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The roles of vibration amplitude and static force in vibrotactile spatial summation*

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Previous work (Verrillo, 1963, 1968) has shown that when measured as a change in absolute threshold, spatial summation occurs only at vibration frequencies above 40 Hz. The present study measured vibrotactile spatial summation at suprathreshold amplitudes. A matching task was used to investigate the effect of varying contactor size on sensory magnitude at three different vibration frequencies. Unlike the threshold data, increasing contactor size resulted in increases in sensory magnitude at 25 and 40 Hz as well as at 160 Hz. The amount of summation varied directly with amplitude for the two lower frequencies. In a second experiment, the effect of increasing static force, independent of contactor size, was investigated. The results indicated that the spatial summation effects noted in the first experiment may be due to increases in static force and not contactor area. The implications of these results for the concept of spatial summation and for the duplex mechanoreceptor hypothesis are discussed.

The occurrence of vibrotactile spatial summation as measured by changes in threshold has been demonstrated in several psychophysical studies (Craig & Sherrick, 1969; Verrillo, 1963, 1968, 1971). When contactor area is increased while either static pressure or penetration is held constant, the amplitude at which Ss can detect high-frequency vibrotactile stimuli is reduced. However, the effect of changing contactor area upon detection is limited to vibration frequencies above 40 Hz; below 40 Hz, detection of vibratory stimuli is poorer and remains independent of contactor area, static pressure, or penetration (Craig & Sherrick, 1969; Verrillo, 1963).

Experiments involving amplitudes of vibration greater than threshold have yielded data which might be interpreted as contradictory to the threshold data. Craig and Sherrick (1969) and Verrillo (1974) were able to show that, at high amplitudes, subjective magnitude increased at both high and low frequencies of vibration when contactor area was increased.

Verrillo (1968) has hypothesized that there is a duplex mechanoreceptor system for vibrotactile stimuli. High-frequency vibration, above approximately 40 Hz, is thought to be mediated by one set of receptors, probably by deep-lying, encapsulated end organs, such as Pacinian corpuscles. There is evidence that Pacinian corpuscles require a critical velocity to be fired (Lowenstein & Mendelson, 1965). This critical velocity would be reached at lower amplitudes for higher frequency vibration than for lower frequency vibration. Low-frequency vibration is thought to be mediated by a second set of receptors. Neurophysiological recordings from first-order cutaneous afferents lend support to such a duplex system (Talbot, Darian-Smith, Kornhuber, & Mountcastle, 1968). Verrillo further hypothesizes that the two cutaneous receptor systems differ from one another in that the low-frequency receptor system does not show spatial and temporal summation at threshold while the high-frequency system does. If the two receptor systems do show functional differences, how could the changes in perceived magnitude as a function of contactor area at low frequencies reported by Craig and Sherrick (1969) be explained?

In neurophysiological studies relating to the two receptor systems, investigators have determined the frequency range over which particular cutaneous afferents are maximally sensitive by measuring the amplitude at which a given frequency of vibration causes the afferent to be phase-locked with each cycle of the stimulus, i.e., be entrained by the stimulus (Mountcastle, Talbot, Darian-Smith, & Kornhuber, 1967; Talbot et al, 1968). These neurophysiological studies have shown that the sensitivity of the two receptor systems is relative. Afferents, maximally responsive to high-frequency vibration, may be entrained by low-frequency vibration if the amplitude of the stimulus is great enough. For example, a low-frequency afferent may be entrained by a 40-Hz stimulus at 10 microns, an amplitude which, at 40 Hz, would not result in entrainment of high-frequency afferents. However, the high-frequency afferents may also show entrainment to a 40-Hz stimulus when the amplitude is increased to 20 microns. Mountcastle et al (1967) and Talbot et al (1968) have also demonstrated that the amplitude at which entrainment occurs corresponds to the

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amplitude required for detection by human Ss. It is hypothesized that Craig and Sherrick, working at amplitudes well above threshold, were stimulating both high- and low-frequency receptors. Such a hypothesis could account for the changes in perceived magnitude as a function of contactor area reported by them.

The neurophysiological data have also shown that the lower the frequency of vibration, for frequencies below approximately 80 Hz, the greater the relative amplitude difference between threshold for a human S and entrainment of the high-frequency afferents. If a 6-dB increase in amplitude is required at 40 Hz to entrain the high-frequency afferents, a 12-dB increase in amplitude might be required at 20 Hz. These data suggest that for low-frequency vibration the relative amplitude above threshold at which spatial summation effects are obtained should decrease as frequency is increased.

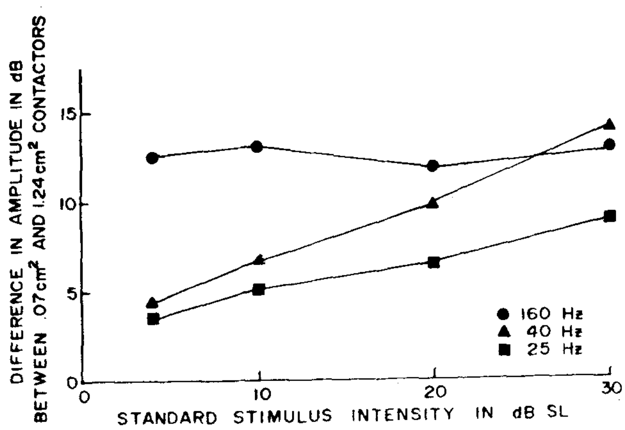

Fig. 1. Difference in amplitude in dB between equal sensory magnitude stimuli with .07- and 1.24-cm² contactors as a function of stimulus intensity. Static pressure on the two contactors was held constant.

EXPERIMENT I

Experiment I examined the effect of changes in contactor area on perceived magnitude using a matching task. These changes were examined at several intensity levels for several different frequencies of vibration. It was hypothesized that the change in perceived magnitude for low-frequency stimuli would be a joint function of the frequency and intensity level of the vibratory stimulus. Specifically, low-amplitude, low-frequency stimuli should show the smallest change in perceived magnitude as contactor area is changed. For a high-frequency stimulus, the changes in perceived magnitude should be independent of the intensity level of the stimulus.

Method

Observers. The three Os used in the experiment were paid undergraduate females. The Os were trained through a number of practice sessions before data collection began.

Apparatus. The sinusoidal stimuli were generated by a Hewlett-Packard 3300A signal generator. The signal generator output was led to two Grason-Stadler 1287 electronic switches which were controlled by Grason-Stadler Series 1200 programming modules. The output from each electronic switch was amplified, attenuated, and passed through impedance-matching transformers before being led to Goodmans V-47 vibrators. The vibrators were mounted on balances to control the static force of the contactors against the O's hand. Two plastic contactors, one 3 mm in diam (.07 cm² in area) and the second 12.5 mm in diam (1.24 cm² in area), were threaded onto the pistons of the vibrators and contacted the skin through circular surrounds. The surrounds were 2 mm in diam larger than the corresponding contactors.

Procedure. In order to set the stimuli in the matching task at the same sensation level (SL), absolute thresholds were determined for 25-, 40-, and 160-Hz stimuli on the thenar eminence of the right hand. Both the .07- and 1.24-cm² contactors were used with a constant static pressure of .6 g/mm². The constant pressure was achieved by adding 4.2 g of force to the balance when the small contactor was used and 74.4 g when the large contactor was used. Thresholds for either the small or large contactor were measured at all three vibration frequencies in a single session. A two-interval, forced-choice (2IFC) method was used to estimate threshold. Each trial was initiated with a .5-sec "ready" period followed by two 1.0-sec observation intervals. A .5-sec sinusoidal test stimulus with a 25-msec rise-fall time occurred at the onset of one of the two observation intervals. The O's task was to indicate in which interval the test stimulus occurred by pressing one of two response buttons corresponding to the two observation intervals. Immediate feedback was given in the form of .5-sec correct and incorrect indicator lights. The ready, observation, and "response" periods were also signaled by indicator lights. In determining threshold, stimulus intensity was varied in a block up-and-down technique which has been described previously (Craig, 1972). The median stimulus intensity over 25 blocks (100 trials) was taken as the absolute threshold. The threshold amplitude was approximately the level at which the O responded correctly 75% of the time.

The procedure for estimating the difference in perceived magnitude as a function of contactor area required a matching task. A standard stimulus was presented to the thenar eminence of the left hand using the .07-cm² contactor at a pressure of .6 g/mm². The 25-, 40-, or 160-Hz standard was raised to 4, 10, 20, or 30 dB SL. The comparison stimulus was the same frequency as the standard stimulus and was presented to the right hand using either the .07- or the 1.24-cm² contactor. Contactor pressure of the comparison stimulus was also .6 g/mm² for both contactors. The standard and comparison stimuli were presented successively in an order that remained the same within a session but was varied randomly between sessions. Both stimuli were .5 sec in duration with 25-msec rise-fall times. A trial consisted of the successive presentation of the two stimuli followed by a 1.5-sec intertrial interval. The method of average error was used, i.e., trials were arranged in alternating ascending and descending series with the comparison stimulus increased or decreased in 1-dB steps after each trial. The O's task was to indicate when she judged the magnitude of the comparison stimulus to be equal to the magnitude of the standard stimulus. The intensity of the comparison stimulus was then recorded, after which the intensity of the standard stimulus was changed and a new series, opposite in direction to the preceding series, was begun. Four matches were averaged to yield a single observation for a given standard stimulus intensity.

Results and Discussion

The results of the matching experiment are shown in Fig. 1. The results from the three Os were similar and have been combined. Each point represents the mean of 18 observations, 6 from each of the three Os. Spatial summation is defined as the difference in peak-to-peak amplitude between the .07-cm² contactor and the 1.24-cm² contactor conditions when matched for equal perceived magnitude. The difference in amplitude in dB between the two contactors is plotted as a function of the standard stimulus intensity measured in dB SL. The threshold amplitudes for the standard stimuli at 25, 40, and 160 Hz were 8.3, 6.7, and 1.9 microns peak-to-peak, respectively. The two low frequencies showed greater summation as intensity was increased, while the 160-Hz stimulus produced a larger and more constant amount of spatial summation throughout the range of intensities tested. The 25- and 40-Hz functions show a continuing dependence upon amplitude for increasing summation, with summation changing from 3 dB to more than 14 dB as the amplitude was varied over a range of 26 dB. The slope of the 25-Hz function suggests that at higher intensities the 25-Hz stimulus would approach the level of summation achieved at 40 and 160 Hz, but mechanical limitations of the vibrator prevented testing at higher amplitudes. The same limitations prevented measurements at higher amplitudes at 40 Hz to determine whether or not the 40-Hz function would continue to increase. The results also show that the amount of summation at a particular dB SL is dependent upon the frequency of the vibratory stimulus. To show the relationship between frequency and amount of summation, the data from Fig. 1 have been replotted in Fig. 2.

If it is assumed that Pacinian corpuscles are the receptors responsible for spatial summation, the results are consistent with the neurophysiological data of Mountcastle et al (1967) and Talbot et al (1968). It would be expected that high-frequency vibration such as 160 Hz would stimulate Pacinian corpuscles at very low amplitudes, and, therefore, a high-frequency vibration would show consistent spatial summation from threshold amplitudes on up through high amplitudes (Fig. 1). Low-frequency vibration would not show spatial summation at very low amplitudes. However, as the amplitude of a low-frequency vibration is increased, greater numbers of Pacinian corpuscles should be stimulated, permitting increasing amounts of summation (Fig. 1). Further, as noted above, it would be expected that as the frequency of vibration is reduced from 40 to 25 Hz, the amount of spatial summation at the same intensity level above threshold should be reduced (Fig. 2).

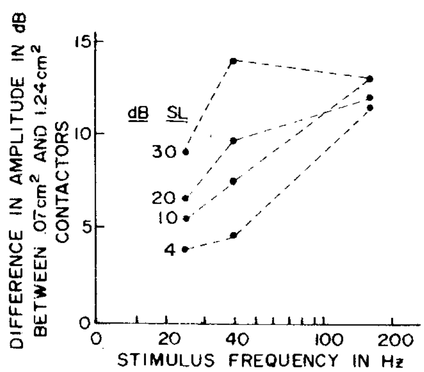

Fig. 2. The data of Fig. 1 replotted as a function of frequency with dB SL as the parameter.

EXPERIMENT II

As noted above, Craig and Sherrick (1969) found a consistent increase in perceived magnitude as contactor area was increased when the same static pressure was applied to all contactor areas. Increasing contactor area while keeping static pressure constant requires increasing amounts of static force. A further observation by Craig and Sherrick was that adding static force while holding contactor area constant resulted in changes in perceived magnitude similar to the changes obtained when both contactor area and static force were increased. This finding led to the conclusion that "there is little increase in sensory magnitude obtained by simply increasing contactor area [Craig & Sherrick, 1969, p. 100]." If this conclusion is correct, the changes in perceived magnitude observed in Experiment I were the result of increasing static force. Experiment II was designed to answer the question of whether or not increasing static force alone is sufficient to account for the results of Experiment I.

Method

Observers. The same three Os who participated in Experiment I were tested in Experiment II.

Apparatus. The apparatus used in Experiment II was essentially the same as that used in Experiment I. Only one contactor size was used, however, since static force and not contactor area was the independent variable. Both the standard and comparison stimuli were presented to the skin using the .07-cm² contactor. The temporal parameters of the 2IFC block up-and-down procedure were controlled by the same Grason-Stadler modular programming system as used in Experiment I.

Procedure. Absolute threshold was measured for vibratory stimuli having frequencies of 25, 40, and 160 Hz at two static forced, 4.2 and 36 g. The .07-cm² contactor was balanced at the point of skin contact and then either 4.2 or 36 g of force were added to the other arm of the balance. In Experiment I, 74.4 g were required to produce the same pressure on the large contactor as that produced on the small contactor. In Experiment II, it was not possible to put 74.4 g of force on the .07-cm² contactor, because such a force would result in excessive penetration into the skin. Absolute threshold was determined for both forces, using the same procedures as in Experiment I. The matching task was identical to the procedure of Experiment I, except that the Os matched stimuli having equal contactor areas but widely different static forces.

Results and Discussion

The sensory magnitude experiment yielded data which indicate that force is also an essential parameter for high-amplitude summation. Figure 3 shows the difference in amplitude in dB between the 4.2- and 36-g stimuli after they were matched in sensory magnitude to the standard stimulus at 4, 10,

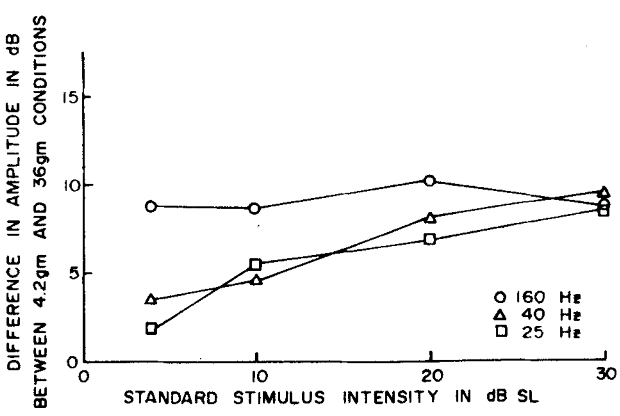

Fig. 3. Difference in amplitude in dB between equal sensory magnitude stimuli with 4.2 and 36 g of static force as a function of stimulus intensity. A .07-cm² contactor was used with both static forces.

20, and 30 dB SL. Each point represents the mean of 18 observations, 6 from each of the three Os. As with constant pressure, the constant area condition results in summation in amounts which are also dependent upon the amplitude of vibration at 25 and 40 Hz.

A direct comparison between Figs. 1 and 3 is somewhat misleading in that there were 4.1 doublings of force and area in Experiment I but only 3.1 doublings of force in Experiment II. In order to see the extent to which increasing force alone might account for spatial summation effects, the results of Experiment II were replotted to show the changes in perceived magnitude per doubling of force as a function of dB SL. In addition, the results of Experiment I were replotted on the same graph to show the changes in perceived magnitude per doubling of force and area. These data are shown in Fig. 4. An inspection of Fig. 4 indicates that, in general, increasing contactor area in addition to force adds little to the change in perceived magnitude as compared to increasing force without changing contactor area.

Although the main point of these experiments was to examine suprathreshold summation, the threshold data were in general agreement with previous studies (Craig & Sherrick, 1969; Verrillo, 1968). The low-frequency stimuli, 25 and 40 Hz, showed a much smaller change in threshold as a function of either contactor area or force than did the high-frequency stimulus, 160 Hz.

GENERAL DISCUSSION

In Experiment I, static pressure was held constant while static force and contactor area were increased, and the result was an increase in sensory magnitude. In Experiment II, contactor area remained constant while static force and, therefore, static pressure were increased. Sensory magnitude again increased, in this case correlated with static force and static pressure but independent of contactor area. The result was that sensory magnitude varied directly with static force in both Experiments I and II. Keeping static pressure constant in Experiment I and contactor area constant in Experiment II still resulted in changes in sensory magnitude. These data do not prove that static force alone is responsible for "spatial summation," but they do show that changes in static pressure and contactor area are not necessary for the occurrence of summation. This conclusion is similar to the conclusion reached by Craig and Sherrick (1969). In a study of the physical response of the skin to vibratory stimulation, Moore and Mundie (1972) have, however, pointed out that static pressure and contactor area rather than static force are the parameters to hold constant to minimize changes in the mechanical characteristics of the skin.

The results of the present experiment are consistent with the hypothesis that high-frequency receptors, probably Pacinian corpuscles, are the receptors which mediate summation effects. Whether or not these high-frequency receptors are stimulated by low-frequency vibration appears to be a joint function of frequency and amplitude. However, it is not clear what the nature of this "summation" process is which the high-frequency receptor system seems to demonstrate to a much greater degree than the low-frequency receptor system. The summation effect may be due to increasing the number of receptors

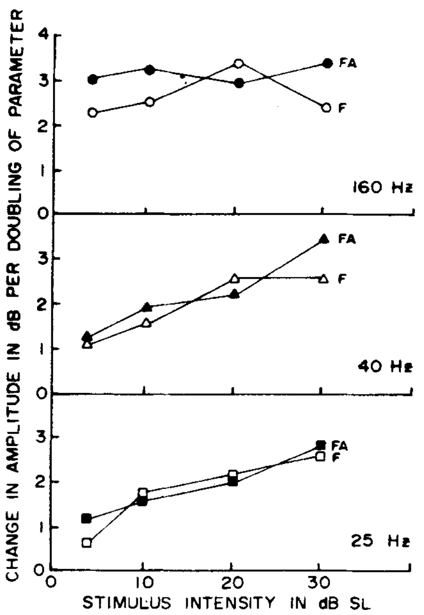

Fig. 4. Change in amplitude in dB per doubling of static force and contactor area (FA) or static force alone (F) as a function of stimulus intensity. The curves are based on 4.1 doublings of the FA parameter and 3.1 doublings of the F parameter.

stimulated, as the results of Verrillo's (1968) experiments would suggest. There is, however, some neurophysiological evidence which may be contrary to the hypothesis that only the high-frequency system shows spatial summation. Johnson (1974) has shown that first-order afferents which can be stimulated by a 40-Hz signal show increases in both the number of spikes per fiber and the total number of active fibers when vibration amplitude is increased. Such changes in the activity of populations of fibers would seem to be a necessary requisite for spatial summation, but it is not known if the sensory system is able to use "number of fibers" as a code for magnitude at low frequencies.

The present experiment indicates that an increase in perceived magnitude may be obtained by increasing static force without changing the contactor area. Whether the increase in perceived magnitude is due to the spread of the mechanical stimulus over a larger area as static force is increased or whether the stimulus is delivered more effectively to the same number of receptors is not clear. Merzenich and Harrington (1969), when recording from single Pacinian afferents in the skin, found that the threshold for spikes was lowered when larger contactors were applied to the skin as well as when the contactor probe was indented more deeply into the skin. These results from Merzenick and Harrington support the idea that summation, in part, is due to more effective coupling between the contactor and the tissue.

While the present results have been discussed in terms of increasing static force, it is obvious that increasing static force, while keeping contactor area constant, results in changes in other measures, such as penetration into the skin. It is not possible to state which of these measures reflects most closely changes in the effective stimulus for perceived magnitude. Clearly, any explanation of vibrotactile spatial summation must take into account both neural and nonneural factors. The presence of summation at 25 and 40 Hz at large vibration amplitudes rules out a simple frequency model. The basis for spatial summation does, however, seem to lie in the activation of a particular population of receptors which are more sensitive to high-frequency vibration. But mechanical coupling factors probably affect the range over which the high-frequency receptors first become responsive to low-frequency stimuli. Increasing static force may act to both increase the areal spread of the stimulus and to alter the mechanical properties of the skin, resulting in an increase in sensory magnitude.

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