

Vibrotactile masking: Effects of one- and two-site stimulation

RONALD T. VERRILLO
Syracuse University, Syracuse, New York

GEORGE A. GESCHIEDER
Hamilton College, Clinton, New York

and

BRUCE G. CALMAN and CLAYTON L. VAN DOREN
Syracuse University, Syracuse, New York

Masked vibrotactile thresholds at the index fingertip were measured as a function of masker intensities, which were applied to the thenar eminence of the same hand. Test and masker frequencies were selected so that the Pacinian and non-Pacinian receptor systems were selectively activated. Remote-site masking was effective only when both masker and test stimulus were within the frequency range of the Pacinian system. Cross-channel masking did not occur.

Two stimuli activating a sensory system simultaneously or in rapid succession can produce a variety of perceptual experiences. The most common and widely studied is masking, in which one stimulus decreases the detectability of another. Depending upon the theoretical orientation of the investigator, masking may be called extinction, inhibition, or suppression. Although masking has been investigated for all of the sensory systems, our concern is with the masking of vibrotactile signals by vibrotactile maskers.

Vibrotactile masking has been studied with both psychophysical and neurophysiological methods. Psychophysical studies have been oriented primarily toward determining masking effects that must be considered in the development of cutaneous communication devices. The effects of maskers on signal detectability have been investigated for locus of the masker (Gilson, 1969b; Sherrick, 1964), temporal relationship between masker and signal (Gilson, 1969b; Sherrick, 1964), number of maskers (Gilson, 1969a), and differences between psychophysical methods (Gescheider, Herman, & Phillips, 1970; Gilson, 1974; Snyder, 1977). More recently, the em-

phasis has shifted toward the theoretical implications of vibrotactile masking phenomena (Craig, 1972, 1974, 1976; B. G. Green, 1975; Hamer, 1979; Labs, Gescheider, Fay, & Lyons, 1978; Verrillo & Capraro, 1975). In most instances, substantial differences in experimental conditions render the comparison of results from different laboratories meaningless.

The impetus of neurophysiological investigations of masking seems to stem primarily from an effort to explain the inhibitory effects of multiple stimuli applied to the skin (Andersen, Etholm, & Gordon, 1970; Bystrzycka, Nail, & Rowe, 1977; Carmody & Rowe, 1974; Gardner & Spencer, 1972; Jänig, Schmidt, & Zimmerman, 1968; Mountcastle & Powell, 1959; Rowe & Carmody, 1970). Some investigators have utilized both neurophysiological and psychophysical methods in their studies of vibrotactile masking (Ferrington, Nail, & Rowe, 1977; Gardner & Spencer, 1972).

The present experiments were conducted to examine the effect of low- and high-frequency sinusoidal maskers upon the detection of low- and high-frequency sinusoidal signals delivered to two ipsilateral sites on the hand. Our objective was to determine, by psychophysical measurement, characteristics of the neural mechanisms responsible for the detection of vibration. The existence of at least two psychophysically measurable vibrotactile systems has been demonstrated clearly (Gescheider, 1976; Verrillo, 1963, 1965, 1966b, 1966c, 1966d, 1968; Verrillo & Gescheider, 1979), and recent experiments have demonstrated that at least three systems may be differentiated (Capraro, Verrillo, & Zwislocki, 1979). Abundant evidence from neurophysiological experiments support both a duplex or a triplex model

This work was supported by Grant NS-09940 from the National Institutes of Health, United States Department of Health and Human Services. Requests for reprints should be sent to Ronald T. Verrillo, Institute for Sensory Research, Syracuse University, Syracuse, New York 13210. Material in this article was presented at the 1980 (101st) meeting of the Acoustical Society of America and at the 1981 meeting of the Psychonomic Society. The authors gratefully acknowledge the willing and dedicated assistance of Alisa M. Goldstein, who was a summer undergraduate research assistant at the Institute for Sensory Research.

for mechanoreception (Harrington & Merzenich, 1970; Merzenich & Harrington, 1969; Talbot, Darian-Smith, Kornhuber, & Mountcastle, 1968), as do the more recent studies of direct recordings from human nerves (Järvilehto, Hämmäläinen, & Laurinen, 1976; Johansson, 1976, 1978; Johansson & Vallbo, 1979; Knibestöl, 1973; Knibestöl & Vallbo, 1970). It has also been established that high-frequency sensitivity is mediated by the Pacinian corpuscle system (Talbot et al., 1968; Verrillo, 1966b, 1966c, 1968). It is thought that the Meissner corpuscle dominates the low-frequency response in glabrous skin (Knibestöl, 1973, 1975; Knibestöl & Vallbo, 1970; Lindblom, 1965; Talbot et al., 1968).

Ferrington et al. (1977) reported that masking (inhibition) of signals within the frequency range of either the Pacinian or the non-Pacinian system is produced by Pacinian input and that the influence of maskers that excite non-Pacinian receptors is minimal. This finding was supported by neurophysiological evidence (Bystrzycka et al., 1977). Ferrington et al. and Bystrzycka et al. made a strong case that there is neural interaction between the two systems and that the interaction takes place at synaptic relays within the central nervous system. The results of these studies are not consistent with other investigations that showed strong interactions within a single channel and no interactions between channels when measuring enhancement (Gescheider, Verrillo, Capraro, & Hamer, 1977; Verrillo & Gescheider, 1975) or adaptation (Gescheider, Capraro, Frisina, Hamer, & Verrillo, 1978; Gescheider, Verrillo, & Frisina, 1979; Verrillo & Gescheider, 1977). The present investigations were designed to resolve the discrepancies among the previous studies. Using stimuli that excited either one or both channels, masking experiments were performed on single sites of the hand and on two ipsilateral sites.

APPARATUS AND METHOD

The apparatus consisted of electronic equipment necessary to deliver sinusoidal signals to two electromagnetic vibrators located within the sound-proofed booth where the subject sat. The vibrators were positioned upon adjustable platforms beneath a rigid surface. The contactors, mounted on the vibrators, protruded through holes in the rigid surface, making contact with the subject's right hand, which rested comfortably, palm down, on the rigid support. One vibrator was positioned to contact the distal phalanx of the index finger, and the other to contact the center of the thenar eminence.

The contactors were circular and concave to follow the contour of the skin. The area of the contactor at the fingertip and at the thenar eminence was .28 cm². The gap between the contactor and the rigid surround was always 1.0 mm. Before each trial, the heights of the vibrators were adjusted independently so that the contactors indented the skin 0.5 mm beyond minimum contact.

Two-interval, forced-choice tracking (Zwislocki, Maire, Feldman, & Rubin, 1958) was used to measure all masked and unmasked thresholds. The subject was required to indicate, by pressing

the appropriate button, in which time interval the signal occurred. The time and response intervals were marked by lights. The time sequence would not repeat until a response had been made. When unmasked thresholds were measured, only the signal was presented, and when masked thresholds were measured, the masker was presented in both intervals but the signal in only one. The occurrence of the signal was distributed randomly between the two time intervals. The amplitude of the signal was computer controlled so that it was attenuated 1.0 dB following three correct responses, consecutive or not. One incorrect response resulted in a 1.0-dB increase of amplitude. Amplitude changes were automatically recorded in 1.0-dB steps on a chart recorder. Threshold was thus set at a criterion of 75% correct responses, which was established by 2 min of stable tracking (approximately 30 adjustments). Stable tracking was defined as deflections of no greater than ± 2.0 dB about a central value.

At the start of each session, unmasked thresholds were determined at the appropriate frequencies for the finger and the thenar eminence. For two-site masking experiments, the masker intensity was set at a selected sensation level at the thenar eminence and the subject tracked the threshold at the finger. After 2 min of stable tracking, which took about 5 min of total time, another masker intensity level was selected randomly and the procedure was repeated.

Measurements were made using combinations of 13 and 300 Hz for the signal and masker frequencies. These frequencies were chosen in order that the Pacinian (300 Hz) and non-Pacinian (13 Hz) receptor populations would be stimulated independently. The 13-Hz frequency was chosen because at that frequency the psychophysical detection thresholds of the Pacinian system are significantly higher than those of the non-Pacinian system (see Figure 4). The 30-Hz stimulus used by Ferrington et al. (1977) was too close to the breakpoint between the two systems to insure an effective isolation of Pacinian and non-Pacinian activation. All stimuli were controlled so that the onset always commenced at the zero crossing of the sinusoid. The maskers were 730 msec in duration, measured at the half-power point, and had a 25-msec rise/fall time. The signals were 300 msec in duration, centered within the masker time, and also had a 25-msec rise/fall time. The two presentation intervals were separated by 620 msec. The masker intensities were set randomly at -10, 0, 10, 20, 30, 40, and 50 dB SL.

In order to clarify the psychophysical results, it was necessary to measure physically the amplitudes of any vibrations that might have been propagated through the hand from the thenar to the fingertip when high-intensity maskers were used at the thenar. This was accomplished by placing a piezoelectric force gauge in series with the accelerometer at the fingertip. Several intensities of the masking stimulus were presented to the thenar, and the output of the force gauge was monitored with a Tektronix 5L4N spectrum analyzer. The height of the spectral peak at the masker frequency was recorded as a measure of the force produced at the fingertip by the masking stimulus at the thenar. The analyzer made it possible to separate the small vibratory signals from high-frequency electrical noise and noise from blood pulsations. Immediately following these measurements, forces at the fingertip were measured again, but this time in response to vibrations at the masker frequency applied directly to the fingertip. Both force and amplitude were measured for a series of intensities.

The amplitude of vibration presented directly to the finger is the same as that produced by propagation from the thenar when the forces measured in both cases are equal. That is, when the vibration is conducted to the fingertip from a remote location, the tissue is compressed against the contactor and produces a reactive force that is measured by the force gauge. On the other hand, when the finger is stimulated directly, the contactor is no longer passive, but produces an active force that in turn compresses the tissue above it. When the active and reactive forces are equal, the amounts of compression are also equal. Therefore, by comparing points of equal force, the amplitudes of propa-

gated vibrations can be determined. This technique was sensitive enough to permit reliable measurement of amplitudes of less than 0.1 μm .

RESULTS AND DISCUSSION

One-Site Masking

Before making measurements of masking from a remote site, preliminary experiments in which masker and signal were presented to the same site were performed. Measurements were made at the thenar eminence and at the pad of the index finger in order to determine the masking characteristics at these sites and to compare these characteristics. In the first experiment, masking on the thenar was measured using a frequency of 300 Hz for both the masker and test stimuli. The contactor size was 2.9 cm². The results shown in Figure 1 are compared with those of Hamer (1979), who used the same procedure at a frequency of 200 Hz with a 2.9-cm² contactor. The frequencies and contactor size in both experiments ensured that both masker and test signal were in the region of maximum sensitivity of the Pacinian system.

The results of our experiment (Figure 1, closed circles) agree well with those of Hamer (1979) (Figure 1, open circles). The difference between masked and unmasked thresholds (threshold shift) is plotted as a function of the sensation level of the masker. The amount of masking, expressed as threshold shift in decibels, increases at masker intensities above 10 dB SL. Note that, at masker intensities below 10 dB SL, the test stimulus becomes detectable at

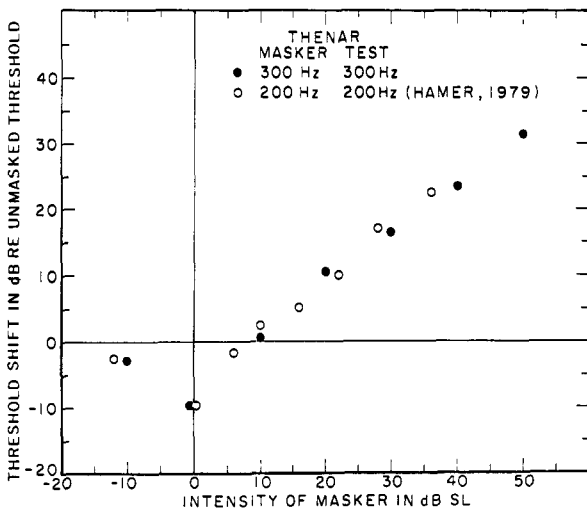


Figure 1. Vibrotactile threshold shift as a function of the intensity of the masker. The masker and test stimulus were both delivered to the thenar eminence and were within the frequency range of maximum sensitivity of the Pacinian system. The results of the present study (●) closely approximate those of Hamer (1979) (○). The contactor area in both experiments was 2.9 cm².

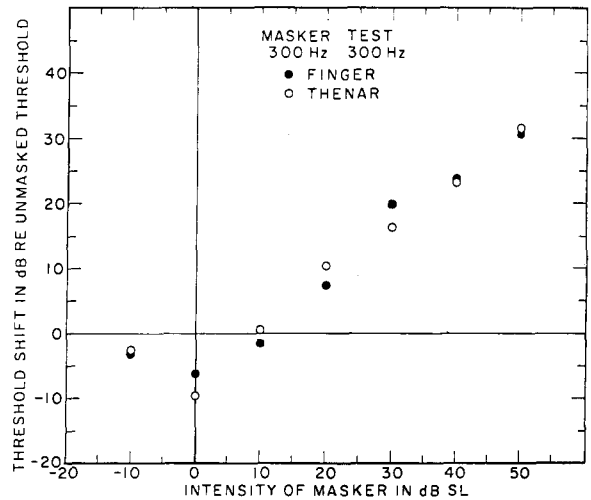


Figure 2. Vibrotactile threshold shift as a function of the intensity of the masker. Results are similar when masker and test stimulus are delivered to the same site on the thenar eminence and the index fingertip. The contactor area was 2.9 cm² on the thenar eminence and .28 cm² on the fingertip.

intensities below the threshold level of the test stimulus. This phenomenon has been called "negative masking," which has been demonstrated in auditory experiments (D. M. Green, 1960; Leshowitz & Raab, 1967; Pfafflin & Mathews, 1962; Raab, Osman, & Rich, 1963a, 1963b; Tanner, 1961) and recently in vibrotactile experiments (Hamer, 1979; Hamer, Verrillo, & Zwislocki, in press). Negative masking remained after the data were converted to effective energy thresholds in Hamer's data and in ours. The results in Figure 1 show the form and extent of the masking characteristic measured at the thenar eminence and are in good agreement with results reported earlier (Hamer, 1979).

Using a .28-cm² contactor, the experiment was then repeated on the finger pad of the index finger. The results are shown in Figure 2 (closed circles) compared with the data of the thenar eminence taken from Figure 1. The two sets of measurements are essentially the same except that the negative masking at a masker intensity of 0 dB SL is reduced by about 3.5 dB for the finger. It is apparent from the results shown in Figure 2 that the masking characteristic is essentially the same at both the thenar eminence and the index finger pad.

A series of experiments in which the frequencies of the masker and test stimuli were chosen such that they both stimulated maximally the Pacinian receptor system (300-Hz masker, 300-Hz test) and the non-Pacinian system (13-Hz masker, 13-Hz test) and in which the two stimuli maximally affected different receptor systems (13-Hz masker, 300-Hz test; 300-Hz masker, 13-Hz test) was conducted on the finger pad.

The results shown in Figure 3 reveal the following

characteristics: (1) Within the Pacinian system (closed circles), there is negative masking at low masker intensities and then strong masking starting at a masker intensity of 10 dB SL and increasing monotonically to 50 dB SL. (2) Within the non-Pacinian system (open circles), the result is approximately the same. (3) When a stimulus within the non-Pacinian system is used to mask the detection of a test stimulus within the Pacinian system (closed triangles), masking is absent until the intensity of the masker exceeds 20 dB SL, but with no negative masking. (4) When a stimulus within the Pacinian system masks a test stimulus within the non-Pacinian system (open triangles), masking does not occur at any intensity of the masker.

The results of the in-channel masking (Figure 3, open and closed circles) need not be discussed further, because they are consistent with the results of previous studies in both audition and vibration. However, it appears that some cross-channel masking does occur when the masker frequency stimulates the non-Pacinian system (Figure 3, closed triangles), but not when it excites the Pacinian system (Figure 3, open triangles). It is our hypothesis, however, that this effect does not represent true cross-channel masking but, rather, that it is the result of the masker selected to excite one receptor system being delivered at intensities sufficient to exceed the threshold level of the other system (Hamer, 1979). Thus, what appears to be cross-channel masking is actually masking within a single channel. This hypothesis was examined in greater detail.

First, with a .28-cm² contactor at frequencies of 10, 25, 40, 64, 100, 150, and 300 Hz, unmasked

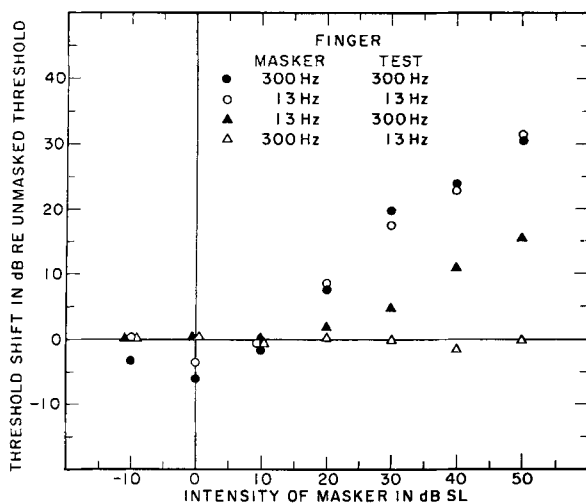


Figure 3. Comparison of masking effects on the fingertip when frequencies are selected to excite individually the Pacinian (●) and non-Pacinian (○) systems, and when masker and test stimuli are selected to excite both systems (▲, △).

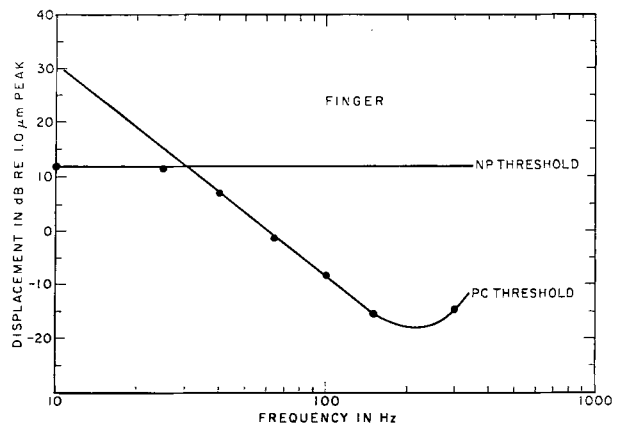


Figure 4. Absolute threshold as a function of frequency (●) measured at the fingertip with a .28-cm² contactor. Theoretical threshold curves of the Pacinian (PC) and non-Pacinian (NP) systems are shown.

thresholds were determined at the fingertip for all subjects. The results (Figure 4) show a flat portion at low frequencies and a U-shaped curve with a slope of -12 dB/octave between 35 and 150 Hz before turning upward above 250 Hz. These results are consistent with data reported previously for the finger (Verrillo, 1971). In accordance with the duplex model of cutaneous mechanoreception (Verrillo, 1968), theoretical curves have been drawn in Figure 4 to represent the psychophysical threshold response characteristics of the non-Pacinian (horizontal curve) and Pacinian (U-shaped curve) systems. These extrapolations have been verified in both physiological (Merzenich & Harrington, 1969; Talbot et al., 1968) and psychophysical (Gescheider, Verrillo, & Van Doren, 1982; Verrillo & Gescheider, 1977) experiments.

If the hypothesis that apparent cross-channel masking is masking within a single system is correct, we should predict that masking of the 300-Hz test stimulus by a 13-Hz masker (Figure 3, closed triangles) should start when the masker intensity exceeds the threshold of the Pacinian system at 13 Hz. It can be seen in Figure 4 that the threshold of the Pacinian system will be exceeded when the intensity of the 13-Hz masker is set at approximately 15 dB SL. That is, the Pacinian threshold at 13 Hz is about 15 dB above the non-Pacinian threshold. Because a small amount of masking was measured at 20 dB SL, we may consider that the masker became effective between 10 and 20 dB SL, which is consistent with the predicted value.

Note that in both of these cross-channel conditions (Figure 3, open and closed triangles) masking was predicted to start at the threshold of the system in which the test stimulus occurred rather than at 10 dB above the threshold as shown in the within-channel conditions (Figure 3, open and closed circles). Hamer (1979) showed that conditions in which

sinusoidal maskers and signals were in phase produced negative masking followed by positive masking, starting at approximately 10 dB SL of the masker. Our results (Figure 3, open and closed circles) agree with this finding. However, when the masker and test stimuli were in quadrature (90 deg out of phase), Hamer found that negative masking disappeared and positive masking began at approximately 0 dB SL. Because the cross-channel conditions present masker and test stimuli that are not harmonically related, they cannot be in phase with each other. Therefore, we must expect that masking should start at the detection threshold of the test channel and not at 10 dB above the detection threshold of the system in which the test stimulus was presented.

Two-Site Masking

The results of experiments in which maskers were delivered to the thenar eminence and test stimuli were presented to the index finger pad are shown in Figure 5. The same combinations of masker and test frequencies that were used in the previous experiment (Figure 3) were repeated. Masking within the Pacinian system (closed circles) is still evident, although the effect does not become apparent until the intensity of the masker is in excess of 30 dB SL. Masking within the non-Pacinian system (open circles), however, is minimal even at the highest intensity level of the masker. Masking of the non-Pacinian system by the Pacinian system (open triangles) between the two sites is nil over the entire range of masker intensities used. Also, the effect of a non-Pacinian masker upon the detection of a Pacinian

test stimulus (closed triangles) is nil to 40 dB SL and minimal at the highest intensity of the masker.

In all instances of cross-channel masking shown in the one-site condition, it can be demonstrated that masking occurs only at levels at which the intensity of the masker in one system exceeds the detection threshold level of the system being masked (Gescheider et al., 1982). Thus, the excitation by masker and test stimuli occurs within the same receptor system, and not across systems. No appreciable masking was measured across channels. The small amount of masking shown in Figure 5 at 50 dB SL with the use of a 13-Hz masker and either a 13-Hz (open circles) or a 300-Hz (closed triangles) test signal might imply both remote masking within the non-Pacinian system and remote cross-channel masking of the Pacinian by the non-Pacinian system. The apparent cross-channel effect may be explained in the following way. The threshold on the thenar eminence at 300 Hz is approximately -10 dB. By extrapolation of a curve parallel to that shown in Figure 4, the threshold of the Pacinian system at 13 Hz should be approximately 32 dB, about 20 dB above that of the non-Pacinian system. Furthermore, remote masking within the Pacinian system (closed circles) begins at approximately 25 dB SL. Remote masking of the Pacinian system by a 13-Hz stimulus intense enough to exceed the Pacinian threshold should therefore start at about 45 dB. This is in the range in which apparent cross-channel masking begins (Figure 5, closed triangles). At a masker level of 50 dB SL, we should expect to produce about 5 dB of masking within the Pacinian system. The masking shown in Figure 5 at 50 dB SL is approximately 4 dB. It is likely, therefore, that intense stimulation at 13 Hz is sufficient to excite Pacinian receptors, thereby producing a masking effect entirely within the Pacinian system. Similar cross-channel effects were explored at a single site by Gescheider, Verrillo, and Van Doren (1982), who systematically raised the intensity of stimuli in one system to a level sufficient to exceed the threshold of the other system. The resultant effect at these masker-intensity levels can be considered to be within-channel masking.

The remote masking within the non-Pacinian system (Figure 5, open circles) is a weak effect and is seen only at the most intense masker level that we used. This is contrary to the finding of Ferrington et al. (1977), but their study was restricted to less intense maskers. To conclude on the basis of a single data point that remote masking occurs within the non-Pacinian system may be unwarranted.

GENERAL DISCUSSION

Our results show the following:

(1) On a single site, either the thenar eminence (Figure 1) or the finger pad (Figures 2 and 3), a

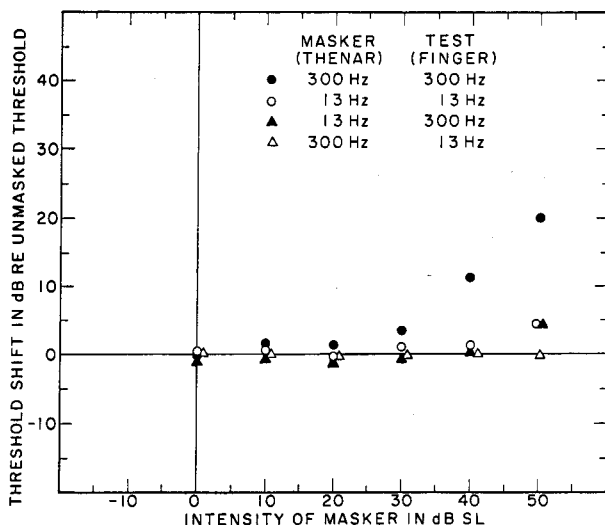


Figure 5. Masking of test stimuli at the fingertip by maskers delivered to the thenar eminence. The contactor size at both sites was .28 cm². Effective masking between sites is seen within the Pacinian system (●), but not within the non-Pacinian system (○), or when the masker excites one system and the test stimulus the other system (▲,△).

signal that is within the frequency range of maximal Pacinian system sensitivity (300 Hz) is an effective masker for a test stimulus within the same range (300 Hz). The amount of masking increases monotonically with the intensity of the masker past 10 dB.

(2) Masking also occurs within the Pacinian system when the masker (300 Hz) is presented to the thenar eminence and the test stimulus (300 Hz) is presented to the index finger pad (Figure 5).

(3) Masking can also be demonstrated on one site (finger) when both the masker and test stimulus are set at a frequency (13 Hz) to which the non-Pacinian receptor system is maximally responsive (Figure 3).

(4) However, when a frequency within the non-Pacinian system (13 Hz) is selected and delivered to different sites, masking within the non-Pacinian system occurs weakly and only at very high levels of the masker (see Figure 5).

(5) True cross-channel masking was not demonstrated on either one site or two sites (see Figures 3, 4, and 5).

These results agree in part with the findings of Ferrington et al. (1977), and in part they disagree. Ferrington et al. showed two-site masking when both frequencies were within the range of the Pacinian system, but they also reported a marked shift in threshold at all frequencies when a 300-Hz masking frequency was used. The latter finding, based on the results of a single subject, utilized a masker set at 100 μm , or approximately 42.5 dB SL. Furthermore, if their data are replotted in terms of decibels (rather than linear micrometers), the effect of the 300-Hz masker on a 10-Hz signal is only 1.5 dB, clearly within the experimental error. The effect of the 300-Hz masker on a 30-Hz test stimulus is approximately 6 dB. This shift is probably due to the fact that the 30-Hz test stimulus is close to the threshold crossover point between the non-Pacinian and Pacinian systems (see Figure 4), so the masker and test stimulus may both be activating the Pacinian system. Their effect of 300 Hz masking a 200-Hz test stimulus is approximately 13 dB, which is close to the 10-dB shift in our data for masking within the Pacinian system (Figure 5, masker intensity of 42 dB SL).

Our finding that the non-Pacinian system is not an effective masker of itself in a two-site experiment is also consistent with the results reported by Ferrington et al. (1977). We cannot conclude, however, as did Ferrington et al., that this result is intrinsic to the functional characteristics of the non-Pacinian receptor system, since our results on a single site show a robust masking of a 13-Hz test stimulus by a 13-Hz masker (Figure 3). Although Ferrington et al. concluded that within-channel masking in the non-Pacinian system does not occur between remote sites, their data are insufficient to con-

clude that this system cannot mask itself. Their result is based on the use of a frequency (30 Hz) capable of activating both systems and a masker-intensity level of approximately 22 dB SL. Had they used a lower frequency, one clearly within the non-Pacinian system, and higher masker intensities, they might have adequately tested the hypothesis that remote masking does not occur within the non-Pacinian system. Our results provide a better test of the hypothesis. Only 4 dB of masking is evident at 50 dB SL (Figure 5, open circles). Thus, we are in agreement with the conclusion of Ferrington et al. that remote masking does not occur within the non-Pacinian system, although masking does occur within this system if masker and test stimulus are delivered to the same site (Figure 3).

The report by Ferrington et al. (1977) that the Pacinian system is capable of masking a test stimulus within the optimal frequency range of the non-Pacinian system is at variance with our findings. We show that all remote masking takes place only within the Pacinian system (Figure 5, closed triangles). The data of Ferrington et al. (their Figure 6) look convincing when plotted as percent change as a function of masker frequency, but they used a constant masker displacement of 100 μm , which produces different sensation levels at different frequencies. A masker displacement of 100 μm is approximately 54 dB SL at 300 Hz, 52 dB SL at 200 Hz, 39 dB SL at 100 Hz, and 26 dB SL at 50 Hz. At frequencies below 50 Hz, their data show little or no cross-channel masking. Viewing their data as a function of masker sensation levels reveals no cross-channel masking.

Pertovaara and Hämäläinen (1981) also studied the effects of within- and cross-channel stimulation in an adaptation experiment in which the masker was presented to the index finger and the test stimulus to the back of the hand 3 to 6 cm away. They reported that, when both masker and test stimuli were within the Pacinian system (40-Hz masker and 150-Hz test; 240-Hz masker and 150-Hz test), there was a "marked" effect. Converting their data to decibels, the threshold shifts amounted to approximately 6 to 8 dB. Since they did not report masker thresholds, it is not possible to determine at what sensation level of the masker these values were obtained. However, remote masking within the Pacinian system is consistent with our results. Pertovaara and Hämäläinen (1981) showed no remote masking when masker and test stimulus are set within different systems (40-Hz masker and 20-Hz test; 240-Hz masker and 20-Hz test), which also agrees with our finding. They did not report a condition in which both masker and test stimuli activated the non-Pacinian system.

The present results support the conclusions of Labs et al. (1978) that the channels operating in vibrotaction are independent. However, these re-

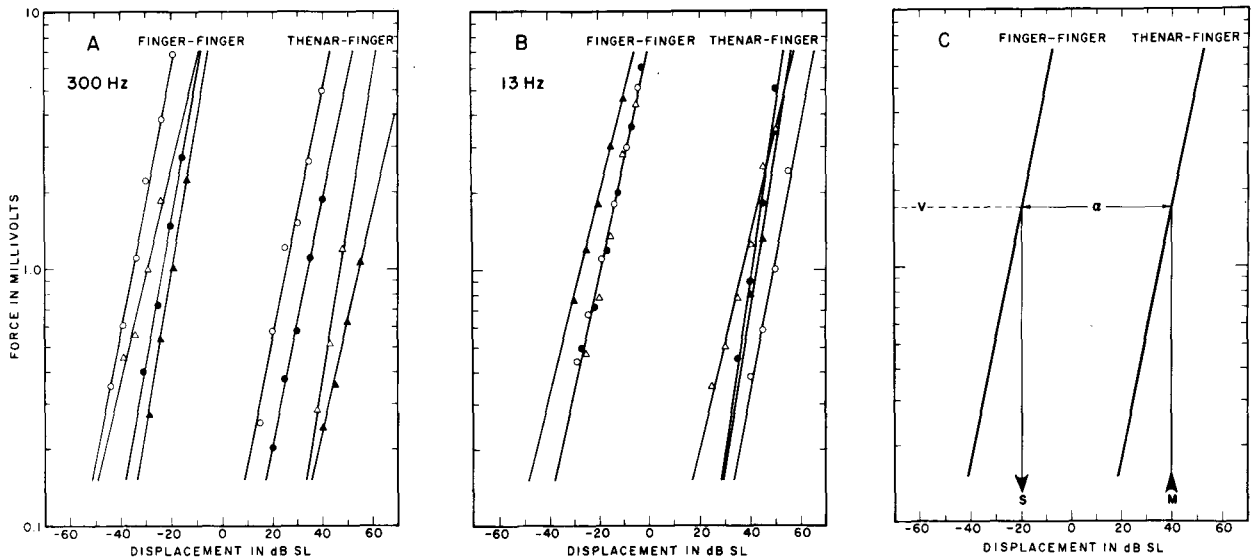


Figure 6. Measurements of the spread of vibration from the thenar eminence to the index fingertip. The right-hand set of curves in each graph represents the force measured at the fingertip produced by a stimulus applied to the thenar. The amplitude of the stimulus is expressed in sensation level re the threshold at the thenar. The left-hand set of curves represents the force measured at the fingertip by the same stimulus applied directly to the fingertip. For these curves, stimulus amplitude is plotted in sensation level re the threshold at the fingertip. All data points are means of two measurements made on each of four subjects. Curves are linear-regression fits to the data, with $r^2 > 0.97$ in all cases. Figure 6C is a schematic representation of the data. The value α is the attenuation of the vibration propagated from the thenar to the fingertip. See text for explanation.

sults do not support the conclusion of Verrillo and Capraro (1975) that there is within the central nervous system an interactive process between receptor systems. In that experiment, narrow- and wide-band noise were used as maskers of 25- and 250-Hz test signals. The wide-band maskers were clearly capable of masking both systems. The low-frequency, narrow-band masker had a frequency spread from 15 to 45 Hz, also capable of affecting the responses of both systems. Only the narrow-band, high-frequency masker was clearly within the range of only one system (Pacianian, 240-270 Hz). Yet both noise maskers produced cross-channel masking with a slope of 0.5. These results were interpreted as true, but anomalous (0.5 slope), cross-channel masking. There is no ready explanation of the conflicting results, but there were several important methodological differences. Verrillo and Capraro used the less accurate Békésy tracking method rather than 2IFC tracking and used continuous noise rather than the pulsed maskers that were used in the present study.

Since there is measurable masking between two locations for the Pacinian and perhaps the non-Pacianian systems, it is necessary to test the possibility that the masking is due to the physical transmission of vibration from the thenar to the fingertip. The measurement technique was discussed under Apparatus and Method, and the results are presented in Figure 6. The right-hand curves in each graph represent the voltages measured from the force gauge for each masker intensity plotted in reference to masker thresholds for 300 Hz (Figure 6A) and 13 Hz

(Figure 6B) measured at the thenar. The left-hand set of curves are the force-gauge voltages recorded during direct stimulation of the fingertip with the same masking stimulus. The amplitude of the applied vibration was measured and referenced to the stimulus threshold *at the fingertip*.

These graphs are most easily interpreted as shown in Figure 6C. At some masker intensity M , a voltage V is measured from the force gauge. The same voltage is also produced by a stimulus at the fingertip of amplitude S . Therefore, the masker M at the thenar produces an equivalent stimulus S at the fingertip. The difference α between these two quantities is, in a sense, an attenuation of the masking stimulus. That is, if α is 60 dB, then a 50-dB-SL masking stimulus at the thenar produces a vibration 10 dB below threshold at the finger. Figures 6A and 6B show that the smallest value of α for any frequency or intensity measured was 50 dB. Therefore, because the maximum masking intensity used was 50 dB SL, physical transmission of vibration produced only subthreshold stimuli at the surface of the skin and cannot have contributed to the masking effects reported.

The finding of masking within the Pacinian system between remote sites is consistent with other functional characteristics of this system. It is known to be capable of summing energy over space (Verrillo, 1963, 1966a), and each corpuscle has a large receptive field without clearly defined borders (Johansson, 1976, 1978). The absence of masking between remote sites shown for the non-Pacianian system is consis-

tent with its lack of spatial summation (Verrillo, 1963, 1966a) and small receptive fields with well-defined borders (Johansson, 1976, 1978). It has been suggested that the properties of the non-Pacinian system make it a candidate for the perception of patterns and texture by the skin (Johansson, 1978; Lindblom, 1965; Verrillo, 1979; Verrillo & Gescheider, 1979). Within-channel masking between remote sites in the Pacinian system and the absence of such an effect in the non-Pacinian system supports the suggestion that it is the non-Pacinian system that is primarily responsible for fine spatial discriminations on the skin. The Pacinian system, on the other hand, because of its summing properties and large, ill-defined receptive fields, would be poorly suited for such discriminations.

REFERENCES

- ANDERSEN, P., ETHOLM, B., & GORDON, G. Presynaptic and post-synaptic inhibition elicited in the cat's dorsal column by mechanical stimulation of the skin. *Journal of Physiology*, 1970, **210**, 433-455.
- BYSTRZYCKA, E., NAIL, B. S., & ROWE, M. Inhibition of cuneate neurons: Its afferent source and influence on dynamically sensitive "tactile" neurones. *Journal of Physiology*, 1977, **268**, 251-270.
- CAPRARO, A. J., VERRILLO, R. T., & ZWISLOCKI, J. J. Psychophysical evidence for a triplex system of cutaneous mechanoreception. *Sensory Processes*, 1979, **3**, 334-352.
- CARMODY, J., & ROWE, M. Inhibition within the trigeminal nucleus induced by afferent inputs and its influence on stimulus coding by mechanosensitive neurones. *Journal of Physiology*, 1974, **243**, 195-210.
- CRAIG, J. C. Difference threshold for intensity of tactile stimuli. *Perception & Psychophysics*, 1972, **11**, 150-152.
- CRAIG, J. C. Vibrotactile difference thresholds for intensity and the effect of a masking stimulus. *Perception & Psychophysics*, 1974, **15**, 123-127.
- CRAIG, J. C. Attenuation of vibrotactile spatial summation. *Sensory Processes*, 1976, **1**, 40-56.
- FERRINGTON, D. G., NAIL, B. S., & ROWE, M. Human tactile detection thresholds: Modification by inputs from specific tactile receptor classes. *Journal of Physiology*, 1977, **272**, 415-433.
- GARDNER, E. P., & SPENCER, W. A. Sensory funneling. I. Psychophysical observations of human subjects and responses of cutaneous mechanoreceptor afferents in the cat to patterned skin stimuli. *Journal of Neurophysiology*, 1972, **35**, 925-953.
- GESCHIEDER, G. A. Evidence in support of the duplex theory of mechanoreception. *Sensory Processes*, 1976, **1**, 68-76.
- GESCHIEDER, G. A., CAPRARO, A. J., FRISINA, R. D., HAMER, R. D., & VERRILLO, R. T. The effects of a surround on vibrotactile thresholds. *Sensory Processes*, 1978, **2**, 99-115.
- GESCHIEDER, G. A., HERMAN, D. D., & PHILLIPS, J. N. Criterion shifts in the measurement of tactile masking. *Perception & Psychophysics*, 1970, **8**, 433-436.
- GESCHIEDER, G. A., VERRILLO, R. T., CAPRARO, A. J., & HAMER, R. D. Enhancement of vibrotactile sensation magnitude and predictions from the duplex model of mechanoreception. *Sensory Processes*, 1977, **1**, 187-203.
- GESCHIEDER, G. A., VERRILLO, R. T., & FRISINA, R. D. Selective adaptation of vibrotactile thresholds. *Sensory Processes*, 1979, **3**, 37-48.
- GESCHIEDER, G. A., VERRILLO, R. T., & VAN DOREN, C. L. Prediction of vibrotactile masking functions. *Journal of the Acoustical Society of America*, 1982, **72**, 1421-1426.
- GILSON, R. D. Vibrotactile masking: Effects of multiple maskers. *Perception & Psychophysics*, 1969, **5**, 181-182. (a)
- GILSON, R. D. Vibrotactile masking: Some spatial and temporal aspects. *Perception & Psychophysics*, 1969, **5**, 176-180. (b)
- GILSON, R. D. Vibratory masking. In F. A. Geldard (Ed.), *Conference on cutaneous communication systems and devices*. Austin, Tex: Psychonomic Society, 1974.
- GREEN, B. G. Signal duration and vibrotactile sensitivity: Effects of vibration frequency and masking. Doctoral dissertation, Indiana University, 1975.
- GREEN, D. M. Psychoacoustics and detection theory. *Journal of the Acoustical Society of America*, 1960, **32**, 1189-1203.
- HAMER, R. D. *Vibrotactile masking: Evidence for a peripheral energy threshold*. Doctoral dissertation (Special Report ISR-S-18, Institute for Sensory Research), Syracuse University, 1979.
- HAMER, R. D., VERRILLO, R. T., & ZWISLOCKI, J. J. Vibrotactile masking of Pacinian and non-Pacinian channels. *Journal of the Acoustical Society of America*, in press.
- HARRINGTON, T., & MERZENICH, M. M. Neural coding in the sense of touch: Human sensations of skin indentation compared with the responses of slowly adapting mechanoreceptive afferents innervating the hairy skin of monkeys. *Experimental Brain Research*, 1970, **10**, 251-264.
- JÄNGER, W., SCHMIDT, R. F., & ZIMMERMAN, M. Two specific feedback pathways to the central afferent terminals of phasic and tonic mechanoreceptors. *Experimental Brain Research*, 1968, **6**, 116-129.
- JÄRVILEHTO, T., HÄMÄLÄINEN, H., & LAURINEN, P. Characteristics of single mechanoreceptive fibres innervating hairy skin of the human hand. *Experimental Brain Research*, 1976, **25**, 45-61.
- JOHANSSON, R. S. Skin mechanoreceptors in the human hand: Receptive field characteristics. In Y. Zotterman (Ed.), *Sensory functions of the skin in primates* (Vol. 27). New York: Pergamon, 1976.
- JOHANSSON, R. S. Tactile sensibility in the human hand: Receptive field characteristics of mechanoreceptive units in the glabrous skin area. *Journal of Physiology*, 1978, **281**, 101-123.
- JOHANSSON, R. S., & VALLBO, Å. B. Tactile sensibility in the human hand: Relative and absolute densities of four types of mechanoreceptive units in the glabrous skin area. *Journal of Physiology*, 1979, **286**, 283-300.
- KNIBESTÖL, M. Stimulus-response functions of rapidly adapting mechanoreceptors in the human glabrous skin area. *Journal of Physiology*, 1973, **232**, 427-445.
- KNIBESTÖL, M. Stimulus-response functions of slowly adapting mechanoreceptors in the human glabrous skin area. *Journal of Physiology*, 1975, **245**, 63-80.
- KNIBESTÖL, M., & VALLBO, Å. B. Single unit analysis of mechanoreceptor activity from the human glabrous skin. *Acta Physiologica Scandinavica*, 1970, **80**, 178-195.
- LABS, S. M., GESCHIEDER, G. A., FAY, R. R., & LYONS, C. H. Psychophysical tuning curves in vibrotactile. *Sensory Processes*, 1978, **2**, 231-247.
- LESHOWITZ, B., & RAAB, D. H. Effects of stimulus duration in the detection of sinusoids added to continuous pedestals. *Journal of the Acoustical Society of America*, 1967, **41**, 489-496.
- LINDBLOM, U. Properties of touch receptors in distal glabrous skin of the monkey. *Journal of Neurophysiology*, 1965, **28**, 966-985.
- MERZENICH, M. M., & HARRINGTON, T. The sense of flutter-vibration evoked by stimulation of mechanosensitive afferents innervating the hairy skin of monkeys. *Experimental Brain Research*, 1969, **9**, 236-260.
- MOUNTCASTLE, V. B., & POWELL, T. P. S. Neural mechanisms subserving cutaneous sensibility, with special reference to the role of afferent inhibition in sensory perception and discrimination. *Johns Hopkins Hospital Bulletin*, 1959, **105**, 201-232.
- PERTOVAARA, A., & HÄMÄLÄINEN, H. Vibrotactile thresholds during background of long duration. *Scandinavian Journal of Psychology*, 1981, **22**, 41-45.

- PFÄFFLIN, S. M., & MATHEWS, M. V. Energy-detection model for monaural auditory detection. *Journal of the Acoustical Society of America*, 1962, **34**, 1842-1853.
- RAAB, D. H., OSMAN, E., & RICH, E. Effects of waveform correlation and signal duration on detection of noise bursts in continuous noise. *Journal of the Acoustical Society of America*, 1963, **35**, 1942-1946. (a)
- RAAB, D. H., OSMAN, E., & RICH, E. Intensity discrimination, the "pedestal" effect, and "negative masking" with white noise stimuli. *Journal of the Acoustical Society of America*, 1963, **35**, 1053. (b)
- ROWE, M. J., & CARMODY, J. J. Afferent inhibition over the response range of secondary trigeminal neurones. *Brain Research*, 1970, **18**, 371-374.
- SHERRICK, C. E., JR. Effects of double simultaneous stimulation on the skin. *American Journal of Psychology*, 1964, **77**, 42-53.
- SNYDER, R. E. Vibrotactile masking: A comparison of psychophysical procedures. *Perception & Psychophysics*, 1977, **22**, 471-475.
- TALBOT, W. H., DARIAN-SMITH, I., KORNHUBER, H. H., & MOUNTCASTLE, V. B. The sense of flutter-vibration: Comparison of the human capacity with response patterns of mechanoreceptive afferents from the monkey hand. *Journal of Neurophysiology*, 1968, **31**, 301-334.
- TANNER, W. P. Application of the theory of signal detectability to amplitude discrimination. *Journal of the Acoustical Society of America*, 1961, **33**, 1233-1244.
- VERRILLO, R. T. Effect of contactor area on the vibrotactile threshold. *Journal of the Acoustical Society of America*, 1963, **35**, 1962-1966.
- VERRILLO, R. T. Temporal summation in vibrotactile sensitivity. *Journal of the Acoustical Society of America*, 1965, **37**, 843-846.
- VERRILLO, R. T. Effect of spatial parameters on the vibrotactile threshold. *Journal of Experimental Psychology*, 1966, **71**, 570-575. (a)
- VERRILLO, R. T. Specificity of a cutaneous receptor. *Perception & Psychophysics*, 1966, **1**, 149-153. (b)
- VERRILLO, R. T. Vibrotactile sensitivity and the frequency response of the Pacinian corpuscle. *Psychonomic Science*, 1966, **4**, 135-136. (c)
- VERRILLO, R. T. Vibrotactile thresholds for hairy skin. *Journal of Experimental Psychology*, 1966, **72**, 47-50. (d)
- VERRILLO, R. T. A duplex mechanism of mechanoreception. In D. R. Kenshalo (Ed.), *The skin senses*. Springfield, Ill: Thomas, 1968.
- VERRILLO, R. T. Vibrotactile thresholds measured at the finger. *Perception & Psychophysics*, 1971, **9**, 329-330.
- VERRILLO, R. T. The effect of surface gradients on vibrotactile thresholds. *Sensory Processes*, 1979, **3**, 27-36.
- VERRILLO, R. T., & CAPRARO, A. J. Effect of extrinsic noise on vibrotactile information processing channels. *Perception & Psychophysics*, 1975, **18**, 88-94.
- VERRILLO, R. T., & GESCHEIDER, G. A. Enhancement and summation in the perception of two successive vibrotactile stimuli. *Perception & Psychophysics*, 1975, **18**, 128-136.
- VERRILLO, R. T., & GESCHEIDER, G. A. Effect of prior stimulation on vibrotactile thresholds. *Sensory Processes*, 1977, **1**, 191-300.
- VERRILLO, R. T., & GESCHEIDER, G. A. Psychophysical measurements of enhancement, suppression, and surface-gradient effects in vibration. In D. R. Kenshalo (Ed.), *Sensory functions of the skin of humans*. New York: Plenum, 1979.
- ZWISLOCKI, J. J., MAIRE, F., FELDMAN, A. S., & RUBIN, H. On the effect of practice and motivation on the threshold of audibility. *Journal of the Acoustical Society of America*, 1958, **30**, 254-262.

(Manuscript received February 25, 1982;
revision accepted for publication January 10, 1983.)