Effects of noise on detection of amplitude increments of sinusoidal vibration of the skin

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Vibrotactile thresholds for detecting a 300-Hz signal in the presence of both a 300-Hz sinusoidal pedestal and a background noise were measured as a function of the amplitudes of the pedestal and noise. Threshold increased monotonically as a function of the amplitude of the noise, but was a nonmonotonic function of the amplitude of the sinusoidal pedestal. Negative masking, in which the pedestal facilitated detection of the test stimulus, was observed in the absence of background noise and in the presence of subthreshold background noise when the pedestal was near or below threshold. Negative masking disappeared when the experiment was conducted in the presence of moderately intense to intense background noise. The results are consistent with a peripheral high-energy threshold for taction.

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INTRODUCTION

Research on vibrotactile masking has determined how parameters of a masking stimulus influence the threshold for detecting a signal. Various studies have examined the effects of spatial and temporal relationships between masking stimulus and signal (Gescheider *et al.*, 1989; Gilson, 1969a; Sherrick, 1964), the number of masking stimuli (Gilson, 1969b), the effect of masking on spatial summation (Craig, 1976), the psychophysical method of measurement (Gescheider *et al.*, 1970; Snyder, 1973; Gilson, 1974), and the relation between masking and intensity discrimination (Gescheider *et al.* 1990). Studies of the effects of the frequency of the masking and test stimuli have provided strong experimental evidence for the existence of separate vibrotactile information-processing channels (Bolanowski *et al.*, 1988; Ferrington *et al.*, 1977; Gescheider *et al.*, 1982; Gescheider *et al.*, 1983a; Gescheider *et al.*, 1985; Hamer, 1979; Hamer *et al.*, 1983; Labs *et al.*, 1978; Martin *et al.*, 1985). The observer is thought to have available a bank of several parallel channels, each operating over a limited range of vibration frequencies. Detection is mediated by the channel most sensitive to the signal (e.g., Gescheider *et al.*, 1982) and maskers are thought to be effective only to the extent that they stimulate the channel used to detect the signal. Recent work provides evidence for the existence of four such channels, sensitive to overlapping frequency bands (Bolanowski *et al.*, 1988). The frequency characteristic of each of these channels is thought to be determined by the response properties of a specific mechanoreceptor type (Bolanowski *et al.*, 1988).

In the present study, we used 300-Hz stimuli to isolate the channel mediated by Pacinian corpuscles (P channel). Vibrotactile intensity discrimination was studied within the P channel using the method of simultaneous masking. The observer was asked to detect a 300-Hz signal in the presence of a 300-Hz masker (pedestal) of the same phase. Vibrotactile thresholds were measured for detecting a 300-ms, 300-Hz signal presented in the presence of both a 730-ms pedestal of the same frequency and a continuous background noise vibration consisting of narrow-band noise, whose spectrum was centered on 300 Hz.

Hamer (1979), Hamer *et al.* (1983), and Verrillo *et al.* (1983) also measured thresholds for the detection of a sinusoidal signal in the presence of a sinusoidal masker of the same frequency and phase. They found positive masking (i.e., the pedestal caused an elevation in the threshold for detecting the signal) at high masker intensities, and negative masking (i.e., the pedestal caused a reduction in the threshold for detecting the test stimulus) when the intensity of the pedestal was subthreshold or at very low amplitudes.

Negative masking is not unique to vibrotaction, and has been extensively studied in hearing (Green, 1960, 1966; Hanna *et al.*, 1986; Legge and Viemeister, 1988; Leshowitz and Raab, 1967; Pfafflin and Mathews, 1962; Raab *et al.*, 1963a, b; Tanner, 1961; Viemeister and Bacon, 1988; Vogten, 1978) and in vision (Cohn *et al.*, 1974; Foley and Legge, 1981; Legge *et al.*, 1987; Legge and Foley, 1980; Legge and Viemeister, 1988; Nachmias and Kocher, 1970; Nachmias and Sansbury, 1974; Pelli, 1985). In hearing, negative masking has been attributed to how the stimulus is defined rather than to an energy threshold. For example, Raab *et al.* (1963a, b), Green (1966) and Vogten (1978) all have claimed that negative masking in hearing can be abolished by redefining the signal intensity in terms of increment energy rather than amplitude. When the increment energy resulting from adding the just-detectable signal to the pedestal is compared to the energy in a just-detectable signal presented alone, negative masking disappears. On the other hand, Hamer (1979) has shown that tactile negative masking remains when the intensity of a sinusoidal signal presented in phase with a pedestal of the same frequency is expressed as increment energy.

Hamer *et al.* (1983) have concluded that the demonstration that negative masking in vibrotaction is not, as it is in hearing, an artifact of the definition of the stimulus can be explained by an energy threshold assumed to exist in the periphery of the tactile nervous system. According to this hypothesis, detection cannot occur unless the total energy of the stimulus exceeds an absolute threshold. Thus it was reasoned that a masker acted as a pedestal, decreasing the energy of the signal necessary to reach the detection threshold. An analytical detection model, that includes such a threshold, was developed to account for negative masking (Hamer, 1979; Hamer *et al.*, 1983). A related model for vision incorporating a "nonlinear transducer function" has been proposed to account for negative masking in the detection of sine-wave gratings presented with masking backgrounds (Foley and Legge, 1981; Legge and Foley, 1980; Nachmias and Sansburg, 1974). Laming (1986) has also accounted for negative masking by assuming such nonlinear transformations of stimulus intensity by the sensory system. For example, he has proposed that the response of the auditory or tactile systems, near the psychophysical threshold, is proportional to the square of stimulus amplitude, whereas the response of the visual system is proportional to the fourth power of the amplitude of luminance modulation. The common feature of these proposed nonlinear input–output functions, including Hamer's, in which the response of the system is greater than zero only when stimulus intensity exceeds a threshold value, is that, near the psychophysical threshold, changes in the input produce greater changes in the output when pedestal amplitude corresponds to a rapidly changing segment of the function rather than when the pedestal amplitude is lower. Consequently, to be detected, the signal must be stronger when presented in the absence of a pedestal or in the presence of a very weak pedestal than when presented with a stronger pedestal whose intensity corresponds to the rapidly changing part of the function.

The purpose of the present study was to examine the effects of background noise of variable amplitude on the observer's ability to detect increments in the amplitude of a sinusoidal pedestal presented at various intensity levels ranging from subthreshold to substantially above threshold. In this way, it was possible to observe the effects of noise on both negative and positive masking and to test the energy threshold hypothesis that vibrotactile negative masking is due to an energy threshold. If negative masking is due to subthreshold maskers acting as pedestals for elevating test stimuli to suprathreshold levels, then the phenomenon should disappear when examined in the presence of suprathreshold noise. It was thought that the masking effect of the background noise should increase the measured detection thresholds for sinusoidal stimuli to a level sufficiently above that of the energy threshold to eliminate negative masking. If negative masking is due to weak sinusoidal masking stimuli acting as pedestals to boost the test stimulus above the energy threshold, then negative masking should not be observed where the test stimulus, by virtue of the background noise, must be presented well above the theoretical energy threshold.

I. METHODS

Three males (35, 47, and 57 years old) and one female (23 years old) served as observers in the experiment. All had previous experience as observers in experiments in vibrotactile sensitivity, including experiments on masking.

The sinusoidal test signal and pedestal were digitally synthesized by an LSI-11/23 computer via 12 bit digital-to-analog converters (2-kHz clock rate) and attenuated by computer-controlled attenuators. Narrow-band noise was produced by limiting white noise to a bandwidth of 250–350 Hz (at half-peak power). Signal, pedestal, and noise were electronically summed and delivered to an electromagnetic vibrator located within a sound-proofed booth in which the observer sat.

The vibrator was positioned upon an adjustable platform beneath a rigid surface. The 2.9-cm^2 circular contactor, mounted on the vibrator, protruded through a hole in the rigid surface. The observer comfortably rested his or her right hand, palm down, on the rigid surface so that the observer's thenar eminence lay upon the contactor. The contactor was a concave disk, following the contour of the skin. The gap between the perimeter of the contactor and the surrounding rigid surface was 1.0 mm. At the start of each session, the height of the vibrator was adjusted so that the contactor indented the skin 0.5 mm beyond minimal contact.

Two-interval, forced-choice tracking (Zwislocki *et al.*, 1958) was used to measure all masked and unmasked thresholds. The observer was required to indicate, by pressing one of two buttons, in which time interval the signal occurred. The next trial did not begin until a response had been made to the previous trial. The signal appeared at random in only one of the two intervals. The amplitude of the signal was increased by 1 dB after each incorrect response and reduced by 1 dB after every third correct response (ignoring incorrect responses). The signal amplitude was recorded on a chart recorder. The run continued until the range of signal intensities for the preceding 2 min (about 30 trials) was less than 4 dB. The final threshold estimate was the center of that range, determined visually from the record of the chart recorder. This procedure (2 IFC tracking) provides an estimate of the intensity at which the probability of correct response is 75% correct.

At the start of each session, a threshold for detecting the 300-Hz pedestal was measured. If background noise was employed, a threshold for the detection of the noise was also measured. For the remainder of the session, masked and unmasked thresholds for the detection of the 300-Hz signal were measured. The sinusoidal stimuli always commenced at a zero crossing of the sinusoid.

Figure 1 shows the timing of a typical trial. The pedestal had a duration of 730 ms with a 25-ms rise/fall time. The signals were 300 ms in duration, centered within the pedestal time, and they also had a 25-ms rise/fall time. All durations were measured at the half-power points. The noise (not shown), when present, was on continuously. The two 730-ms intervals were separated by 1000 ms. Each new trial commenced immediately after the observer's response to the previous trial.

The observer always had to choose which of two obser-

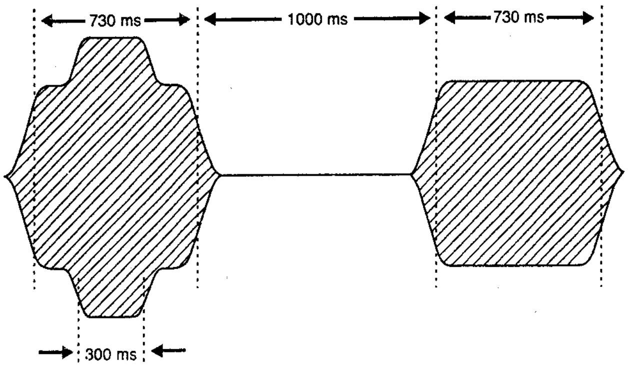

FIG. 1. Envelope of the stimuli during a typical 2AFC trial. In this illustration the first interval happens to contain the signal, but the signal may appear in either the first or second interval. All times are with respect to half power points. Each new trial begins immediately after the observer's response to the previous trial.

vation intervals contained the signal. The pedestal and noise, if present, were present in both intervals. The two observation intervals were indicated to the observer by lights that were synchronized to the onset of the pedestal. Thresholds for detecting the signal in the presence of and in the absence of a pedestal were measured at each of the noise levels ranging from − 16 dB to 40 dB SL. The sensation level of the pedestal was held constant within the session and the sensation level of the background noise was varied. At each noise level, data were taken only after a period of time when adaptation to the noise was complete as indicated by the stability of threshold measurements. Observers were usually tested for only one 45-min session per day, but were occasionally tested twice in one day separated by a time interval of several hours. A total of three thresholds for each observer were measured under every condition of the experiments.

Threshold for detecting the noise was measured by the method of limits, using two ascending and two descending series with 2-dB steps. Threshold for detecting the pedestal was measured by 2IFC tracking at the beginning of each session. Since we determined that thresholds for detecting the same stimulus by the two methods did not systematically differ and because the noise channel of our apparatus was not equiped for 2IFC tracking, we measured all noise thresholds by the method of limits.

II. RESULTS AND DISCUSSION

Observers did not differ substantially in their thresholds for detecting the signal presented alone as indicated by a standard deviation of 2.09 dB for the four observers. Because the absolute sensitivities of the observers were similar, we elected to present averaged data. The mean threshold is plotted as a function of noise level in Fig. 2. All thresholds were expressed in dB *re*: 1.0 micrometer peak displacement. There is a separate set of points for each sensation level of the pedestal. Thus the sensation level of the pedestal and noise are expressed in dB relative to the threshold for each type of stimulus presented alone. In the absence of a pedestal, threshold for detecting the signal was unaffected by the background noise until the noise was intense enough to be detected, after which thresholds increase with further increases in its intensity and, as also reported by Hamer *et al.* (1983), no negative masking attributable to the presentation of noise is evident. Negative masking is seen when weak pedestals are presented in the absence of noise or in the presence of weak noise, and positive masking results from the presentation of more intense pedestals. It is clear that the function describing the change in threshold as noise intensity changes is greatly influenced by the intensity of the pedestal. For suprathreshold pedestals, at low noise levels, threshold is greatly influenced by changes in the intensity of the pedestal, but little affected by changes in noise level. On the other hand, when the noise level is high, threshold is greatly influenced by changes in noise level, but little affected by changes in the intensity of the pedestal.

Subjectively, the task changes as the intensity of the noise increases: At low noise intensities, the signal is detected as an increment upon the pedestal amplitude, at high noise intensities, the signal is detected only when it is sufficiently intense to emerge from the background noise.

Figure 3 presents another view of the data in Fig. 2. Threshold is now plotted as a function of the sensation level of the pedestal. In the absence of external noise (closed circles), a nonmonotonic masking function is seen with maximal negative masking when the pedestal is at 0 dB SL. This finding is in close agreement with the results of Gescheider *et al.* (1990), Hamer *et al.* (1983), and Verrillo *et al.* (1983) who also reported negative masking when the signal was presented in phase with a near threshold pedestal. The slope of the masking functions for conditions in which the noise was absent or very weak are slightly less than 1.0, illustrating the near miss to Weber's law (McGill and Goldberg, 1968)

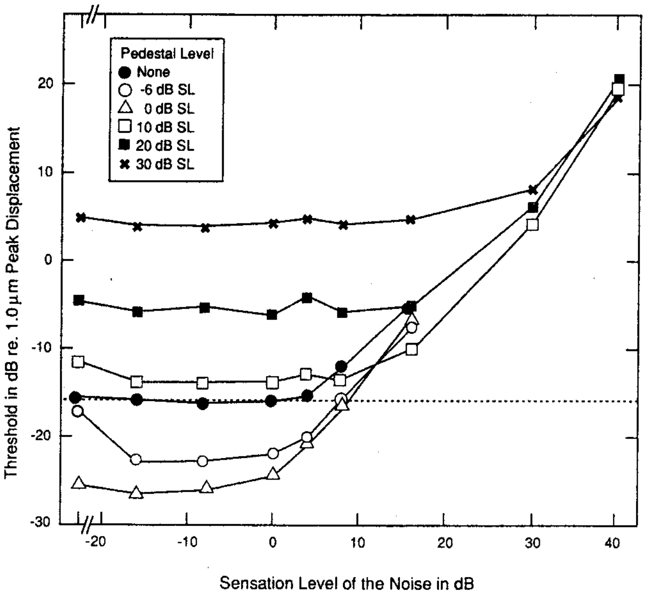

FIG. 2. Threshold as a function of the background noise level, at various levels of the sinusoidal pedestal.

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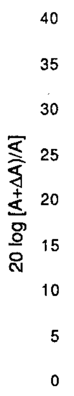

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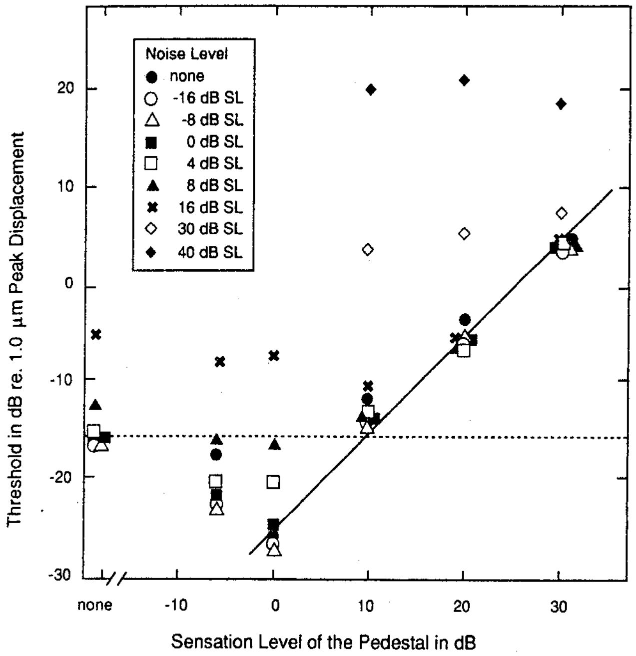

FIG. 3. Threshold as a function of the sensation level of the pedestal at various levels of the background noise.

previously reported for vibrotaction by Gescheider *et al.* (1990).

The phenomenon can also clearly be seen when the data are plotted as increment detection difference thresholds (Fig. 4) in which the relative DL is expressed as the decibel difference (20 log $[(A + \Delta A)/A]$) between the amplitude of the signal ΔA plus pedestal A and the pedestal. Computed in this way the relative difference threshold drops from about 3.5 to 2.0 dB as the pedestal is increased from 10 to 30 dB SL. DLs obtained by Gescheider *et al.* (1990) using a comparable method in which observers also reported which of two bursts of vibration contained an amplitude increment (two-burst continuous pedestal method) are also plotted in Fig. 4. Over the range of 10 to 30 dB SL, the data obtained in the absence of background noise in these two studies are in very close agreement. The effects of negative masking, in the present study, when the pedestal was 0 dB SL, was manifested in a sharp drop in the DL at this sensation level. At a slightly higher sensation level, the DL increases, but with further increases in pedestal amplitude the DL gradually decreases in accordance with the near miss to Weber's law. It should be pointed out that intensity discrimination is superior when measured by either a gated-pedestal method or a continuous-pedestal method (Gescheider *et al.*, 1990), but the near miss is seen with both methods. As was true in Craig's (1974) study of vibrotactile intensity discrimination, masking stimuli elevate the DL, particularly for weak pedestals, resulting in an extreme deviation from Weber's law.

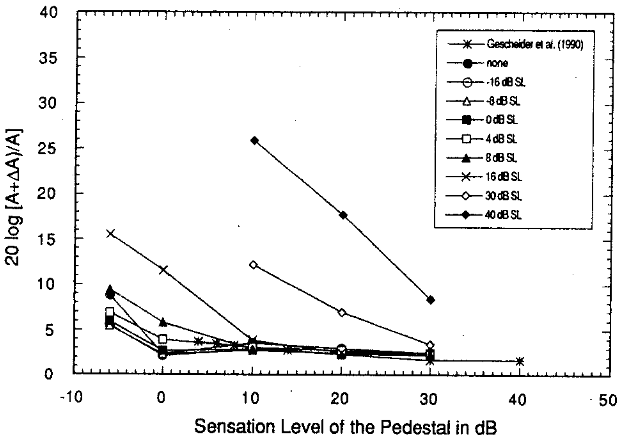

FIG. 4. Relative difference thresholds in dB (20 log $[(A + \Delta A)/A]$) where A is pedestal amplitudes and ΔA is signal amplitude plotted as a function of sensation level of the pedestal with no background noise and with various background noise levels. Data obtained from Gescheider *et al.* (1990) are also plotted for comparison.

The negative masking shown in Fig. 3 is consistent with a peripheral energy threshold for vibration (Hamer, 1979; Hamer *et al.*, 1983). In fact, the form of the negative masking function has been successfully predicted from an energy threshold model (Hamer, 1979; Hamer *et al.*, 1983). At very weak noise levels, we obtained similar results, but higher noise levels abolished the negative masking.

In Hamer's model, displacement of the mechanoreceptive membrane resulting from stimulation, is converted to a variable that is proportional to stimulus energy, a threshold level of which must be exceeded in order to generate action potentials (Hamer, 1979). It is because of the general lack of spontaneous activity in rapidly adapting tactile fibers that this threshold becomes significant in the psychophysical detection situation (Valbo and Johansson, 1976). According to the model, negative masking occurs because a weak pedestal adds to the signal, raising the total energy to a level above the threshold. The same signal alone would have failed to exceed threshold. At higher levels of neural activity, such as those produced by the application of external noise, threshold level becomes inconsequential, negative masking disappears and detectability is determined by the neural signal-to-noise ratio.

In contrast to vibrotaction, lack of "true" negative masking in hearing implies the absence of an energy threshold. The apparent absence of an energy threshold in hearing could be the result of the relatively high levels of spontaneous activity found in peripheral-auditory-nerve fibers. Such high levels of ongoing activity could eliminate the possibility of threshold effects in a psychophysical experiment.

It is significant that in visual contrast discrimination, noise backgrounds presented at various levels do not eliminate negative masking (Pelli, 1981, 1990). This result suggests that the process of detection is similar with and without the noise masker and therefore cannot be due to a peripheral energy thresholds as it appears to be in vibration.

In addition to negative masking there is other evidence that supports the energy-threshold hypothesis for tactile stimulus detection. Eijkman and Vendrik (1963) and Vendrik and Eijkman (1968), for example, found that the probability of detecting tactile or electrocutaneous stimuli was constant until a critical value of stimulus intensity was exceeded. In addition, the results of a series of studies of vibrotactile signal detection also support the energy threshold concept (Gescheider *et al.*, 1968, 1969; Gescheider and Wright, 1971; Gescheider *et al.*, 1971a,b). These investigators found that d' was zero and reaction time was constant until a critical value of vibration amplitude was exceeded after which d' increased and reaction time decreased with further increases in amplitude. The stimulus amplitude at which the measures of response first became stimulus dependent was the same for both response measures and was found to be independent of the *a priori* probability of signal presentation.

Recordings from rapidly adapting mechanoreceptor afferents in cat (Sato, 1961; Gray and Mathews, 1951; Scott, 1951; Loewenstein, 1958; Hunt, 1960), monkey (Lindblom, 1965; Lindblom and Lund, 1966; Talbot *et al.*, 1968; Mountcastle *et al.*, 1972), and man (Hagbarth and Vallbo, 1968; Vallbo and Hagbarth, 1968; Knibestol, 1973; Vallbo and Johansson, 1976) indicate the existence of energy thresholds at the level of the receptors. These units showed no activity in the absence of stimulation and exhibited nerve impulses only when a liminal stimulus was applied. Furthermore, Vallbo and Johannson (1976) have demonstrated that, under some conditions, human observers could detect single nerve impulses initiated from stimulation of cutaneous mechanoreceptive nerve fibers. Although a single nerve impulse was necessary for a detection response, it did not always result in one, suggesting the existence of central limiting factors such as internal noise or inadequate attention. This finding is consistent with Hamer's (1979) model which includes both a peripheral energy threshold and central neural noise.

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Bolanowski, S. J., Jr., Gescheider, G. A., Verrillo, R. T., and Checkosky, C. M. (**1988**). "Four channels mediate the mechanical aspects of touch," J. Acoust. Soc. Am. **84**, 1680–1694.

Cohn, T. E., Thibos, L. N., and Kleinstein, R. N. (**1974**). "Detectability of a luminance increment," J. Opt. Soc. Am. **64**, 1321–1327.

Craig, J. C. (**1974**). "Vibrotactile difference thresholds for intensity and the effect of a masking stimulus," Percept. Psychophys. **15**, 123–127.

Craig, J. C. (**1976**). "Attenuation of vibrotactile spatial summation," Sensory Process. **1**, 40–56.

Eijkman, E., and Vendrik, A. J. H. (**1963**). "Detection theory applied to the absolute sensitivity of sensory systems," Biophys. **3**, 65–77.

Ferrington, D. G., Nail, B. S., and Rowe, M. (**1977**). "Human tactile detection thresholds: Modification by inputs from specific tactile receptor classes," J. Physiol. **272**, 415–433.

Foley, J. M., and Legge, G. E. (**1981**). "Contrast detection and near threshold discrimination in human vision," Vision Res. **21**, 1041–1053.

Gescheider, G. A., Bolanowski, S. J., Jr., and Verrillo, R. T. (**1989**). "Vibrotactile masking: effects of stimulus-onset asynchrony and stimulus frequency," J. Acoust. Soc. Am. **85**, 2059–2069.

Gescheider, G. A., Bolanowski, S. J. Jr., Verrillo, R. T. Arpajian, D. J., and Ryan, T. (**1990**). "Vibrotactile intensity discrination measured by three methods," J. Acoust. Soc. Am. **87**, 330–338.

Gescheider, G. A., Herman, D. D., and Phillips, J. N. (**1970**). "Criterion shifts in the measurement of tactile masking," Percept. Psychophys. **8**, 433–436.

Gescheider, G. A., O'Malley, M. J., and Verrillo, R. T. (**1983a**). "Vibrotactile forward masking: Evidence for channel independence," J. Acoust. Soc. Am. **74**, 474–485.

Gescheider, G. A., Sklar, B. F., Van Doren, C. L., and Verrillo, R. T. (**1985**). "Vibrotactile forward masking: Psychophysical evidence for a triplex theory of cutaneous mechanoreception," J. Acoust. Soc. Am. **78**, 534–543.

Gescheider, G. A., Verrillo, R. T., and Pelli, D. G. (**1983b**). "Vibrotactile negative masking," Soc. Neurosci. Abstr. **9**, 775.

Gescheider, G. A., Verrillo, R. T., and Van Doren, C. L. (**1982**). "Prediction of vibrotactile masking functions," J. Acoust. Soc. Am. **72**, 1421–1426.

Gescheider, G. A., and Wright, J. H. (**1971**). "Reaction time as a function of magnitude estimations of vibrotactile internal noise," J. Psychol. **79**, 91–95.

Gescheider, G. A., Wright, J. H., and Evans, M. B. (**1968**). "Reaction time in the detection of vibrotactile signals," J. Exp. Psychol. **77**, 501–504.

Gescheider, G. A., Wright, J. H., and Polak, J. W. (**1971a**). "Detection of vibrotactile signals differing in probability of occurrence," J. Psychol. **78**, 253–260.

Gescheider, G. A., Wright, J. H., Weber, B. J., and Barton, W. G. (**1971b**). "Absolute thresholds in vibrotactile signal detections," Percept. Psychophys. **10**, 413–417.

Gescheider, G. A., Wright, J. H., Weber, B. J., Kirchner, B. M., and Milligan, E. A. (**1969**). "Reaction time as a function of the intensity and probability of occurrence of vibrotactile signals," Percept. Psychophys. **5**, 18–20.

Gilson, R. D. (**1969a**). "Vibrotactile masking: Some spatial and temporal aspects," Percept. Psychophys. **5**, 176–180.

Gilson, R. D. (**1969b**). "Vibrotactile masking: Effects of multiple maskers," Percept. Psychophys. **5**, 181–182.

Gilson, R. D. (**1974**). "Vibrotactile masking," in *Cutaneous Communication Systems and Devices*, edited by F. A. Geldard (Psychonomic Society, Austin, TX), pp. 53–56.

Gray, J. A. B., and Matthews, P. B. C. (**1951**). "Response of Pacinian corpuscles in the cat's toe," J. Physiol. **113**, 475–482.

Green, D. M. (**1960**). "Acoustics and detection theory," J. Acoust. Soc. Am. **32**, 1189–1203.

Green, D. M. (**1966**). "Comments on 'Effects of waveform correlation and signal duration on detection of noise bursts in continuous noise,' " J. Acoust. Soc. Am. **39**, 748–749.

Hagbarth, K. E., and Vallbo, A. B. (**1968**). "Activity from skin mechanoreceptors recorded percutaneously in awake human subjects," Exp. Neurol. **21**, 270–289.

Hamer, R. D. (**1979**). "Vibrotactile masking: evidence for a peripheral energy threshold," Ph.D. dissertation and Special Report ISR-S-18, Institute for Sensory Research, Syracuse University, Syracuse, NY.

Hamer, R. D., Verrillo, R. T., and Zwislocki, J. J. (**1983**): "Tactile masking of Pacinian and non-Pacinian channels," J. Acoust. Soc. Am. **73**, 1293–1303.

Hanna, T. E., von Gierke, S. M., and Green, D. M. (**1986**). "Detection and intensity discrimination of a sinusoid," J. Acoust. Soc. Am. **80**, 1335–1340.

Hunt, C. C. (**1960**). "On the nature of vibration receptors in the hind limb of the cat," J. Physiol. **155**, 175–186.

Knibestol, M. (**1973**). "Stimulus-response functions of rapidly adapting mechanoreceptors in the human glabrous skin area," J. Physiol. (London) **232**, 427–452.

Labs, S. M., Gescheider, G. A., Fay, R. R., and Lyons, C. H. (**1978**). "Psychophysical tuning curves in vibrotaction," Sensory Process. **2**, 231–247.

Laming, D. (**1986**). *Sensory Analysis* (Academic, Orlando), pp. 135–152.

Legge, G. E., and Foley, J. M. (**1980**). "Contrast masking in human vision," J. Opt. Soc. Am. **70**, 1458–1471.

Legge, G. E., and Viemeister, N. F. (**1988**). "Sensory analysis in vision and audition: A commentary on *Sensory Analysis* by Donald Laming," Behav. Brain Sci. **11**, 301–302.

Legge, G. E., Kersten, D., and Burgess, A. E. (**1987**). "Contrast discrimination in noise," J. Opt. Soc. Am. A **4**, 391–404.

Leshowitz, B., and Raab, D. H. (**1967**). "Effects of stimulus duration on the detection of sinusoids added to continuous pedestal," J. Acoust. Soc. Am. **41**, 489–496.

Lindblom, U. (**1965**). "Properties of touch receptors in distal glabrous skin of the monkey," J. Neurophysiol. **28**, 966–985.

Lindblom, U., and Lund, L. (**1966**). "The discharge from vibration-sensitive receptors in the monkey foot," Exp. Neurol. **15**, 401–417.

Loewenstein, W. R. (**1958**). "Generator processes of repetitive activity in a Pacinian corpuscle," J. Gen. Physiol. **41**, 825–845.

Martin, J. H., Zambelli, A., Takehiko, B., and Spencer, W. A. (**1985**). "Mechanoreceptive submodality channel interactions: Psychophysical observations on differential activation of flutter and vibration," Brain Res. **327**, 269–277.

McGill, W. J., and Goldberg, J. P. (**1968**). "A study of the near-miss involving Weber's law and pure tone intensity discrimination," Percept. Psychophys. **4**, 105–109.

Mountcastle, V. B., LaMotte, R. H., and Carli, G. (**1972**). "Detection thresholds for stimuli in humans and monkeys: Comparison with threshold events in mechanoreceptive afferent nerve fibers innervating the monkey hand," J. Neurophysiol. **35**, 122–136.

Nachmias, J., and Kocher, E. C. (**1970**). "Visual detection and discrimination in luminance discrimination," J. Opt. Soc. Am. **60**, 382–389.

Nachmias, J., and Sansbury, R. V. (**1974**). "Grating contrast: Discrimination may be better than detection," Vis. Res. **14**, 1039–1042.

Pelli, D. G. (**1981**). "Effects of visual noise," Ph.D. disseration.

Pelli, D. G. (**1985**). "Uncertainty explains many aspects of visual contrast detection," J. Opt. Soc. Am. A **2**, 1508–1532.

Pelli, D. G. (**1990**). "The quantum efficiency of vision," in *Vision: Coding and Efficiency*, edited by C. Blakemore (Cambridge U.P., Cambridge), pp. 3–24.

Pfafflin, S. M., and Mathews, M. V. (**1962**). "Energy-detection model for monaural auditory detection," J. Acoust. Soc. Am. **34**, 1842–1853.

Raab, D. H., Osman, E., and Rich, E. (**1963a**). "Intensity discrimination, the 'pedestal' effect, and 'negative masking' with white-noise stimuli," J. Acoust. Soc. Am. **35**, 1053.

Raab, D. H., Osman, E., and Rich, E. (**1963b**). "Effects of waveforms correlation and signal duration on detection of noise bursts in continuous noise," J. Acoust. Soc. Am. **35**, 1942–1946.

Sato, M. (**1961**). "Response of Pacinian corpuscle to sinusoidal vibration," J. Physiol. (London) **159**, 391–409.

Scott, D. (**1951**). "Response of Pacinian corpuscles to sinusoidal vibration," Fed. Proc. **10**, 123.

Sherrick, C. E. (**1964**). "Effects of double simultaneous stimulation of the skin," Am. J. Psychol. **77**, 42–53.

Snyder, R. E. (**1973**). "Vibrotactile masking: A comparison of psychophysical procedures," Ph.D. dissertation, Indiana University, Bloomington, IN.

Talbot, W. H., Darian-Smith, I., Kornhuber, H. H., and Mountcastle, V. B. (**1968**). "The sense of flutter-vibration: Comparison of the human capacity with response patterns of mechanoreceptive afferents from the monkey hand," J. Neurophysiol. **31**, 301–334.

Tanner, W. P., Jr. (**1961**). "Application of the theory of signal detectability to amplitude discrimination," J. Acoust. Soc. Am. **33**, 1233–1244.

Vallbo, A. B., and Hagbarth, K. E. (**1968**). "Activity from skin mechanoreceptors recorded percutaneously in awake human subjects," Exp. Neurol. **21**, 270–289.

Vallbo, A. B., and Johansson, R. (**1976**). "Skin mechanoreceptors in the human hand: Neural and psychophysical thresholds," in *Sensory Functions of the Skin in Primates*, edited by Y. Zotterman (Pergamon, Oxford), pp. 185–199.

Vendrik, A. J. H., and Eijkman, E. G. (**1968**). "Psychophysical properties determined with internal noise," in *The Skin Senses*, edited by D. R. Kenshalo (Thomas, Springfield, IL), pp. 254–262.

Verrillo, R. T., Gescheider, G. A., Calman, B. G., and Van Doren, C. L. (**1983**). "Vibrotactile masking: Effects of one- and two-site stimulation," Percept. Psychophys. **33**, 379–387.

Viemeister, N. F. (**1970**). "Auditory discrimination of intensity, internal noise, and temporal processing," Ph. D. dissertation, Indiana University, Bloomington, IN.

Viemeister, N. F., and Bacon, S. P. (**1988**). "Intensity discrimination, increment detection, and magnitude estimation for 1-kHz tones," J. Acoust. Soc. Am. **84**, 172–178.

Vogten, L. L. M. (**1978**). "Simultaneous pure-tone masking: The dependence of masking asymmetries on intensity," J. Acoust. Soc. Am. **63**, 1509–1519.

Zwislocki, J. J., Maire, F., Feldman, A. S., and Rubin, H. (**1958**). "On the effect of practice and motivation on the threshold of audibility," J. Acoust. Soc. Am. **30**, 254–262.