Vibrotactile spatial summation[1]

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By means of a two-interval, forced-choice technique, absolute thresholds were obtained at several sites on the skin for short bursts of mechanical vibration. The difference between the energy required for a single vibrator, in dB, to reach threshold and the energy required for two vibrators presented successively to reach threshold was taken as the measure of probability summation. Spatial summation was computed as the difference between the energies required for threshold for the two vibrators presented successively and simultaneously. Both probability summation, 0.52 dB lowering in threshold, and spatial summation, 1.94 dB lowering in threshold, remained constant as a function of the distance between the two vibrators on the thigh. Similar amounts of summation were obtained unilaterally and bilaterally on the fingers. When the frequency of vibration was lowered to 9 Hz, no spatial summation was found. When the frequencies of vibration at the two test sites were different, 160 Hz at one locus, 360 Hz at the other locus, there was no spatial summation.

A recent series of publications by Verrillo has been concerned with the effect of certain stimulus parameters on the threshold for cutaneous vibration (Verrillo, 1962; 1963; 1965; 1966; 1968). Among the most important of these parameters was the surface area of the vibrating contactor. For contactors varying in area from .005 cm^2 to 5.1 cm^2, Verrillo found that, with larger contactors and for frequencies 80 Hz and above, doubling the contactor area resulted in an approximate 3 dB decrease in the displacement amplitude required for threshold (1966). As Verrillo points out in his article, similar studies in vision have also resulted in an approximate 3 dB decrease in intensity required for threshold when the area of stimulation was doubled (1966). An analogous approach in audition that involves measuring absolute threshold for bursts of noise as a function of the bandwidth of the noise demonstrated that doubling the bandwidth of the noise within certain limits also produced an approximate 3 dB decrease in the energy required for threshold (Gassler, 1954).

A second approach to the problem of spatial summation is to increase the area of stimulation by adding a second locus of stimulation. Visual research has demonstrated that the absolute threshold is lower for two flashes of light presented simultaneously but separated spatially from one another, as compared to the threshold for a single flash (Beitel, 1934). Similarly, the probability of reporting the presence of light flashes is increased with the addition of a second flash of light (Bouman & Van den Brink, 1952; Van den Brink & Bouman, 1954; Van den Brink, 1966). Analogous auditory experiments show that the amount of energy in each tone required for threshold is less for two or more tones presented simultaneously than for a single tone (Gässler, 1954).

One of the first demonstrations of threshold spatial summation for vibrotactile stimuli was made by Kietzmann in 1927. He obtained absolute thresholds for the left and right index fingers separately and compared these with the threshold obtained when both index fingers were stimulated simultaneously. The latter threshold was lower than either of the thresholds obtained using only one source of vibration. A somewhat more elegant demonstration of summation was made by Békésy in 1958. The stimulator was a large vibrating frame with two small points for contactors, the distance between which could be varied. For separations of 0.5, 4.0, and 10.0 cm, it was found that the threshold was lowest at 4.0 cm, a value equal to that of the two-point limen for that area of skin. Békésy concluded, "that the addition of a second stimulating point within a certain 'action' radius increases the sensitivity for vibrations by neural summation [1958, p. 403]."

Neither of the latter studies provides an accurate estimate of the difference in the amount of energy required for threshold with one stimulus as compared with two simultaneously presented stimuli. The nature of the apparatus in the Kietzmann study makes it difficult to obtain such an estimate, while in the Békésy demonstration the threshold for a single stimulus was not given. Also, in both studies there was essentially a single source of vibration having two points of contact with the skin. Employing two independent sources of vibration permits greater variation of the stimulus conditions, such as presenting one frequency of vibration at one locus of stimulation and a different frequency at a second locus, or measuring probability summation by presenting stimuli successively rather than simultaneously. The present investigation was undertaken to obtain an estimate of the amount of spatial summation and some of the factors which affect this summation as measured by changes in absolute threshold between two vibrotactile stimuli that were independently controlled.

EXPERIMENT 1

Investigations in other sense modalities have often examined the effect of interstimulus distance on the amount of spatial summation at threshold. The success that these investigations have had in indicating both the level of neural organization, i.e., peripheral or central, at which summation may occur, and some of the anatomical or functional units that may be responsible for summation, provides one reason for studying the effect of distance on summation. When mechanical vibration of the skin is the stimulus, there is a second and more compelling reason: the possibility of physical interaction.

Whenever the skin is set into forced vibration, waves are known to travel great distances along its surface (Keidel, 1956). It is possible that waves set in motion from two sources of vibration on the skin might interact physically at some distance between the two sources of vibration to produce a disturbance that would be sensed at that point. To demonstrate what role, if any, physical interaction plays in spatial summation, it is necessary to vary systematically the amount of physical interaction and note any changes in spatial summation. One possible way of varying physical interaction is to vary the distance between the two sources of vibration. Measurements of the surface waves set up by vibratory disturbances have indicated that, when the distance from the source of vibration is increased, the amplitude of surface waves decreases (Békésy, 1955; Franke, von Gierke, Oestreicher, & von Wittern, 1951).

It should be noted that surface waves are not the only kind of waves created by vibrations; there are subsurface waves as well. The surface waves are, however, thought to reflect the effects of subsurface waves (Franke et al, 1951), but the exact relation between distance and amplitude of the latter is not known. For this reason an exact hypothesis concerning the effect of distance on summation cannot be formulated. Nevertheless, it is reasonable to assume that if physical interaction is important, then summation in a homogeneous medium should be, to a first approximation, a direct function of distance. If physical interaction is responsible for threshold summation of two spatially separated sources of vibration, then increasing the distance between the two sources should decrease the amount of summation.

Method

Subjects. The Ss in this experiment as well as the other experiments to be reported were paid volunteers and laboratory personnel. All Ss were males and received several hours of practice before data collection was begun.

Apparatus. The apparatus consisted of two major components. The first component generated the vibratory signals at the proper frequency, intensity, duration, and in the proper temporal sequence. This component consisted of two collateral circuits, one for generating each vibratory signal. The output of a General Radio Type 1304-A oscillator went to two onset generators. The output of the onset generators was led to two Langevin Model 128-WJ amplifiers. the outputs of which in turn led to two Hewlett-Packard Model 350C attenuators. Two inertia vibrators (Sherrick, 1965) were fitted with rectangular contactors 2.5 x 3.3 cm and were controlled by the attenuators through matching transformers. The impedance match between the transformers and the vibrators was adjusted to insure linearity between the changes in attenuator settings and changes in voltage across the coils of the vibrators.

The onset generators were gated by two relays that were energized by Textronix Type 161 pulse generators. By varying the width of the square wave output from each of the pulse generators, the duration of the vibratory signals could be controlled. Also, by varying the delay of the square wave output, it was possible to control the temporal relations between the two signals to permit either simultaneous or sequential presentation. The pulse generators were both triggered by a single Tektronix waveform generator, Type 162.

The second major component of the apparatus was a switching circuit that controlled the presentation of the stimuli to the S at the proper time, controlled the warning light, the interval tones, correct response lights, and recorded the number of trials and number of correct responses. To begin a trial the S pressed a switch that activated a 12 rpm synchronous motor. Connected to the motor was a shaft fitted with a series of four cams, each of which turned on and off a microswitch. The first microswitch turned on a warning light on a panel in front of the S to indicate the beginning of a trial. The second switch energized a relay that turned on a 1000-Hz signal that energized earphones worn by the S to indicate the first observation interval. The third switch turned on the signal again to indicate the second observation interval. By means of a double-throw relay which triggered the waveform generator, a Gerbrands Ratio Programmer determined randomly in which of the two observation intervals the vibratory signal or signals would be presented.

Procedure. The general procedure followed in all the experiments to be described was to obtain the absolute threshold to a burst of vibration at one locus. then at a second locus situated some distance from the first. The two vibratory signals were then presented successively and the absolute threshold was again obtained. The difference in the amount of energy required to reach absolute threshold at a single locus and at two loci with a successive presentation was taken as a measure of the amount of probability summation. Finally, the threshold was measured for the two signals presented simultaneously. The difference in the threshold between the successive and simultaneous conditions was the measure of spatial summation. When two stimuli are presented simultaneously, the amount by which the threshold drops below the threshold for a single stimulus may be divided into two quantities–probability summation, the statistical sum of two independent events (Pirenne, 1943), and some kind of physiological integration which may be termed "spatial summation." In order to have an estimate of spatial summation uncontaminated by probability summation, it is necessary to subtract from the total amount by which the threshold is lowered that part which is the result of probability summation.

The threshold technique employed was a merger of the two-interval, forced-choice procedure with a block-up-and-down method (Campbell, 1963). A variation of a tracking procedure, the block-up-and-down method concentrates observations in the region of threshold. In the present experiment four trials constituted a block, i.e., after four trials a decision was made by the E whether or not to change the stimulus intensity. If the S made four correct responses out of four trials, the stimulus intensity was decreased by 1 dB, and another block of four trials was begun. If the S made three out of four correct responses, the intensity was left unchanged, and another block was begun. If S made two or fewer correct responses, the intensity was increased by 1 dB. This procedure was continued until the S completed approximately 20 blocks of four trials each. The median of the 20 blocks was the estimate of the threshold value.

At the beginning of an experimental session the Ss were seated comfortably in a chair. The two vibrators were glued with collodion to the ventral surface of the S's right thigh along the midline. The vibrators were spaced either 8, 12, or 20 cm apart from center to center, depending upon the experimental condition selected. Throughout the session, the S wore earphones through which white noise was fed to mask the sounds of the equipment. Ss were instructed that they would receive a vibratory signal through the first vibrator in one of two observation intervals marked by successive tones in their earphones. The S was to indicate the interval in which he felt the signal by pressing the appropriate one of two buttons in front of him. When he was correct, a light on the panel corresponding to the interval would flash. When incorrect, no light would flash. The vibratory signal was a 200-msec burst of 100-Hz vibration with a rise time of 20 msec.

When the S began a trial by pressing the start button, a warning light was flashed. Twelve hundred msec later the tone sounded for 1200 msec indicating the first observation interval. After a 600-msec period of noise alone, the tone sounded again for 1200 msec to indicate the second observation interval. The onset of the vibratory signal was 250 msec after the onset of one of the tones.

The first threshold was taken on one of the vibrators presented alone. Next, the S was instructed to attend to the other vibrator and the threshold for it was determined, after which the S was given a 5-min rest period. The voltage output of the amplifier leading to the vibrator with the lower threshold was reduced by the amount by which it differed from the other threshold. This was done so that in the successive and simultaneous threshold determinations the same attenuator settings would result in the same sensation level at each vibrator.

The threshold for each of the two vibrators was checked to determine if the threshold at either of the two vibrators had changed radically. If either of the thresholds had shifted radically, the session was terminated at this point. If not, the threshold was measured for the two vibrators presented successively. In the successive condition the time between the offset of the first vibratory signal and the onset of the second was 450 msec, in order that both signals be separated temporally as much as possible and still be contained in the same observation interval. The final threshold was run with the bursts from the two vibrators presented simultaneously and mechanically in phase. To control for fatigue effects, the simultaneous threshold was occasionally taken before the successive threshold.

Results and Discussion

The mean from nine observations at each of three interstimulus distances is shown in Table 1. The results are presented as the amount of energy in dB by which the threshold is lowered under the particular conditions. There was a significant amount of probability summation ($p < .05$, Wilcoxon Paired Replicates Test), but there were no significant differences between groups. The mean amount of probability summation from all three groups was calculated and found to be 0.52 dB. Table 1 also shows the mean amount of spatial summation. There was a significant amount of spatial summation at each of the three interstimulus distances ($p < .01$), but no significant differences as a function of the distance between the two vibrators. The mean amount of spatial summation from all three groups was 1.94 dB. The total amount of threshold shift, probability summation plus spatial summation, or, in other words, the difference in threshold for a single vibrator as compared with the threshold in the simultaneous condition, is also shown in Table 1.

Table 1
Mean Amount of Summation in dB at Three Interstimulus Distances

Distances	Prob. Sum.	Spatial Sum.	Total Shift
8 cm	0.49	1.87	2.36
12 cm	0.30	2.22	2.52
20 cm	0.77	1.73	2.50
	M = 0.52	M = 1.94	

With the two inertia vibrators glued to the skin, measurements were made of the amplitude of the surface waves as a function of the distance from the vibrator. With a 100-Hz vibration, the amplitude of the surface waves at 10 cm from the vibrator was as much as 35 dB below the amplitude at the vibrator. Moreover, when both vibrators were turned on, there was little physical interaction noted at skin sites between the two vibrators. The fact that the amplitude of vibration decreases as the distance from the source of vibration increases, whereas spatial summation does not change as a function of distance, makes it unlikely that physical interaction contributes significantly to spatial summation. This conclusion is in agreement with Békésy's finding in his experiments that there was no simple relationship between interstimulus distance on the skin and spatial summation (1958).

EXPERIMENT 2

In Experiment 2 the locus of stimulation was shifted from the ventral surface of the thigh to the fingertips. The numerous changes in sensitivity of the skin associated with changes in the locus of stimulation, as well as neurological changes such as the relative size of cortical representation and density of innervation, have been discussed by Békésy (1960, p. 608). Moreover, the mechanical conduction properties of tissues change radically with changes in locus (Keidel, 1956). If spatial summation could be demonstrated on the fingertips and were quantitatively equal to summation on the thigh, it would be an indication of the generality of the findings of Experiment 1 for the rest of the skin. In addition to measuring spatial summation between two sites of stimulation on one hand, spatial summation could also be measured with one vibrator on one hand, the second vibrator on the other hand. The results from the two sets of measurements could then be compared to determine whether shifting from unilateral to bilateral stimulation has any effect on spatial summation.

Method

Apparatus. The inertia vibrators of Experiment 1 were replaced by Goodmans V-47 vibrators fitted with round plastic contactors of 1 cm diam. Fixed platforms on which the S rested his fingers were bored with holes of 1.2 cm diam and were adjusted such that the top of the platform was exactly level with the top of the contactor. For the bilateral condition, three foot switches, one to start the trial and one for each of the two intervals, replaced the hand switches.

Procedure. The procedure in Experiment 2 was identical with that of Experiment 1. The loci stimulated in the first condition of the experiment were the first and third fingertips of the right hand, in the second condition the first and fourth fingers of the right hand. The contactors were located on the palmar surface approximately 1 cm from the end of the fingers. In addition, when the first and third fingers were stimulated, two separate oscillators, one for each vibrator, generated the signals rather than splitting the output from a single oscillator as was done in the other conditions of the experiment. The effect of using two oscillators was to allow random phase relations between the two vibratory signals. There is some indication in the literature that differences in phase between two vibratory signals increases sensitivity which in the present experiment might cause an increase in summation (Békésy, 1958).

In the bilateral condition the loci were the index fingertips of both the left and right hands on the palmar surface 1 cm from the end of the finger. For some threshold determinations in Experiment 2, the S's fingers were glued to the contactors with collodion. There was no indication that this procedure affected thresholds or summation in any significant way. The signal used throughout the experiment was a burst of 160-Hz vibration with a duration of 200 msec. The reason for the change in frequency from 100 Hz, the frequency employed in Experiment 1, was that 100 Hz is very near the resonant point of the V-47 vibrator. A vibrator energized with a frequency close to its resonant point often does not exhibit linearity of amplitude changes with changes in coil voltage.

Table 2
Mean Amount of Summation in dB Between Different Loci

Fingers Stimulated	Prob. Sum.	Spatial Sum.	Total Shift
1st and 3rd	0.16	1.94	2.10
1st and 4th	0.67	1.83	2.50
1st, left and right	0.34	1.66	2.00

Results and Discussion

The means for the three conditions are shown in Table 2. The amount of spatial summation for the first and third, and the first and fourth fingers, based on six observations each, was significant at the .05 level; the amount of spatial summation for the two index fingers, based on 13 observations, was significant at the .01 level. There were no significant differences in spatial summation among the three conditions.

Comparing the mean amount of spatial summation on the thigh, 1.94 dB, with the result from the first and third fingers, also 1.94 dB, it is clear that, despite the many differences between the thigh and the fingertips and the differences in the stimulus conditions, such as the frequency of vibration and the addition of a stable surround, there is no significant difference in the amount of spatial summation. Because there was no independent variation of locus or stimulus characteristics, it is not possible to state what the separate effects of these factors might be. It is possible that spatial summation remained constant between the conditions of Experiment 1 and Experiment 2 because any change towards increasing the amount of summation caused by one or more of these factors was offset by a change towards decreasing the amount of summation by another. It seems more plausible that none of the factors associated with moving from the thigh to the fingertips has any effect on spatial summation.

Comparing the amount of spatial summation for the first and third fingers with that for the first and fourth fingers, there does not appear to be any effect of allowing random phase shifting between the two vibratory signals. One reason no effect of phase was noted might be that Békésy's demonstration of increased sensitivity as a function of phase differences (1958) was dependent upon a shift in localization. In the present experiment the intensity of vibration at threshold was so low, probably as a result of the two-interval, forced-choice technique, that Ss reported they were unable to localize the site of stimulation and thus did not experience any shift in localization. A second possible reason might be that in Békésy's demonstration the phase difference between the two signals was constant, whereas in the present experiment the phase relations were changing from trial to trial.

The results from the bilateral condition support Kietzmann's (1927) finding of spatial summation between the two index fingers. With vibrators located on the two index fingers, it is extremely unlikely that there is any significant amount of physical interaction between them. The fact that under this condition there was no significant decrease in spatial summation supports one of the conclusions of Experiment 1, viz: physical interaction is not a significant factor in spatial summation. The results of Experiments 1 and 2 in which spatial summation was obtained over relatively large interstimulus distances also suggest that the summation process takes place in the central nervous system and not in the periphery.

EXPERIMENT 3

A number of investigators have discovered relationships which would suggest the existence of at least two receptor systems for vibrotactile stimuli: one system response to low-frequency vibrations and a second responsive to higher frequency vibrations (Békésy, 1965; Mountcastle, Talbot, Darian-Smith, & Kornhuber, 1967; Verrillo, 1968). The most important relation for the present study is the one that exists between the surface area of the vibrating contactor and the frequency of vibration as they affect absolute threshold. It has already been mentioned that Verrillo (1963) found that doubling the contactor area resulted in a 3 dB

Table 3
Mean Amount of Summation in dB at Selected Frequencies

Frequency	Prob. Sum.	Spatial Sum.
9 Hz	0.41	-0.21
160 and 360 Hz	1.04	-0.06

decrease in the amplitude of vibration required for threshold. The relation held only for frequencies of 80 Hz and higher. For 25 and 40 Hz, doubling the area produced no change in threshold. This finding, among others, led to the hypothesis that the functioning of the low-frequency receptor system is independent of contactor area. Within the framework of the present experiment, it was possible to determine whether the same relation held when the contactor area was, in effect, increased by adding a second vibrator rather than increasing the contactor area of a single vibrator. In addition to employing a lower frequency of vibration, the possibility was also tested that two different frequencies would show spatial summation at threshold.

Apparatus and Procedure

The apparatus and procedure were the same as in Experiment 2. The sites of stimulation were the first and third fingers of the right hand. In the first part of the experiment, the frequency of the oscillator was set at 9 Hz and the duration of the signals was increased to approximately 300 msec. In order to avoid switching transients, the onsets of the two signals were increased to 100 msec. In the second part of the experiment, two separate oscillators were used: one, set at 160 Hz, energized the vibrator on the first finger, and the other, set at 360 Hz, energized the vibrator on the third finger.

Results and Discussion

The results of six observations at 9 Hz are shown in Table 3. The mean amount of spatial summation was significantly less than that obtained on the first and third fingers in Experiment 2 in which, under essentially the same conditions, except for frequency, there was 1.94 dB of spatial summation. The difference in spatial summation as a function of frequency is, therefore, in agreement with Verrillo's (1963) results obtained by increasing the area of a single contactor.

The results with two different frequencies, presented in Table 3, show that there was not a significant amount of spatial summation. It would appear that frequency of vibration is one of the determinants of whether spatial summation at threshold will occur or not. Such a finding might prove important for the interpretation of neurophysiological recordings made from first-order afferent fibers from tactile receptors. Investigators who have made such recordings often take as "threshold" the point at which frequency following is first observed (Mountcastle et al, 1967). The present experiment indicates that at threshold there is some kind of neural representation of frequency and further that some coding of frequency, not necessarily the same code that is found in peripheral fibers (Uttal & Smith, 1968), is maintained in the central nervous system.

One might question whether, in the successive condition in Experiments 1, 2, and 3, 450 msec between stimuli was enough time to insure that there would be no spatial summation, i.e., whether the two stimuli would, in fact, be two independent events. Although there was no spatial summation demonstrated in either part of Experiment 3, the amount of probability summation did not differ significantly from that obtained in the other experiments. This suggests that the threshold changes attributed to probability summation are not the result of partial spatial summation resulting from the temporal overlap of excitations.

In Experiments 1 and 2, in which spatial summation was demonstrated between two loci, the maximum amount of spatial summation never exceeded 2.22 dB. Even if probability summation is included, the total threshold shift was still less than the 3 dB per doubling of area at a single locus reported by Verrillo (1968). One of the major differences between the present study and Verrillo's experiments is in the use of two rather than one site for stimulation. One might speculate that summation is partly dependent on the stimulation of nerve endings arising from a single afferent fiber. If that is the case, it would be predicted that as the distance between two sites of stimulation was decreased to a very small separation, a slight increase in summation would be found. Although Békésy (1958) did not report finding greater spatial summation at 0.5 cm than at 10.0 cm interstimulus distance, his method was not chosen to reveal small differences in summation. Further experimentation would be required to determine whether, by decreasing the interstimulus distance, one could approach the condition of doubling the area at a single locus.

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NOTES

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