Absolute thresholds in vibrotactile signal detection*

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Vibrotactile signals were presented to S's index fingertip during a specified observation interval at a signal probability of either .30 or .70. The S's task was to report the presence or absence of the signal as quickly as possible and to estimate the magnitude of the sensory event experienced during the observation interval. Measures of detection probability, reaction time, and sensation magnitude were found to be a function of signal intensity only for vibration amplitudes greater than 1 micron. This finding, coupled with the finding of bimodality in the frequency distributions of the sensation magnitude judgments for the no-signal trials, suggested the operation of absolute thresholds in vibrotactile signal detection.

Early psychophysical theory was dominated by the concept of a sensory threshold below which events were thought to be indiscriminable from one another. The threshold concept fell into disfavor when it became apparent that experimentally determined values of the threshold were inexorably confounded with such nonsensory factors as stimulus expectation, motivation, and payoff contingencies. The theory of signal detection (TSD), developed to provide a more comprehensive conceptual framework for the explanation of detection behavior, represented a rejection of the threshold concept in favor of the concept of an adjustable judgment criterion. Although TSD has received very strong experimental support (see Green & Swets, 1966; Swets, Tanner, & Birdsall, 1961), such findings do not disprove the operation of sensory thresholds. The concept of a high threshold located near the upper end of the noise (N) distribution has, however, generally been refuted by experimental data. Contrary to the predictions of high-threshold theory, experiments using yes-no, rating, and forced-choice procedures have revealed that S can order sensory events over a wide range of magnitudes within the N distribution (e.g., Green & Swets, 1966; Swets et al, 1961). This should not be possible if these magnitudes fall below an absolute threshold located somewhere in the upper region of the N distribution. Hence, if there is an absolute sensory threshold, it must be located at a point on the sensory continuum (1) well within the N distribution and (2) below the S's judgment criterion. If this is the case, then predictions from low-threshold theory become very similar to those of TSD, and although the data from detection experiments are not inconsistent with the notion of a low threshold, there is as yet little direct evidence for such a concept.

The purpose of the present experiment was to determine if the threshold concept was applicable in a situation requiring S to detect vibrotactile signals over a wide range of stimulus intensity. It was predicted that detection behavior would be exactly the same on trials where very weak stimuli were presented as on trials where no stimuli were presented if an absolute threshold were operative in the detection of vibrotactile stimuli. To test this prediction detection probability, reaction time (RT), and direct estimates of sensation magnitude were obtained both for trials containing a stimulus and for trials not containing a stimulus. A second test of threshold theory was made by examining the shape of the empirically derived N distribution, particularly in the region below the point where S located his judgment criterion. This was done by plotting empirical frequency distributions of the direct estimates of sensation magnitude obtained on trials where no stimulus was presented, regardless of whether S reported "signal present" or "signal absent" for those trials. According to TSD the N distribution is normal in form. Threshold theory, on the other hand, predicts that marked deviations from normality should occur in the region of the N distribution falling below absolute threshold, since all sensory events below threshold theoretically have identical sensation magnitudes. Thus, the shape of the empirical distribution of direct estimates of the sensation magnitudes for the no-signal trials constituted a further test of threshold theory.

METHOD

Subjects

The Ss were four male undergraduates at Hamilton College.

Apparatus

The signals were 60-Hz sinusoidal vibrations applied for 500 msec to S's left index fingertip by a Goodmans V-47 vibrator. Signal intensity was regulated in 1-dB steps by a decade attenuator box. With his left index fingertip resting on a vibrator contactor 6.5 mm in diam, S sat with his right hand touching a bidirectional telephone switch which could be closed to the left or right from its open position. A 1-sec white light served as a ready signal and was followed 1 to 2 sec later by a 1-sec observation interval which coincided with the 1-sec presentation of a green light. The S's task was to judge the presence or absence of the tactile stimulus as quickly as possible following the onset of the green light. He made his judgment by closing the telephone switch to the right to indicate "signal present" or to the left to indicate "signal absent." The closing of the switch in either direction stopped a timer (Hunter 120A Klockounter), activated automatically at the onset of the observation interval. Reaction times were recorded to the nearest millisecond. Knowledge of results was given to S after each judgment.

Procedure

During a session, signals with peak-to-peak amplitudes of 1.00, 1.12, 1.24, 1.40, 1.56, 1.75, 1.96, 2.25, 2.47, 2.78, 3.11, 3.49, 3.92, 4.40, 4.92, 5.53, 6.21, 6.97, 7.82, 8.77, and 9.84 microns were presented in random order. It should be pointed out that the present task was not a conventional signal-detection situation where S is informed that a signal of constant intensity will be employed within a given experimental session. It was assumed that in the present task S would not be able to employ different decision criteria for different signal intensities since there would be no way of knowing the intensity of the signal to be presented on a given trial. In terms of TSD, the present situation involved (1) a single N distribution, the location of which remained fixed over the entire session, (2) a signal-plus-noise (SN) distribution for

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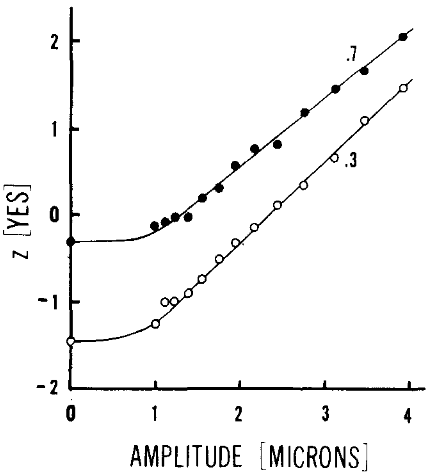

Fig. 1. Proportion of signal-present decisions expressed in z units as a function of signal amplitude for p(S) of .30 and .70.

each signal intensity employed in the session, and (3) a single decision criterion (see Gescheider, Wright, Weber, Kirchner, & Milligan, 1969). Each S made a total of 72 judgments for each of the 21 signal amplitudes when signal probability [p(S)] was .70 and also when p(S) was .30. The number of judgments on N trials was 3,528 when p(S) was .30 and 648 when p(S) was .70. The two values of p(S) were counterbalanced over 36 sessions, and S was told the value of p(S) at the beginning of each session. The signal and no-signal trials occurred in random order for each S in each session. The S was required to make on every trial a judgment consisting of a signal-present/signal-absent decision and a direct estimate of the magnitude of the sensory event that occurred during the observation interval. At the beginning of and several more times during each session, a 3.11-micron signal was presented as a standard for all sensation-magnitude judgments. The S was told that the sensation magnitude produced by the standard was 10 units and that all magnitude estimations should be made relative to this value. It was assumed that sensation magnitude judgments for observation intervals containing a stimulus would reflect momentary magnitudes of SN, whereas such judgments for observation intervals not containing a stimulus were assumed to reflect momentary magnitudes of N. Prior to the beginning of the experiment, Ss were given several 1-h practice sessions using the above procedure, with the exception that p(S) was .50.

RESULTS

Detection Probability

The data for the four Ss were very similar in form and therefore were averaged. Figure 1 presents the probability of reporting a signal, expressed in z scores, as a function of signal intensity in microns displacement of the vibrator. The data point for 0 microns represents the proportion of "false alarms" and the remaining data points represent the proportions of "hits" for the various signal strengths. The z scores for signals above 3.92 microns could not be determined accurately, since signals above this value were almost always detected correctly. For both signal probabilities the relationship between z (yes) and microns displacement of the vibrator is an increasing linear function for signal amplitudes greater than about 1.3 microns but becomes curvilinear between 0.6 and 1.3 microns and essentially flat between 0 and 0.6 microns. The shape of this curve, which was virtually identical for all Ss, strongly suggests that there is an absolute threshold on the order of 0.6 to 1.3 microns displacement of the vibrator. Moreover, the value of the threshold estimated from Fig. 1 is independent of signal probability. The independence of the threshold and signal probability is particularly noteworthy in view of the large effects exerted by signal probability on the probability of reporting the presence or absence of a signal (Fig. 1). If the threshold is computed by the conventional method of determining the intensity of the stimulus detectable 50% of the time, the value is found to be 1.3 microns for p(S) of .70 and 2.3 microns for p(S) of .30. It is clear that such a procedure yields threshold values which are strongly contaminated by the particular location of S's judgment criterion, which in turn is known to be strongly influenced by p(S) (e.g., Green & Swets, 1966; Swets et al, 1961).

It should be pointed out that the convergence of the two functions in Fig. 1 with increasing signal amplitude may have considerable significance for application of TSD to the detection of vibrotactile signals. If the N and SN distributions were normal in form with equal variances, the downward

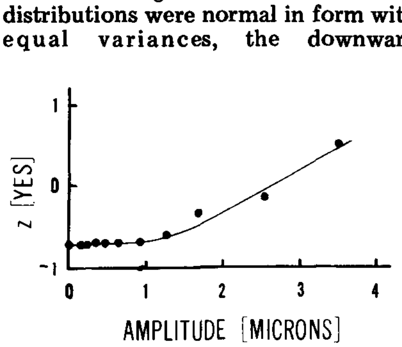

Fig. 2. Proportion of signal-present decisions expressed in z units for several weak signal amplitudes.

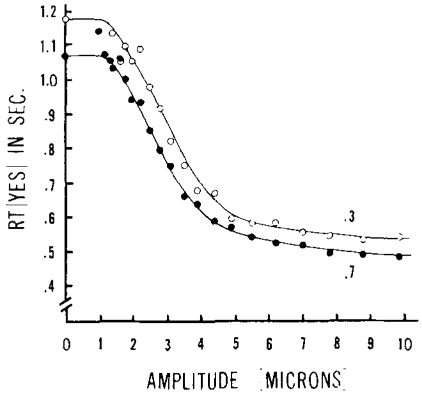

Fig. 3. Mean RT for signal-present decisions as a function of signal amplitude for p(S) of .30 and .70.

criterion shift produced by increasing p(S) would result in an increase in detection probability which, when expressed in z scores, would be constant for all signal amplitudes. In the present study, the deviation from this prediction can be accounted for by assuming that the variance of the SN distributions increases with signal amplitude. This assumption is further supported by the finding of a large increase in the variance of the magnitude estimation judgments as a function of signal amplitude.

Detection Probability for Signal Amplitudes Below Absolute Threshold

Because of the critical importance of the horizontal segment of the detection probability curve, a separate experiment was conducted in order to obtain empirical estimates of detection probability for signal amplitudes between 0 and 1 micron. Each of two highly trained Ss was required to make 60 judgments of the presence or absence of signals of 0, .16, .22, .32, .45, .64, .92, 1.27, 1.68, 2.54, and 3.55 microns, presented in random order under essentially the same conditions employed in the main experiment, with the exception that p(S) was .91. In support of the threshold concept, detection probability was found to be virtually equivalent for all signal amplitudes between 0 and 1 micron (Fig. 2).

Reaction Time

The same effect can also be seen in the RT data for correctly reporting the presence of a signal (Fig. 3) and in the RT data for incorrectly reporting the absence of a signal (Fig. 4). Since only a small number of signal-present RTs were obtained for the three weakest signals when p(S) was .30, mean RTs are absent for those values of signal amplitude (Fig. 3). Also, too few signal-absent decisions were made when signal amplitudes were above

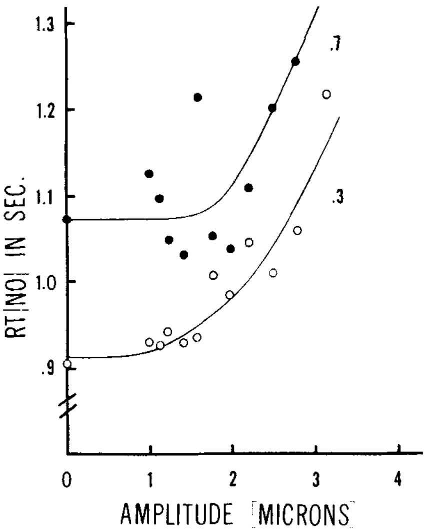

Fig. 4. Mean RT for signal-absent decisions as a function of signal amplitude for p(S) of .30 and .70.

2.78 microns to present reliable RT data for those values (Fig. 4). Consistent with the results of previous studies demonstrating the applicability of TSD to RT in the detection of vibrotactile signals (e.g., Gescheider, Wright, & Evans, 1968; Gescheider et al, 1969), RTs for correct signal-present decisions decreased as a function of vibration amplitude, while RTs for incorrect signal-absent decisions increased as a function of vibration amplitude. More important, however, was the finding of no change in RT as a function of signal strength between 0 and 1 micron. This finding provides additional support for the contention that there is an absolute threshold for the detection of vibrotactile stimuli in the vicinity of 1 micron signal amplitude.

Direct Estimates of Sensory Magnitude

Plotted in Figs. 5 and 6 as a function of signal strength are the mean direct estimates of sensory magnitude. Both figures strongly support the notion of an absolute threshold for the detection of vibrotactile stimulation on the order of 1 micron. Mean magnitude estimations failed to increase as a function of signal strength up to 1 micron, but increased sharply as a function of signal strengths greater than 1 micron. The data in Fig. 5 represent the weighted averages of the sensory magnitudes for the trials on which S reported the presence of a signal and for the trials on which S reported the absence of a signal. It was felt that this averaging procedure would yield the most accurate estimates of the mean of the N and SN distributions, since the sensory magnitudes for all observations, both above and below criterion, are included in the computation of these means. According to TSD, the location of the N or SN distributions should not be influenced by such variables as p(S) which determine the location of S's criterion. In the present experiment, however, the mean sensation magnitude judgments were slightly but consistently higher under p(S) of .70 than under p(S) of .30 (Fig. 5). Since the results of other reported experiments using different response measures have not yielded evidence to support the hypothesis that p(S) influences the location of the N or SN distributions, it is evident that p(S) had a small biasing effect on S's judgments.

The data in Fig. 6 represent the mean magnitude estimates only for the trials on which S reported the absence of a signal and thus provide estimates of the means of sensory observations below criterion in the N and all SN distributions. The data of Fig. 6 are particularly interesting in that they show that S can order correctly the sensory magnitudes produced by signals of different strengths even when they are below his decision criterion and thus are judged incorrectly not to be present.

Frequency Distributions of Sensation Magnitude

Figure 7 shows the frequency distributions of the sensation magnitudes reported by each S for the trials on which no signal was presented. The abscissa of each distribution extends from 0 to 15 units of sensation magnitude. Contrary to the TSD predictions of a unimodal N distribution, all of the distributions tend to be bimodal. The frequencies of

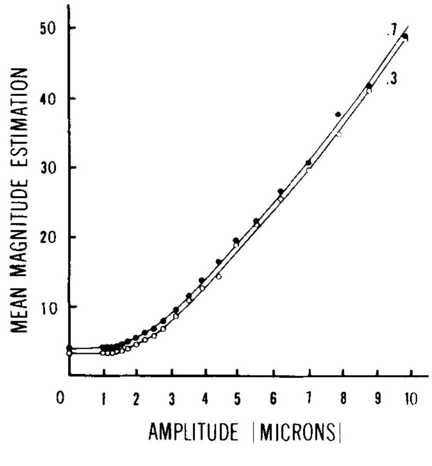

Fig. 5. Weighted mean magnitude estimation accompanying the signal-present and signal-absent decisions as a function of signal amplitude for p(S) of .30 and .70.

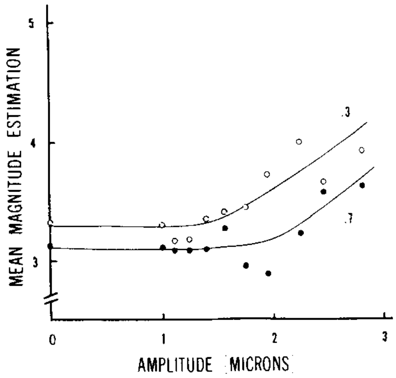

Fig. 6. Mean magnitude estimation for signal-absent decisions as a function of signal amplitude for p(S) of .30 and .70.

estimated sensory magnitude near the lower mode appear to represent a cluster of sensation magnitude judgments in the vicinity of an absolute threshold, whereas the cluster of sensation magnitudes near the higher mode appears to represent the distribution of internal noise central to TSD.

The relative size of the two modes, their separation, and the overall spread of the distributions were considerably different for the four Ss. These differences are probably the result of individual differences in the scale units used by Ss in making their judgments and individual differences in the location of the absolute thresholds. Consistent with TSD, the basic shape of the distribution for a particular S was not affected greatly by p(S), except in the case of H.H., whose judgments tended to be larger and more variable under p(S) .70 than under p(S) .30. Furthermore, the effects presented in Fig. 7 are not an artifact of including magnitude estimations for both signal-present and signal-absent decisions in the same frequency distribution (filled points). Essentially the same results are obtained when only the signal-absent decisions are considered. The open circles in Fig. 7 represent the proportions of signal-absent decisions for particular sensation magnitudes, except in those cases where *all* such decisions were signal-absent decisions. In these cases the proportions of sensation magnitudes for signal-absent decisions are designated by the same filled points used to designate the proportions of sensation magnitudes for the signal-present and signal-absent decisions combined. Again, all of the distributions of sensation magnitude tend to be bimodal rather than unimodal in form as predicted by TSD. This suggests the operation of an absolute threshold at the lower end of the N distribution.

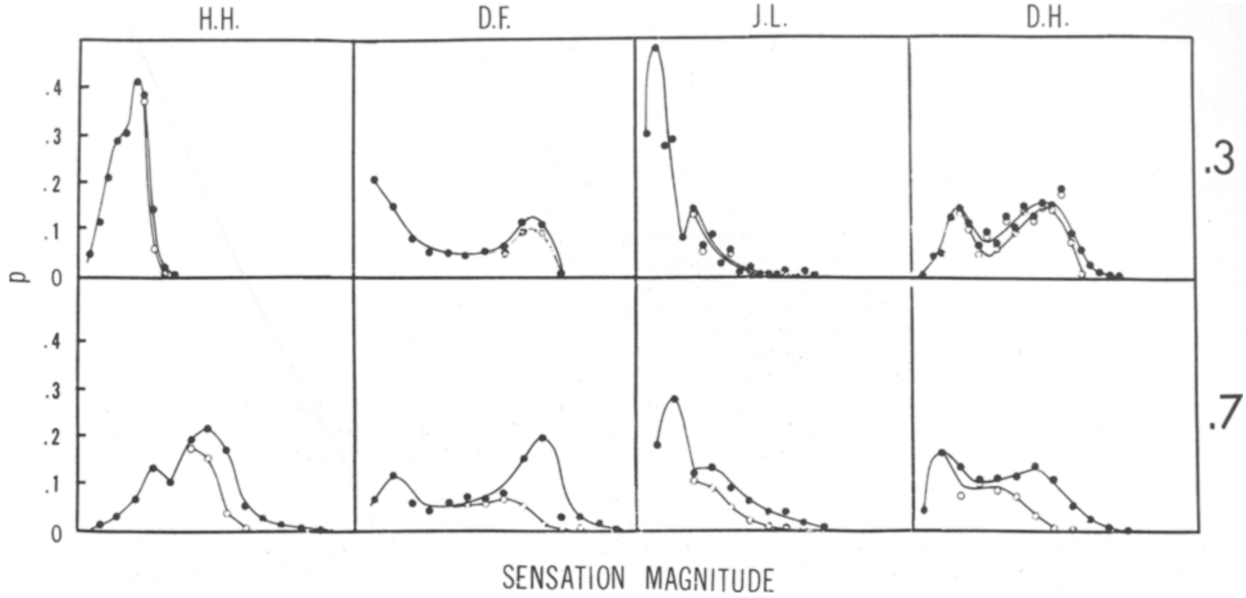

Fig. 7. Individual frequency distributions of the sensation magnitude judgments for the no-signal trials on a scale from 0 to 15 when p(S) was .30 and .70.

DISCUSSION

The results of the present study support the applicability of the threshold concept to the detection of vibrotactile stimuli. Measures of detection probability, RT, and sensation magnitude were found to be a function of signal intensity only if vibration amplitude exceeded approximately 1 micron. Frequency distributions of the sensation magnitude judgments for the no-signal trials were bimodal as predicted by low-threshold theory rather than normal as predicted by TSD. These findings are consistent with those of Eijkman and Vendrik (1963) and Vendrik and Eijkman (1968), who found that the probability of detecting tactile and electrical stimuli did not change until a certain stimulus strength was exceeded. The perception of warmth and cold, on the other hand, showed a linear increasing function throughout the entire range of stimulus intensities. These investigators concluded that absolute thresholds might be present for touch and electrical stimulation but not for the temperature senses.

The finding of an absolute threshold on the order of 1 micron in the detection probability, RT, and magnitude estimation data does not invalidate the assumptions of TSD if the type of threshold identified in the present investigation can be thought of as a *stimulus* threshold rather than as a *neural* threshold. Unlike the neural threshold concept, the stimulus threshold is not bound by the assumption that there is a cutoff point on the continuum of either neural activity or sensation magnitude below which events cannot be discriminated. It is simply assumed that as stimulus intensity increases, a critical intensity value must be exceeded before the mean of the SN distribution becomes greater than the mean of the N distribution. Hence, the data of the present experiment can be interpreted in terms of stimulus-threshold theory if it is assumed that d' is zero for all signal strengths less than 1 micron. Thus, the stimulus threshold concept is not inconsistent with the basic premises of TSD, although it has not been a component of the theory.

The bimodality of the frequency distributions of the sensation magnitude judgments for the no-signal trials (Fig. 7) strongly suggests that the type of threshold identified in the present investigation is a neural rather than a stimulus threshold. If the N and SN distributions are normal in form, as assumed in TSD, then the distribution of sensation magnitude judgments should also be normal in form. However, if a neural threshold exists, the distribution of sensation magnitude judgments must deviate markedly from normality in the region of the threshold. Observations below such a threshold should be the same in sensory magnitude and form a separate distribution, the variability of which might reflect such factors as the inability of S to assign the same number to sensory observations of identical magnitude. The distributions of sensation magnitude judgments obtained in the present study are exactly in accord with the predictions of neural-threshold theory, in which it is assumed that sensory events below a point on the lower end of the N distributions are indistinguishable.

If thresholds exist, their effects upon detection behavior must be determined. The fact that TSD without a threshold concept has accounted for much of the psychophysical data on detection behavior is rather compelling evidence that if thresholds exist, they are almost always lower than S's judgment criterion and consequently seldom influence detection behavior. Although the data of the present study show that there are thresholds, they are also consistent with the premise of TSD that S's judgments of the presence or absence of a signal are based primarily upon whether or not a sensory event exceeds an adjustable decision criterion located within the N distribution. As in earlier studies (Gescheider et al, 1968; Gescheider et al, 1969), the effects of vibrotactile signal probability on detection probability and RT indicate that S lowers his criterion as signal probability increases. The shape of ROC curves for vibrotactile stimulation supports the notion that S is able to shift the location of his criterion along a discriminable continuum of sensory observations that extend well into the N distribution (Gescheider et al, 1968; Gescheider, Wright, & Polak, 1971; Swets, Markowitz, & Franzen, 1969). Furthermore, clear evidence that S can discriminate among variations in sensory magnitude below criterion comes from the finding that mean sensation magnitude for signal-absent decisions increases as a function of signal strength above 1 micron (Fig. 6). According to TSD, increases in signal intensity shift the SN distribution to a higher point on the sensation magnitude continuum. Thus, as the areas under the SN distributions below criterion become smaller, they also become located at a point higher on the sensation magnitude continuum. This, in turn, produces an increase in mean sensation magnitude for signal-absent decisions as signal strength increases.

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