; Gilson, 1969a), masker-signal temporal relationship (Sherrick, 1964; Gilson, 1969a), number of maskers (Gilson, 1969b), and psychophysical method (Gescheider *et al.*, 1970; Snyder, 1973; Gilson, 1974). The impetus behind much of this effort has been provided by the development of cutaneous communication devices.

Progress in understanding the processing of vibrotactile information, whether for clinical applications or basic research, would be well served by an investigation of masking properties within and of interactions among the sensory channels that subserve single sites on the skin. Accordingly, the objectives of the present research were to explore masking effects within single vibrotactile channels, and to begin the process of determining to what extent a masker presented in one channel can influence the detection of a signal presented to another.

The receptor populations subserving vibrotaction manifest themselves psychophysically as a broken, U-shaped, threshold-frequency curve (Békésy, 1939; Verrillo, 1962, 1963; and others). When a rigid surround is used to prevent vibrations from spreading laterally as waves on the surface of the skin, thresholds become nearly independent of frequency at low frequencies, then decrease at the rate of about 12 dB/octave up to 200 Hz (Verrillo, 1963). In a series of articles involving correlation of information from receptor physiology, cutaneous anatomy, and psychophysics, Verillo showed indirectly that the U portion of the threshold curve, which ranges from about 40 to 700 Hz (peak sensitivity at about 250 Hz), is mediated by Pacinian (P) corpuscles. Which receptors are responsible for the flat, low-frequency portion of the threshold-frequency curve is not clear. We shall refer to this part of the threshold-frequency curve simply as the non-Pacinian (NP) portion. The P and NP channels are further distinguished by their properties of spatial and temporal integration. The P channel integrates energy over the area (Verrillo, 1963) and duration of the stimulus (Verrillo, 1965), whereas the NP channel exhibits negligible spatial or temporal integration (Verrillo, 1963, 1965; Green, 1975; Gescheider, 1976a).

The present experiments were all performed on the thenar eminence of the right hand. We were able to choose stimulus parameters so that according to preceding experiments, either (1) signal and masker were both likely to be detected by the P channel, (2) signal and masker were both likely to be detected by the NP channel, (3) the signal was likely to be detected by the P channel while the masker stimulated only the NP channel, or (4) the signal was likely to be detected by the NP channel while the masker stimulated only the P channel. We call the former two conditions in-channel masking, the latter two, cross-channel masking.

We have measured masked thresholds in both the P and NP channels, using sinusoidal maskers as well as bandpass noise centered arithmetically on the signal frequency. Both types of maskers were used to ascertain possible differences in the effects produced by deterministic and stochastic maskers.

In the cross-channel experiments we have determined masked thresholds by using maskers that preferentially stimulated one vibrotactile channel while a sinusoidal signal was detected in the other channel. If the two channels are entirely independent, the threshold for the signal should be independent of the masker level. We find that, under most conditions, cross-channel data are consistent with duplex, or perhaps triplex, models which assume that two or more independent sensory channels subserve vibrotaction.

I. METHODS

A. Procedure

Both the signal and masking vibrations were presented simultaneously via a single contactor and were always applied to the thenar eminence of the right hand of adult sub-

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jects. All thresholds were measured by means of a two-interval, forced-choice (2IFC) tracking method (Zwislocki *et al.*, 1958). The subject's task was to decide whether the test stimulus had been presented in the first or second of two time intervals, 700 ms each, separated in time by 620 ms. The *a priori* probability of the signal occurring in either interval was 0.5. The subject was given 3.4 s between the offset of the second interval and the onset of the first of the following pair of intervals to respond and get ready for the next trial. After every response, feedback was provided by a flash of white light to signal an incorrect response. The total cycle time for a trial was 5.4 s.

A staircase rule was used that yielded tracking at 75% correct responses. For each incorrect response the intensity of the signal was increased by 1 dB; after three correct responses, whether they were consecutive or not, the intensity of the signal was decreased by 1 dB. Every threshold measurement required 40 to 50 trials ($\sim$4 min of stable tracking) for completion. In measurements of masked threshold the masker was present in both time intervals. In measurements of unmasked signal threshold, or of the threshold of the masker alone (used to establish masker sensation levels for the rest of the experimental session), only one of the time intervals contained a stimulus.

In every experimental session (lasting 1 to 2 h), the first thresholds measured were the unmasked signal threshold and the threshold of the masker presented alone. Then, 8 and 10 masked thresholds were measured. The maskers, which ranged in sensation level (SL) from 12 dB below the threshold of the masker ($-$12-dB SL) to 34 dB above it ($+$34-dB SL), were always presented in ascending order of masker SL with approximately 2 min of rest between measurements to minimize any cumulative adaptation effects. Every experimental session yielded one complete masking function for a subject. Threshold shift (TS) was calculated by subtracting the unmasked signal threshold from the masked signal threshold in dB. Three to five masking functions were determined for each experimental condition for each subject tested.

All subjects were adults in their mid-twenties attending Syracuse University.

B. Apparatus and stimuli

The vibratory stimuli were transmitted through a vibrator mounted on an adjustable platform that could be raised or lowered smoothly with an accuracy of 0.01 mm (Verrillo, 1963, 1968). To insure that contact with the skin was maintained throughout the full cycle of a sinusoidal oscillation, the contactor was pushed into the skin 0.5 mm beyond the point of initial contact. A rigid, concentric surround having an internal diameter 2 mm larger than that of the contactor was used to prevent the spread of surface waves on the skin. Vibration amplitudes were determined by means of the calibrated voltage output of an accelerometer that was attached to the moving element of the vibrator.

Every experimental subject was seated in a soundproofed booth with the right arm resting comfortably on a rigid surface. The subject's hand was placed on the surface so that the contactor stimulated the center of the right thenar eminence. To insure that the contactor stimulated the same spot throughout an entire experimental session, the subject's hand was gently taped to the surface with masking tape. Minimal vertical pressure necessary to prevent horizontal slippage was applied. All subjects reported that the tape was comfortable, not distracting, and allowed them to concentrate more easily on the task. Subjects were prevented from hearing the vibrations by auditory narrow-band noise centered at the test frequency and presented through circumaural earphones (Verrillo and Capraro, 1974).

The signal consisted of a 300-ms burst of sinusoidal vibration with rise and fall times of 25 ms, and the masker, of a 700-ms burst (either sinusoid or narrow-band noise) with 25-ms rise and fall times. The signal was centered in time within the masker so that the onset of the masker preceded the onset of the signal by 200 ms.

A large contactor (2.9-cm^2 area) was always used in the in-channel experiments involving the P channel. Because the P channel exhibits spatial summation (Verrillo, 1963) and the NP channel exhibits virtually none (Verrillo, 1963; Gescheider, 1976a), the use of a large contactor greatly sensitizes the P channel relative to the NP channel at all frequencies above approximately 40 Hz. Thus a large contactor insured that the signal would be detected in the P channel at high frequencies. A small contactor (0.005-cm^2 area) was used in the NP, in-channel experiments. This desensitizes the P channel so that we could be reasonably sure that an exclusively NP-masking function was being determined at frequencies below 40 Hz.

Two categories of in-channel experiments were performed in each of the two vibrotactile channels: in-channel sinusoidal masking, in which the masker was a sinusoidal burst having the same frequency and phase as the signal, and in-channel noise masking, in which the masker was a burst of narrow-band noise with a center frequency equal to the frequency of the sinusoidal signal.

Masking with sinusoids was determined at three frequencies, 70, 200, and 400 Hz, to determine whether masking was frequency dependent within the P channel. A masking function (12 different masker SLs from $-$12 to $+$34-dB SL) was completed in two sessions. In one session the masker SLs of $-$12, $-$6, $-$4, $-$2, 0, 2, 6, and 34 were presented, in the other, those of 6, 10, 16, 22, 28, and 34. The data of the two sessions at 6 and 34 dB were redundant and were averaged. Two frequencies (20 and 40 Hz) were used in experiments within the NP channel. Threshold shifts were measured at $-$12, $-$6, $-$4, 0, 2, 10, 22, 28, and 34-dB masker SL.

In noise-masking experiments in the P channel the signal was a 200-Hz sinusoid, and the masker, a narrow-band noise centered on a frequency of 200 Hz (NBH noise). In the corresponding NP-channel experiments, the signal was a 20-Hz sinusoid, and the masker, a narrow-band noise centered at 20 Hz (NBL noise). The spectra of the NBL and NBH noises are shown in Fig. 1. Threshold shifts were measured at $-$12, $-$4, 0, 2, 10, 22, 28, and 34-dB masker SL in every session.

Signal frequencies of 20 and 200 Hz were used in the

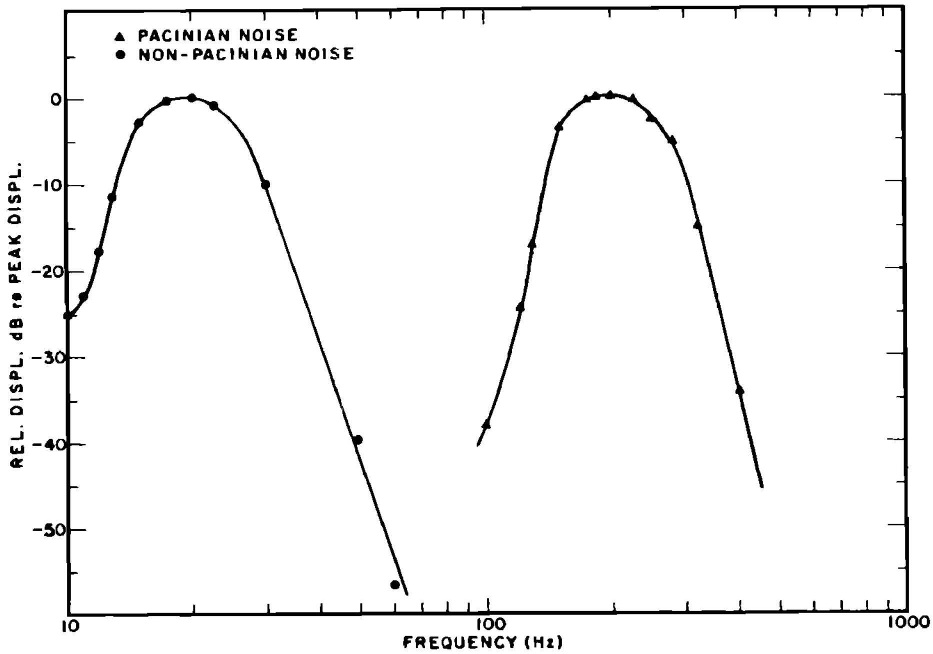

FIG. 1. Spectra of the narrow-band low, NBL, (●) and narrow-band high, NBH, (▲) noise maskers with center frequencies of 20 and 200 Hz, respectively.

cross-channel experiments, and the contactor size was varied in order to manipulate the relative sensitivities of the P and NP channels. In the experiments involving a 200-Hz signal, the masker was the NBL noise with a center frequency (20 Hz) 3.3 octaves below the signal frequency. Three contactor sizes were used: small (0.005 cm^2), intermediate (0.32 cm^2), and large (2.9 cm^2). An additional experiment was performed using the intermediate-size contactor, in which the NBL-noise masker was replaced with a sinusoidal (23 Hz) masker. Masker SLs in the experiments with the two larger contactors were − 12, − 6, − 4, 0, 2, 10, 22, 28, and 34 dB. In the experiment with the small contactor, − 6-dB SL was omitted.

In the cross-channel experiments in which a 20-Hz signal was used, the masker was always NBH-noise centered at 200 Hz, 3.3 octaves above the frequency of the signal. The large (2.9 cm^2) and intermediate (0.32 cm^2) contactors were used. Masker SLs were at − 12, − 4, 0, 2, 10, 22, 28, and 34 dB.

II. RESULTS

A. In-channel sinusoidal masking

Figures 2 and 3 present sample sinusoidal-masking data of individual subjects for the P and NP channels, respectively. The P-channel thresholds were obtained with 200-Hz stimuli, the NP ones, with 20-Hz stimuli. Data points to the left of zero on the abscissa represent signal thresholds measured in the presence of subthreshold (75% detection) maskers. Data points below zero on the ordinate represent masked-signal thresholds that are below the unmasked-signal threshold and mean that the detectability of the signal was improved by the presence of the masker.

It is evident that the P- and NP-sinusoidal masking data

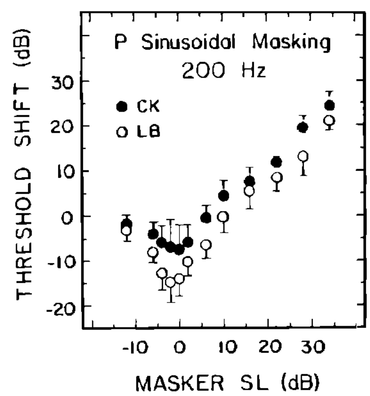

FIG. 2. Pacinian, in-channel, sinusoidal masking in two subjects who showed the greatest (L.B.) and smallest (C.K.) amounts of negative masking. The test and masker frequency was 200 Hz. Each data point represents the mean of five measurements. The detection threshold of C.K. was − 20.8 dB and of L.B., − 26.3 dB *re* 1 μm peak. Bars are 1.0 SD.

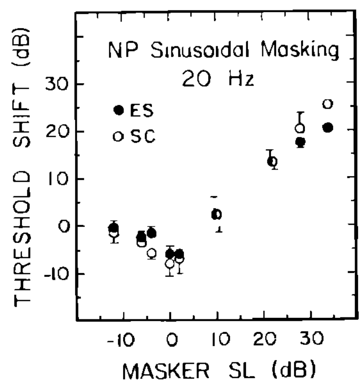

FIG. 3. Non-Pacinian, in-channel, sinusoidal masking in two subjects who showed the greatest (S.C.) and smallest (E.S.) amounts of negative masking. The test and masker frequency was 20 Hz. Each data point represents the mean of three measurements. The detection threshold of E.S. was + 7.4 dB and of S.S., + 9.9 dB *re* 1 μm peak. Bars are 1.0 SD. In this and in subsequent figures, SD bars are not shown if they are smaller than the data point.

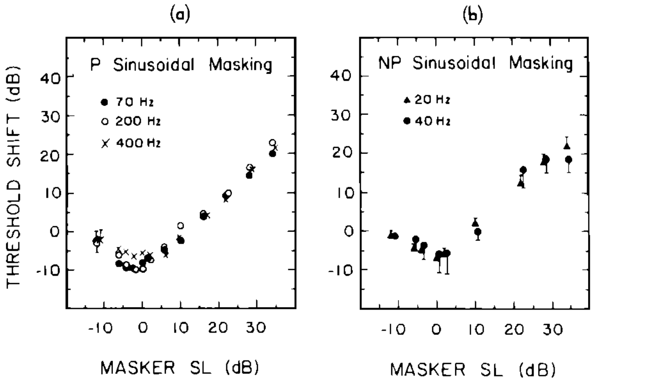

FIG. 4. Summary of the sinusoidal masking data. (a): Masking within the Pacinian channel, measured at 70 Hz (●), 200 Hz (○), and 400 Hz (×). Each data point represents the mean of five measurements on three subjects. The mean detection thresholds were − 5 dB at 70 Hz, − 22.2 dB at 200 Hz, and − 16.7 dB at 400 Hz. Average SDs for all frequencies are shown as bars at − 12-dB SL. (b): Masking within the non-Pacinian channel, measured at 20 Hz (▲) and 40 Hz (●). Each 20-Hz point represents the mean of three measurements on five subjects. Each 40-Hz point represents three measurements on three subjects. The mean detection thresholds were + 9.2 dB at 20 Hz and + 11.9 dB at 40 Hz. All measurements *re* 1-μm peak. Bars are 1.0 SD.

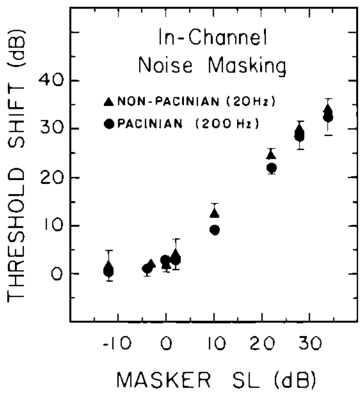

FIG. 5. In-channel masking functions with narrow-band noise as masker within the Pacinian (●) and non-Pacinian (▲) channels. In the P experiments the signal was 200 Hz and the masker NBH noise. In the NP experiments the signal was 20 Hz and the masker NBL noise. Each data point (●) represents the mean of three measurements on four subjects, and (▲) three measurements on three subjects. The mean detection thresholds were + 9.7 dB at 20 Hz and − 22.9 dB at 200 Hz *re* 1-μm peak. Bars are 1.0 SD.

are similar to each other. At masker levels above approximately 10-dB SL the data in both Figs. 2 and 3 fall approximately on a straight line with a slope of 1.0. At lower masker levels the data form a V-shaped function, a substantial portion of which occurs at negative ordinate values. We will refer to this phenomenon as negative masking, a term first used in auditory psychophysics (Raab *et al.*, 1963a,b). The data shown in Figs. 2 and 3 were chosen to represent the full range of individual negative masking observed in each vibrotactile channel and show the smallest (filled circles) and largest (open circles) amounts of negative masking.

The masking data obtained at other frequencies within each channel (70 and 400 Hz for the P channel, and 40 Hz for the NP channel) were very similar, although the negative masking phenomenon was least pronounced at 400 Hz. This can be seen in Fig. 4 which shows all the sinusoidal masking data averaged across subjects for every condition. Figure 4(a) presents mean masking data of three subjects, five runs each, at 70 Hz (filled circles), 200 Hz (open circles), and 400 Hz (×'s). Figure 4(b) shows mean NP-masking data obtained at 20 Hz (filled circles, five subjects, three runs each) and 40 Hz (open circles, three subjects, three runs each). Negative masking is present in both channels, although it may be less pronounced in the NP channel. In both channels, changing the frequency of the stimulus by an octave or more does not have a profound effect on the masking curve.

B. In-channel noise masking

Figure 5 presents the mean noise-masking data for the P (filled circles; four subjects) and the NP (filled triangles; three subjects) channels. Note that, as in the sinusoidal masking, the noise masking in the two vibrotactile channels is quite similar. However, there is no negative masking; instead, positive masking extends to negative masker SLs. Both sets of data approach a straight line with a slope of 1.0 at masker SLs greater than 0 dB. The absence of negative masking and the slope of 1.0 facilitate the interpretation of the cross-channel masking.

C. Cross-channel masking

1. Predictions from the duplex model

Assuming that the channels are independent, a masker that selectively stimulates the NP channel should not alter the detectability of a signal in the P channel. Conversely, a P masker should not affect signal detectability within the NP channel. Evidence to support the assumption of independence is found in studies of adaptation, enhancement, and suppression (Verrillo and Gescheider, 1975, 1977; Gescheider *et al.*, 1977). It is only when the masker is of sufficient intensity to stimulate the signal channel directly that it is expected to cause a threshold shift. There is also abundant evidence that when the sensitivity of a channel is reduced by changes in contactor size (Verrillo, 1963), duration (Gescheider *et al.*, 1977), adaptation (Verrillo and Gescheider, 1977; Gescheider *et al.*, 1978), or masking (Labs *et al.*, 1978), the result is a parallel shift in the channel's threshold-frequency response. Given the evidence for independence and a parallel threshold shift in a desensitized channel, cross-channel masking can be predicted from the duplex model.

Predictions of cross-channel masking functions derived from the duplex model are illustrated graphically in Fig. 6. In Fig. 6(a) are shown idealized intra-channel threshold-frequency functions composed of a single horizontal line for the NP channel and of U-shaped curves at three different levels of sensitivity for the P channel. The P functions have a slope of − 12 dB/octave at frequencies below 200 Hz (Verrillo, 1963). The different levels of P sensitivity are produced by different contactor sizes, ranging from the largest to the smallest (curve 3). The dashed lines represent the sections of the P curves at which thresholds are higher than those in the NP channel.

The pairs of masking curves in Fig. 6(b) and (c) have been constructed from the corresponding functions of Fig.

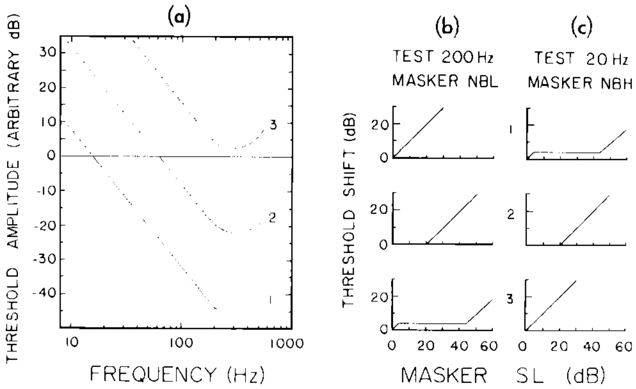

FIG. 6. Schematized prediction of cross-channel masking functions from a duplex model. (a): P and NP threshold-frequency characteristics for three different contactor sizes: large (curve 1), intermediate (curve 2), and small (curve 3). Changing contactor size shifts only the P function since only the P channel exhibits spatial summation. A single horizontal line may represent the NP function for all three sizes. At frequencies below 200 Hz the P function is linear with a slope of -12 dB/octave. The dashed lines represent P thresholds that exceed the threshold of the NP channel. A test signal is assumed to be detected by the most sensitive channel at the frequency of the test signal. (b): Predicted cross-channel masking functions for each contactor size: large (1), intermediate (2), and small (3). Predictions are for a 200-Hz signal and NBL noise masker. (c): Same as (b), but for a 20-Hz signal and an NBH noise masker. The ordinate is scaled in arbitrary dB to provide adequate spacing so that the predictions can be observed more easily. See text for details.

6(a). Masking curves in Fig. 6(b) represent schematically the predicted threshold shifts of a 200-Hz sinusoidal signal masked by NBL noise centerd at 20 Hz. The curves in Fig. 6(c) schematize threshold shifts of a 20-Hz sinusoidal signal masked by NBH noise centered at 200 Hz.

When the largest contactor is used, the threshold of the P channel at 20 Hz may be close to or below that of the NP channel [Fig. 6(a), curve 1]. Thus, the NBL noise should begin to mask a signal detected by the P channel as soon as the masker itself is detectable (0-dB SL). This is depicted by the masking curve with a slope of 1 in Fig. 6(b), 1. (Compare with in-channel noise-masking data presented in Fig. 5.) As the size of the contactor is decreased [Fig. 6(a), curves 2 and 3], P thresholds at 20 Hz are elevated above those of the NP channel. Therefore the NBL-noise masker will be stimulating the NP channel exclusively for an increasingly larger range of sensation levels. Over this range of masker sensation levels the threshold for the 200-Hz signal will be unaffected by the NPL-noise masker. Hence, a region of no-threshold shift (TS) is predicted [Fig. 6(b), 2]. Further reduction of the contactor size desensitizes the P channel so that its threshold at 200 Hz is above that of the NP channel [Fig. 6(a), curve 3]. A raised plateau in the masking function [Fig. 6(b), 3] should then result. At low masker SLs, both the masker and signal are detected by the NP channel and TSs with a slope of 1.0 should be observed. When the NBL masker has desensitized the NP channel sufficiently, the 200-Hz signal will be detected by the P channel and no further increases in TS will occur. The NBL noise is now stimulating only the NP channel; and the 200-Hz signal is being detected by the P channel, producing a plateau in the masking function [Fig. 6(b), 3]. The plateau will end when the masker becomes intense enough to exceed the P-channel threshold and directly mask the 200-Hz signal detected in the P channel. At this point, increasing masking should reappear [second rising portion of the masking curve, Fig. 6(b), 3].

The analysis for a low-frequency (20 Hz) signal and an NBH-noise masker is analogous to the preceding one, but in reverse order. When the smallest contactor is used, the NBH masker and the 20-Hz signal are both detected in the NP channel [Fig. 6(a), curve 3] and a masking curve with a slope of 1.0 from 0-dB SL should result [Fig. 6(c), 3]. As the contactor area is progressively increased [Fig. 6(a), curves 2 and 1], the NBH masker must be increased to higher SLs before it begins to stimulate the NP channel and interfere with detection of the 20-Hz signal. For contactors of intermediate size a masking curve having a region of no-TS is predicted [Fig. 6(c), 2]. Masking with a slope of 1.0 will begin at masker SLs that are intense enough to directly mask the 20-Hz signal within the NP channel. When the contactor size is increased so that the P channel is more sensitive than the NP channel at 20 Hz [Fig. 6(a), curve 1], a masking curve with a plateau is predicted [Fig. 6(c), 1]. At low masker SLs the 20-Hz signal will be detected by the P channel and will be masked directly by the NBH noise; TS will increase with masker SL from 0-dB SL. As the NBH noise is increased, the threshold of the P channel will be elevated so that the 20-Hz signal will be detected by the NP channel. With masker and signal now in different channels, no further TS will occur and a plateau in the masking curve [Fig. 6(c), 1] will result. The plateau will extend until NBH noise becomes sufficiently intense to directly stimulate the NP channel. Higher masker SLs will again cause increased TSs.

D. Comparison of predictions with measurements

Predicted individual cross-channel masking functions (dashed lines) are compared with empirical data in Figs. 7 and 8. The predicted curves are based on averaged individual unmasked P and NP thresholds measured for the test sinusoids during the sessions which generated the data shown in Figs. 7 and 8, and for the masker frequencies during three other sessions in which sinusoidal thresholds at these frequencies were measured. From the thresholds, the relative sensitivities of the two channels at the relevant frequencies were determined. The absolute P and NP thresholds of sinusoids used to calculate the predicted masking functions are listed in the legends of Figs. 7 and 8.

In Fig. 7 are shown the data obtained with a 200-Hz (P) signal and either an NBL-noise masker (NP) or a 23-Hz masker (small dots). They were obtained with a large [2.9 cm^2, Fig. 7(a)], an intermediate [0.32 cm^2, Fig. 7(b)], and a small [0.005 cm^2, Fig. 7(c)] contactor, respectively. Several features of the data should be apparent. First, 23 Hz produced approximately the same amount of masking as the NBL noise. This may be interpreted to mean that the random fluctuation of the noise amplitude did not have any appreciable effect on cross-channel masking, as compared to a masker with a constant, deterministic amplitude. Second, with the exception of Fig. 7(c), the data agree fairly well with the predictions (dashed lines). Note that the predicted

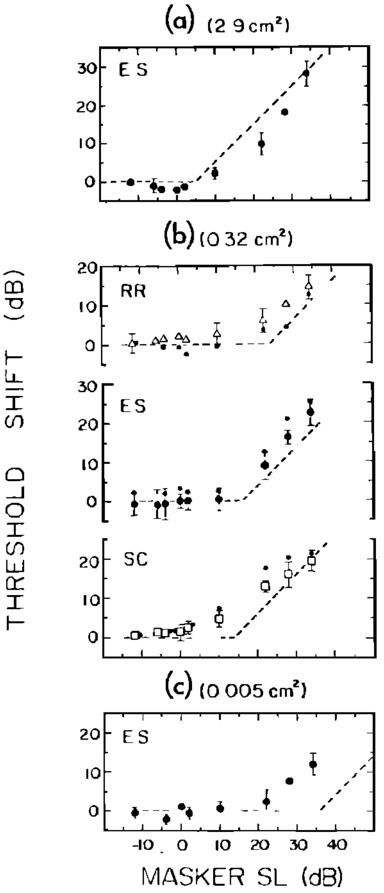

FIG. 7. Individual cross-channel masking data and predictions based on the duplex model. The signal was 200 Hz (P) and the masker NBL noise (NP). Data and predictions (dashed lines) are shown for three contactor sizes. (a): The contactor size was large (2.9 cm^2). The mean absolute thresholds used to generate the predicted function for subject E.S. were − 24.8 dB *re* 1.0-μm peak (200 Hz) and 10.2 dB *re* 1.0-μm peak (NP threshold). (b): The contactor size was intermediate (0.32 cm^2). The small data points are from an experiment in which the signal was 200 Hz and the masker was 23 Hz, shown here for comparison. The mean absolute thresholds in dB *re* 1.0-μm peak were (R.R.) − 7.3 (200 Hz) and 6.9 (NP threshold); (E.S.) − 10.9 (200 Hz) and 11.9 (NP threshold); (S.C.) − 17.9 (200 Hz) and 6.9 (NP threshold). (c): The contactor size was small (0.005 cm^2). The mean absolute thresholds in dB *re* 1.0-μm peak were 6.1 (P) and 10.2 (NP). Each data point represents the mean (± 1.0 SD) of three measurements. For clarity, SD bars have been omitted from the sinusoidal masking points [small data points in (b)], and some noise-masking points.

threshold shifts are schematized and do not reflect the gradual transition from no masking to the masking function following approximately the slope of 1.0. Such a transition is clearly evident in the in-channel masking data of Fig. 5. It produces a threshold shift of about 3 dB at the masker SL of 0 dB. Nevertheless, the predictions do tend to underestimate somewhat the amount of cross-channel masking. This is not true in Fig. 7(a), but is evident in the remaining graphs, and especially in Fig. 7(c). Finally, the data are in qualitative agreement with the prediction that the region of practically no masking should extend to increasingly larger masker SLs, as the contactor area decreases.

Figure 8 shows what happened when an NP, 20-Hz signal was delivered in the presence of a P, NBH-noise masker. The data for the large contactor (2.9 cm^2) are shown in Fig. 8(a), those for the medium contactor (0.32 cm^2), in Fig. 8(b). The dashed lines schematize the predicted threshold

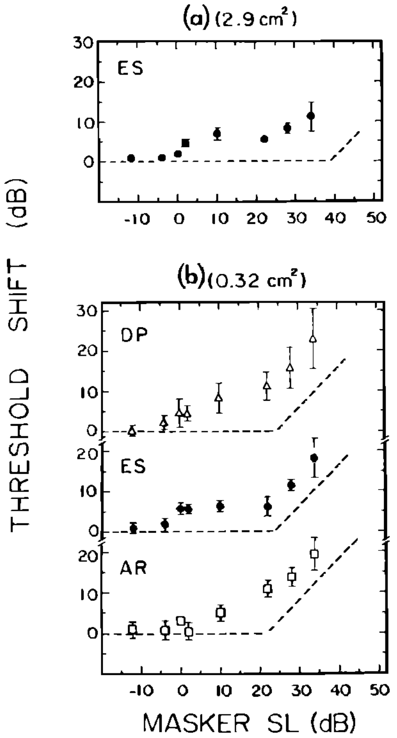

FIG. 8. Individual cross-channel masking data and predictions (dashed lines) based on the duplex model. The signal was 20 Hz (NP) and the masker NBH noise (P). Data points represent the mean (± 1.0 SD) of three measurements. (a): Large contactor (2.9 cm^2). The absolute thresholds in dB *re* 1.0-μm peak used to generate the predicted functions were 13.3 dB (20 Hz) and − 26.0 dB (P). (b): Intermediate contactor (0.32 cm^2). The absolute thresholds in dB *re* 1.0-μm peak were (D.P.) 14.5 (20 Hz) and − 10.0 (P); (E.S.) 10.1 (20 Hz) and − 13.7 (P); and (A.R.) 11.1 (20 Hz) and − 10.8 (P).

shifts according to the scheme of Fig. 6. Here the discrepancy between the predicted and empirical values is greater than in Fig. 7 which corresponds to a signal primarily in the P channel and a masker primarily in the NP channel. The main discrepancies appear to be of two kinds—there is some masking in the mid-region that was not predicted and more masking than predicted at high masker SLs. These effects are the greatest in subject E.S. The data of subject A.R. are the closest to the predicted curve, and the difference is only on the order of 5 dB, except in the corner region of this curve which neglects the gradual transition in the empirical masking curve (Fig. 5).

III. DISCUSSION

A. In-channel masking

The in-channel sinusoidal and noise masking functions are similar in the P and NP channels, approximating a slope of 1.0 above about 10-dB SL. This is consistent with both the vibrotactile in-channel noise masking experiments of Verrillo and Capraro (1975) and with auditory masking within a critical band (e.g., Hawkins and Stevens, 1950).

In the sinusoidal masking experiments both the P and NP masking functions show little dependence on stimulus frequency (Fig. 4). This is consistent with the data of Labs *et al.* (1978) who found that the vibrotactile frequency characteristics of masking did not change in shape as the signal frequency was changed.

However, two effects of stimulus frequency are worth noting in the present study. First, in the NP experiment [Fig. 4(b)] a tendency toward a plateau appears in the 40-Hz masking function above 28-dB masker SL. The simplest interpretation of this effect is that, at the high masker levels, the combined amplitude of the 40-Hz signal and the in-phase 40-Hz masker is sufficient to exceed the threshold of the P channel. Since the signal is near the absolute threshold in that channel, a flattened masking function results (e.g., Fig. 4). When a 20-Hz stimulus is used, the P threshold should be about 12 dB higher and therefore would not be exceeded by the 20-Hz stimulus even when presented at the highest masker SL tested (34 dB).

Second, although both the P and NP channels display a substantial amount of negative masking at low masker levels, the effect appears to be somewhat larger and more frequency dependent in the P channel. On the average, the magnitude of the effect is smaller at 400 Hz than at either 70 or 200 Hz.

Negative masking has been reported in auditory experiments when a signal was being detected in the presence of a correlated or in-phase masker (Green, 1960; Tanner, 1961; Pfafflin and Mathews, 1962; Raab *et al.*, 1963a,b; Leshowitz and Raab, 1967; Vogten, 1978). In vision, a similar phenomenon was observed in experiments on detection of contrast increments in sinusoidal, spatial-frequency gratings (Nachmias and Sansbury, 1974; Legge and Foley, 1980; Foley and Legge, 1981), on detection of a sinusoidal grating in the presence of a masking grating at a different spatial frequency (Legge and Foley, 1980), and on discrimination of luminance increments (Nachmias and Kocher, 1970; Cohn *et al.*, 1974).

It is generally accepted in audition that negative masking is an artifact of the definition of the test stimulus. If the test stimulus is considered to be the actual increment in energy due to the addition of a signal to a masker, and if the ordinate of the masking plot (TS) is in units of the increment energy, no negative masking appears (Green, 1966; Raab *et al.*, 1963a,b; Leshowitz and Raab, 1967). When a sinusoidal signal with amplitude S is summed in phase with a sinusoidal masker with amplitude M and the same frequency as the signal, the total energy of the sum is proportional to

$$(S+M)^2 = S^2 + M^2 + 2SM.$$

We define TS as $10 \log S^2/S_u^2$, where S is the amplitude of the signal at masked threshold and S_u is the amplitude of the signal at unmasked threshold. The ordinate in this definition is in terms of signal energy (S^2). But the energy increment due to the addition of the signal to the masker is given by $S^2 + 2SM$, the total energy $(S+M)^2$ minus the energy of the masker (M^2). If TS is redefined in terms of increment energy, $10 \log(S^2 + 2SM)/S_u^2$, all negative masking observed in auditory experiments disappears. However, in vibrotaction, negative masking is not entirely an artifact of the stimulus definition. When the data from the in-channel, sinusoidal-masking experiments are replotted with the ordinate defined in terms of increment energy, some negative masking usually remains. One example for the P channel (70 Hz) is shown in Fig. 9. For comparison, the data are shown both in terms of increment energy (open circles) and signal energy (filled circles). Negative masking also remains on a plot of increment energy when the stimulus frequency is 200 Hz. At 400 Hz the negative masking is negligible in the group data. However, one out of three subjects showed a strong effect at all three frequencies. A similar transformation of the NP sinusoidal data reveals a persistence of negative masking in the group data at 20 Hz, but not at 40 Hz. However, the data of one out of three subjects did show negative masking at 40 Hz. The persistence of negative masking when the data are replotted in terms of increment energy appears to be both subject and frequency dependent.

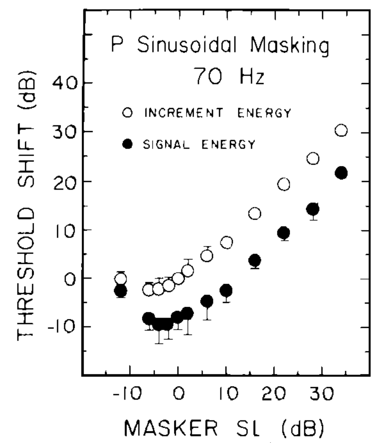

FIG. 9. Sinusoidal masking within the Pacinian channel. The ordinate is defined either in terms of signal energy (●) or increment energy (O). The signal and masker were both at 70 Hz. Each data point represents the mean of five measurements on three subjects. Note that negative masking persists after the data are converted to increment energy. Note that without energy threshold there should be a positive TS at 0-dB masker SL. Bars are 1.0 SD.

One explanation for the nonartifactual negative masking is that a true energy threshold exists in the vibrotactile channels. An analytical detection model, which includes such a threshold, has been developed from basic psychophysical, physiological, and signal-processing considerations (Hamer, 1979). In the model, uncorrelated Gaussian noise having a zero mean and a constant average power independent of the stimulus power is added to the masker above the threshold stage. A following detector is assumed to operate on a neural variable proportional to the stimulus energy. In a 2 IFC task the interval chosen by the subject as the one containing the signal is the interval in which the peak value reached by this variable is the greatest.

Figure 10 shows the data from one of the P sinusoidal-masking experiments [from Fig. 4(a), open circles]. The solid curve represents the prediction from the model with the energy threshold, the dashed curve, the prediction from the same model when the threshold is eliminated (see Appendix for the equations and parameter values used to generate the theoretical curves). It is clear that the model without the energy threshold fails to predict the data, whereas the model that includes the threshold predicts the data well. The Wilcoxon signed-rank test (Lehmann, 1975) shows that the data points do not differ significantly from the energy-threshold model, whereas they do differ significantly ($p < 0.05$) from the model without the energy threshold. The threshold mod-

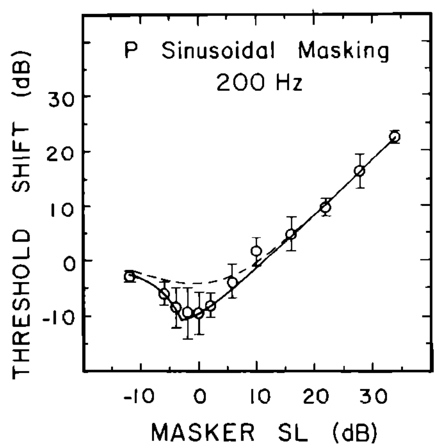

FIG. 10. Pacinian in-channel sinusoidal masking. The ordinate is TS in terms of signal energy (see text). The signal and masker were both at 200 Hz. The solid curve is theoretical, based on a detection model including an energy threshold followed by noise. The dashed curve is the result of eliminating the threshold from the model (see the Appendix). Each data point represents the mean threshold of three subjects, based on the means of five threshold measurements on each subject. Bars are ± 1.0 SD.

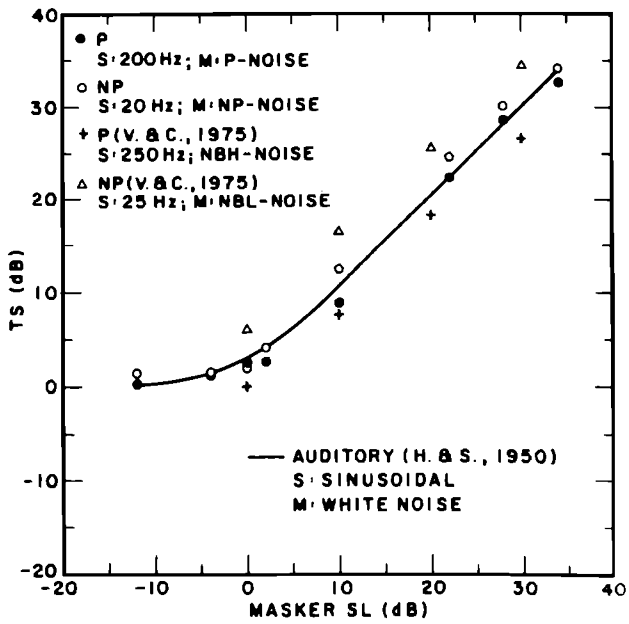

FIG. 11. Comparison of the in-channel noise masking data from Fig. 5 of the present study (●, ○) with data from another vibrotactile masking study (+ , △; Verrillo and Capraro, 1975) and comparable auditory results (solid curve; Hawkins and Stevens, 1950). Note that the data from both modalities closely parallel each other.

el also accounted successfully for the P sinusoidal-masking data at 70 and 400 Hz, as well as the NP sinusoidal-masking data at 20 Hz. The lower the energy threshold, the closer will be the predictions from the threshold and no-threshold models (see the Appendix). In the P channel the negative masking was smallest at 400 Hz. Thus the energy threshold apears to be lower at this frequency than either at 70 or 200 Hz. It also appears to be channel-dependent, being somewhat lower in the NP than in the P channel. In addition, comparison of the magnitudes of negative masking in the responses of two subjects (Fig. 2) indicate that the energy threshold is subject dependent.

An important consequence of the energy threshold is that a masker below detection threshold acts as a pedestal, decreasing the stimulus energy (defined either in terms of "signal" or "increment energy") necessary to reach the detection threshold. This would explain the negative TSs for maskers below 0-dB SL in Fig. 4. The threshold model also predicts that negative TSs will occur when maskers above detection threshold are used. Other psychophysical evidence for a threshold in taction can be found in the literature (Eijkman and Vendrik, 1963; Vendrik and Eijkman, 1968; Gescheider *et al.*, 1971; Gescheider, 1976b). A related model for vision incorporates a "nonlinear transducer function" predicting the negative masking that occurs in the detection of sine-wave gratings in the presence of masking gratings (Nachmias and Sansbury, 1974; Legge and Foley, 1980; Foley and Legge, 1981).

The noise masking was virtually identical in both the P and NP channels (Fig. 5). No negative masking appears in either set of data. Presumably the random variability of the masker amplitude negates the effect of the energy threshold. The data are therefore more comparable with similar masking data in audition where no energy threshold seems to exist. The noise-masking data do indeed match the auditory tone-in-noise masking represented by the solid curve in Fig. 11 (Hawkins and Stevens, 1950). In addition, the vibrotactile in-channel noise-masking data of Verrillo and Capraro (1975) parallel both the present masking data and the auditory masking data. The NP masking in both the present and the Verrillo and Capraro studies shows greater TSs at each masker SL than either the P-noise masking or the auditory masking.

B. Cross-channel masking

In general, TSs do not occur until maskers reach 10 dB, and in some cases 20- to 30-dB SL. This is consistent with preceding experiments on sinusoidal cross-channel masking (Hamer and Verrillo, 1975), but not with Verrillo and Capraro's (1975) experiments on cross-channel noise masking. In the latter experiments, TSs increased linearly with masker SL from 0 dB with a slope of 0.5. We too find that individual TSs in cross-channel masking tend to follow slopes somewhat smaller than 1.0, perhaps due to a restricted dynamic range of masker SLs over which significant TSs are measured. However, the slopes are greater than 0.5. At present we have no explanation for the discrepancy other than to point to several methodological differences between the two studies. Verrillo and Capraro used continuous, not pulsed, maskers and used the less reliable Békésy tracking instead of 2IFC tracking.

As in the in-channel experiments with noise masking, no clear negative masking occurred in the cross-channel experiments, although Fig. 7 suggests some negative masking. Our detection model with energy threshold predicts slight negative masking in heterofrequency experiments (Hamer, 1979). Legge and Foley (1980) found negative masking to be smaller when the masking and signal frequencies were different in visual-contrast experiments. The variability of our data does not allow us to decide if some negative masking did occur. Cross-channel masking appears to be nearly the same whether the masker is a random noise or a sinusoid [Fig. 7(b)], whereas in audition a pure-tone masker causes a smaller TS than a noise masker at the same SL (Hawkins and Stevens, 1950; Egan and Hake, 1950).

Finally, the cross-channel masking functions depend on the size of the contactor area. Most notably, the SL to which a masker can be raised without appreciably affecting signal detectability changes with area (Fig. 7), as predicted by the duplex model (Fig. 6). The prediction assumes that at least two independent channels subserve vibrotaction. We have defined a cross-channel masking experiment as one in which the signal and masker are stimulating different channels exclusively over a finite range of masker levels. Because of channel independence, no masking should occur over this range.

The data of most of the cross-channel experiments were in qualitative and in gross quantitative agreement with the predictions. However, a tendency toward more masking than predicted is evident, especially in Fig. 8 where the masker was in the P channel and the signal in the NP channel. The discrepancy may be explained on the basis of one of two assumptions: (1) a true interaction within the central nervous system takes place between the P and NP channels, and (2) adaptation occurred in the NP channel during the experimental sessions. Recall that TS was determined relative to an unmasked signal threshold measured at the beginning of each session, and masked thresholds were always measured in ascending order of masker SL.

Ferrington *et al.* (1977) have suggested that neural signals in P and NP channels can interact in the CNS. They claim that the two channels are not independent and true cross-channel masking is purported to occur. They claim also that the interaction is asymmetrical so that P neural signals can mask NP signals, but not the reverse. This is in agreement with Figs. 7 and 8 which indicate stronger masking of an NP signal by a P masker than vice versa in regions where the duplex model predicts no masking. However, Ferrington *et al.* may have incorrectly assessed in which channel, P or NP, the test stimuli were detected. The large gap they used between the contactor and the rigid surround would tend to enhance the sensitivity of the P channel, while diminishing that of the NP channel (Gescheider *et al.*, 1978). Thus it is very likely that their 30-Hz stimulus was detected in the P channel. Ferrington *et al.* assumed that it was detected in the NP channel and interpreted a TS in the presence of a 300-Hz (P) masker as a true CNS interaction. All their remaining data are easily interpreted in a similar fashion and, therefore, are compatible with channel independence. Recent heterolocal masking experiments, under conditions similar to those of Ferrington *et al.*, showed that at a sufficiently low frequency (13 Hz) no CNS interaction occurred. The results were consistent with the assumption of independent channels (Verrillo *et al.*, 1983). Accordingly, the evidence obtained thus far does not support the possibility of an interaction between the P and NP systems within the CNS.

A second possible explanation of the data of Fig. 8(b), based on adaptation of the NP channel, follows from the experiments of Capraro *et al.* (1979), who have presented evidence suggesting that the NP channel is comprised of at least two broadly tuned subchannels: an NP-low-frequency channel that exhibits subthreshold adaptation and an NP-high-frequency channel that does not. Adapting stimuli cause thresholds to be elevated in the NP-low channel even when they are below their detection threshold. In the present experiments subthreshold adaptation may have desensitized the NP-low channel to the 20-Hz stimulus causing TSs to occur at lower masker SLs than expected (Fig. 8).

If we accept the notion of subthreshold adaptation to explain the unexpected TSs at low masker SLs, another asymmetry becomes apparent. Figure 7(b) shows that an NP masker has no effect on the detectability of a P signal (200 Hz) up to 10- to 20-dB SL when, presumably, it is sufficiently intense to exceed the detection threshold in the P channel. This suggests that the P channel does not exhibit subthreshold adaptation. Further experimentation is necessary to assess the implications of such an asymmetry between P and NP channels, and to sort out the explicit effects that a non-unitary NP channel can have on the results of cross-channel masking experiments.

It should be mentioned that predicted abscissa values of Figs. 7 and 8 were based on sinusoidal, not noise, thresholds measured is separate sessions. This may have added to the discrepancy between the predicted and measured locations of the rising portions of the masking curves.

In conclusion, we have measured in-channel and cross-channel masking in both the P and NP vibrotactile channels of the glabrous skin of the hand. The in-channel data were virtually identical in the two channels. The sinusoidal data showed a substantial amount of negative masking which, unlike similar negative masking in audition, was not entirely an artifact of the definition of the test stimulus. The negative masking could be explained in terms of a model including an energy threshold followed by noise (Hamer, 1979).

We used a duplex model to make individualized predictions of cross-channel masking for every subject. In general, the predictions were qualitatively and, in some cases, quantitatively successful. Deviations from the predictions for the most part seem to require only second-order corrections or refinements of the duplex model. The results of one experiment (Fig. 8) seem at first glance to be at variance with channel independence. However, they may be explained on the basis of a previously uncovered triplex system of independent channels with one channel exhibiting subthreshold adaptation.

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APPENDIX

The theoretical curves in Fig. 10 are described by the following equations. (For derivations see Hamer, 1979.)

For maskers below the level of the energy threshold:

$$TS = 10 \log (S^2/S_u^2) = 10 \log(1 - M/M_0)^2, \qquad (A1)$$

where M is the amplitude of the masker, M_0 the amplitude of the masker at its threshold, S, the amplitude of the signal at the masked threshold, and S_u, the amplitude of the signal at the unmasked threshold. All units are in microns. Equation (A1) is *parameter free*, depending only on masker SL which is the independent variable in the experiment.

For maskers that exceed the threshold:

$$TS = 10 \log \frac{S^2}{S_u^2} = 10 \log \left\{ \left[1 + K \left(\frac{M^2}{M_0^2} - T \right) \right]^{1/2} - \frac{M}{M_0} \right\}^2. \qquad (A2)$$

This equation has two free parameters: K and T. The values of K and T used to fit the data with the solid curve in Fig. 10 were 1.5839 and 0.5062, respectively. The value of K is related to the more traditionally defined signal-to-noise ratio, which in this case is 0.0668, or -11.75 dB. T is the threshold-related parameter. The dashed curve in Fig. 10 is the result of setting T equal to zero in Eq. (A2). Eliminating the threshold from Eq. (A2) gives us a one-parameter detection model that depends only on K.

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