Effect of stimulus frequency on subjective vibrotactile magnitude functions

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Subjective magnitude functions were determined by the method of magnitude estimation at 60 and 250 Hz at the fingertip and thenar eminence, both with and without a rigid surface surrounding the contactor. When the surround was in place, the slopes of the curves were independent of stimulus frequency. The slopes became frequency dependent when the surround was removed—the lower frequency produced a steeper slope at both body sites. An explanation of the effect is suggested. It involves the frequency characteristics and spatial sensitivity of the receptors.

The literature dealing with subjective magnitudes of vibrotactile sensations contains an apparent discrepancy that has remained unresolved for a number of years. The discrepancy concerns the value of the exponent at different frequencies when the growth of sensation is measured by matching methods or by direct scaling. Stevens, using the methods of magnitude estimation (1959) and cross-modality matching (1968), showed that the exponent of the power function for vibrotactile changes as a function of stimulus frequency—120 and 250 Hz produced flatter growth curves than did 60 Hz, when measured at the fingertip. A similar result was obtained by Talbot, Darian-Smith, Kornhuber, and Mountcastle (1968) and Franzén (1969), who also determined sensation-magnitude functions by magnitude estimation at the fingertips for low and high frequencies.

The discrepancy appeared when Verrillo, Fraioli, and Smith (1969) reported slightly steeper curves measured at the thenar eminence at 25 and 750 Hz, but no effect of frequency at intervening frequencies. It is extremely difficult to compare directly and evaluate the conflicting results from these and other laboratories since methods and experimental conditions varied widely.

The current experiments replicate as closely as possible the experimental conditions used by Stevens (1968) and by Verrillo, Fraioli, and Smith (1969) in order to evaluate several experimental parameters that might account for the discrepant results. The two studies differed in at least two major conditions: (1) Stevens stimulated the tip of the middle finger, Verrillo et al. used the thenar eminence; (2) Verrillo et al. made measurements, using a rigid surround to

confine the vibratory disturbance to the immediate area of the contactor, Stevens did not use a surround. A third important difference concerns the static position of the contactor with respect to the surface of the skin. Stevens used a counterbalanced beam which applied equal pressure to the skin for all subjects, whereas Verrillo et al. maintained a constant displacement of tissue. This parameter was not considered in the present investigation.

The aim of the experiments was to determine the source of the discrepancy between the results reported by Stevens (1959, 1968), which showed the slope of the vibrotactile subjective-magnitude function to be dependent upon stimulus frequency, and those of Verrillo et al. (1969), in which the slopes were independent of frequency.

APPARATUS AND METHOD

A detailed description of the apparatus and method may be found in Verrillo et al. (1969).

Vibratory signals were delivered to the subjects by means of a Goodmans 390A vibrator located on a movable platform that permitted fine adjustments in the position of the vibrator with respect to the surface of the skin. The subject sat with his right hand and forearm comfortably resting on a rigid surface situated above the vibrator. The vibratory disturbance was prevented from spreading over the surface of the skin by inserting the contactor into a hole in the rigid surface, leaving a 1.0-mm gap between contactor and rigid surface. The static position of the contactor was carefully adjusted in each testing session so that it pressed 0.5 mm into the surface of the skin, which prevented loss of contact during the excursions of the contactor (Verrillo, 1962). The subject and vibrator assembly were located within a booth to eliminate unwanted sounds and vibrations. Steady, narrow-band random noise was delivered to the subject via earphones in order to mask the sounds emitted by the vibrator. Displacement amplitude was monitored by means of a calibrated accelerometer (Endevco 2221c) mounted directly on the moving element of the vibrator. Acceleration voltages were converted to decibels referred to 1.0 micron of peak displacement.

Subjective intensity functions were determined by the method of magnitude estimation (Stevens, 1955). Six subjects were requested

This research was supported by Grant NS-09940 from the National Institutes of Health, U.S. Department of Health, Education and Welfare.

Figure 1. Magnitude estimation curves obtained over the thenar eminence at 60 and 250 Hz using a surround. The slopes for both frequencies are 0.46.

to assign numbers without a reference standard to a randomly presented series of 10 stimulus intensities, which ranged from 2 to 44 dB above threshold (2, 6, 10, 14, 20, 24, 30, 34, 40, 44 dB SL), determined at the start of each session. The first of three runs was discarded and the mean of Runs 2 and 3 was taken as the assigned number. Individual data were then plotted in terms of assigned number as a function of sensation level, and geometric means of the six subjects were calculated at each intensity to produce curves of subjective magnitude.

Measurements were made at the fingertip (middle finger, right hand) and the thenar eminence of the right hand with the rigid surround in place (Verrillo et al., 1969), and again, without the surround (Stevens, 1959; 1968). Magnitude-estimation curves at 60 and 250 Hz were determined using a contactor size of 0.28 cm² (Stevens, 1959, 1968). The timing sequence, 900 msec on and 500 msec off, and the envelope rise-decay time of 50 msec are those of Stevens.

The slope values reported in the following sections refer to the upper portions of the curves; values for the lower portions will be specified as such. It should be noted that the slopes of the curves have been computed in terms of *intensity* rather than amplitude of displacement (see Verrillo & Chamberlain, 1972).

RESULTS

Magnitude Estimation With Surround

Figure 1 shows the results obtained at the thenar eminence at two frequencies (60 and 250 Hz) with a rigid surface surrounding the 0.28-cm² contactor. The replication of the surround condition used by Verrillo,

Fraioli, and Smith (1969) produced no change in the growth of subjective magnitude as a function of stimulus frequency. Both frequencies yielded a slope of 0.46, which is consistent with the similarity of slopes 0.41 at 64 Hz and 0.40 at 250 Hz, observed in the earlier study. The steeper slopes found in the present experiment reflect the use of a smaller contactor (0.28 cm²) than that used by Verrillo, Fraioli, and Smith (2.9 cm²). An inverse relationship between contactor size and slope of the subjective-magnitude function has been reported (Verrillo, 1974). The lower slope was the same (1.0) for both frequencies. The 0.46 slope agrees well with the value of 0.49 obtained by Verrillo and Chamberlain (1972) for a 250-Hz signal at the thenar eminence with a surround, using a 0.28-cm² contactor. The same experimental conditions yielded slopes of 0.52 for 25 Hz and 0.50 for 250 Hz in a previous experiment by Verrillo (1974).

The data obtained at the fingertip, using a rigid surround, are shown in Figure 2. The slopes for the 60- and 250-Hz signals are 0.45 and 0.44, respectively, and 1.2 for both frequencies in the lower portion, which again shows that frequency has little effect on the slope at the fingertip when a rigid surround is used. The slope for 250 Hz is in close agreement with

Figure 2. Magnitude estimation curves obtained at the fingertip at 60 and 250 Hz with a surround. The slope for 60 Hz is 0.45; the slope for 250 Hz is 0.44.

Figure 3. Magnitude estimation curves obtained over the thenar eminence at 60 and 250 Hz without a surround. The slope for 60 Hz is 0.40; the slope for 250 Hz is 0.35.

that reported for the fingertip (0.45) by Verrillo and Chamberlain (1972), and at 60 Hz the result approximates the slope value of 0.45 reported by Franzén (1969) for a 50-Hz signal. Franzén obtained a slope of 0.29 at 250 Hz, however, in a study in which he supported the hypothesis that the growth of subjective magnitude is a function of stimulus frequency. This value is far smaller than any slope reported in the literature for a similar set of experimental conditions. The reason for this disparate finding is not readily apparent.

Magnitude Estimation Without Surround

The results obtained at different frequencies changed considerably when the rigid surface surrounding the contactor was removed. Magnitude-estimation curves measured over the thenar eminence without surround are shown in Figure 3. The slope for 60 Hz (0.40) is now steeper than that of the 250-Hz curve (0.35). In the lower portions of the curves, the slope was 1.3 for 250 Hz and 1.7 for 60 Hz. The absence of a limiting surround resulted in a frequency effect upon the slope of the magnitude-estimation curve; the lower frequency produced a steeper slope in both the upper and lower portions of the curves.

A similar result was obtained at the fingertip (Figure 4), where the slopes for 60 and 250 Hz were

0.45 and 0.40, respectively. The lower slopes were 1.8 for 60 Hz and 1.5 for 250 Hz. The result confirms the effect reported originally by Stevens (1959), who used a 0.28-cm² contactor and obtained slopes of 0.45 and 0.42 for 60- and 120-Hz signals. Stevens (1968) later reported the same effect for 60 Hz (0.50) and 250 Hz (0.34) for a 0.28-cm² contactor with no surround. Data for the fingertip reported by Talbot et al. (1968) show the effect at 40 Hz (0.47) and 120 Hz (0.42) for a contactor of unspecified dimension used without a surround. Results reported by Gibson (1960) are ambiguous, since the dependence of slope on frequency depends upon the manner in which the data are plotted. Stevens (1968) suggests that, if the functions obtained without a surround are plotted in terms of the "effective threshold" rather than measured thresholds, the dependence of slope upon frequency is evident.

The results of the present experiment are consistent with data reported by Verrillo and Chamberlain (1972), who obtained subjective-magnitude functions at 250 Hz at the fingertip with and without surround. The slope with surround was 0.44 (present study 0.44) and 0.40 without (present study 0.40).

Slope Value and Threshold

Several recent publications (Verrillo & Chamber-

Figure 4. Magnitude estimation curves obtained at the fingertip at 60 and 250 Hz without a surround. The slope for 60 Hz is 0.45; the slope for 250 Hz is 0.40.

Table 1

Site	Surround	Frequency			
		60 Hz		250 Hz	
		Threshold	Slope	Threshold	Slope
Thenar	With	+13.0	.46	-6.0	.46
Finger	With	+5.5	.46	-9.0	.44
Finger	Without	+5.0	.45	-12.0	.40
Thenar	Without	+4.0	.40	-15.0	.35

lain, 1972; Verrillo, 1974) have reported a correlation between vibrotactile sensitivity and the slope of the subjective-magnitude function. Experimental conditions which resulted in lower thresholds also produced flatter magnitude curves. Thresholds were varied by manipulating the surround conditions and the site of stimulation (Verrillo & Chamberlain, 1972) and by varying the contactor size (Verrillo, 1974). Regardless of the manner in which the threshold shift was effected, the relationship between threshold and slope was maintained. It was hypothesized that, for a given frequency, the shift in both slope and threshold was governed by the number of receptors activated by the stimulus. Those stimulus conditions that yield low thresholds and shallow slopes are those which activate a greater number of receptors.

The data from the present experiments, shown in Table 1, support the hypothesis. Within each frequency, the slope of the subjective-magnitude functions decrease as the thresholds of detectability decrease. The experimental variables manipulated to produce these changes were the body site stimulated and the presence or absence of a limiting surround. If the data are inspected without regard to frequency, the general trend for slope to decrease with threshold is still present, but the slopes for the thenar eminence at 60 Hz are not consistent with the rest of the data. The relationship between slope and threshold is maintained firmly only when the threshold differences can be attributed logically to differences in the number of activated receptors rather than to the frequency-response characteristic of the individual receptor. As an example, removing the surround increases the number of receptors activated by the stimulus, which, in turn, results in a lowered threshold and a flatter magnitude function. On the other hand, changing the frequency from 60 to 250 Hz lowers the threshold, a receptor characteristic (Sato, 1961; Verrillo, 1966a, b), but does not alter the slope of the subjective-magnitude curve when a surround is used. The change in slope that occurs when the surround is absent is discussed in the following section.

Average deviations were determined to assess the degree of variability among individual responses. The extreme values are reported here as an index of the variability in the data. At 2.0 dB SL the average deviations ranged from 0.32 to 0.73 log units, and at

44 dB SL the values were 0.10 to 0.25 log units. Variability decreased as a function of intensity, a phenomenon reported in a previous publication (Verrillo et al., 1969). Values for the thenar eminence with surround closely approximate those obtained in the earlier study.

DISCUSSION

The obtained results show clearly that the relationship between the slope of the subjective-magnitude curve and stimulus frequency is governed primarily by the surround condition of the contactor. The effect was observed in upper and lower portions of the curves. When a rigid surround was used to confine the stimulus to the area of the contactor, the slope of the curve was independent of frequency. Removal of the surround allows surface waves to spread across the skin, increasing the effective area of stimulation, which produces lower thresholds. The slopes of subjective-magnitude curves become dependent upon frequency when the rigid surround was removed. The values of the slopes obtained without surround are consistent with those reported by Stevens (1959), and when a surround was used they agree with results reported by Verrillo et al. (1969), who used a surround. Since it was the discrepancy between the results of Stevens and the senior author which prompted the current experiments, we attempted to replicate as closely as possible the experimental conditions used by Stevens. Our close agreement with Stevens, when using his conditions, removes the discrepancy.

The reasons why removal of the surround causes the subjective-magnitude slopes to become frequency dependent was not determined by direct experimentation, but a reasonable explanation is suggested. Verrillo and Chamberlain (1972) determined that removing the surround results in lower thresholds and flatter subjective-magnitude curves. They suggested that the slope was determined by the number of receptors activated under the effective area of stimulation. Verrillo (1974), using a rigid surround, supported this hypothesis by demonstrating that a large contactor produces a flatter slope than a small contactor. It is reasonable to assume that a greater number of receptors were activated by the large contactor and that removing the surround has a similar effect. This is contrary to what physiological experiments would lead us to expect. Johnson (1974) has calculated that as the total activity of mechanoreceptive fibers increases, the slope of the intensity function increases. The opposite appears to be true when area is increased in psychophysical experiments for vision (Mansfield, 1973) and vibration (Verrillo & Chamberlain, 1972; Verrillo, 1974). We cannot at this time resolve this apparent paradox.

The question remains as to why the removal of the surround results in a flatter slope at 250 Hz than at 60 Hz. It is known that the Pacinian corpuscle is maximally sensitive to vibration in the region of 250 Hz, where the threshold response is 15 to 20 dB lower than that of a 60-Hz signal (Sato, 1961; Verrillo, 1963, 1966b, 1968; and others). It is also known that the Pacinian corpuscle can be excited over considerable distances by vibrations applied to a region remote from the site of the receptor (Merzenich & Harrington, 1969; Talbot et al., 1968). Indeed, the subjective experience is that the sensation produced by a 250-Hz signal is more diffuse than that produced at 60 Hz, which is more localized, although the same contactor area is used.

The high sensitivity of the Pacinian corpuscle to 250-Hz vibrations and its capacity to be activated readily by a remote mechanical disturbance provide the basis for our hypothesis. It seems reasonable to suggest that, in the absence of a limiting surround, a proportionately greater number of receptors are activated at 250 Hz than are activated at 60 Hz. In other words, the effective stimulus area is greater for the 250-Hz signal. The resultant flatter subjective-magnitude function is consistent with the observation that larger contactor areas produce flatter curves (Verrillo, 1974). This hypothesis is offered as a possible explanation for the observations reported. We concur with Johnson (1974) that the paucity of solid information concerning skin mechanics prevents us from a more detailed analysis of responses resulting from complex stimuli.

SUMMARY AND CONCLUSIONS

The experiments of the current series were designed to test several variables that may account for discrepancies reported in the literature regarding the effect of frequency on the slope of the subjective-magnitude function. Several studies reported slopes dependent on stimulus frequency, and others showed the slopes to be independent of frequency. The relevant stimulus parameters were carefully controlled in order to replicate experimental conditions used by previous investigators, particularly Stevens (1959, 1968) and the senior author (Verrillo et al., 1969). All published reports of subjective-magnitude curves having slopes dependent on stimulus frequency are based on experiments performed at the fingertip, and almost without exception a rigid surface surrounding the contactor was not employed. Results which show the slopes to be independent of frequency have been obtained over the thenar eminence with a rigid surround to prevent the spread of vibration across the surface of the skin. In the current experiments, we have examined the effect of body site (finger and thenar eminence) and surround upon the slope of magnitude-estimation

curves determined at 60 and 250 Hz.

The results show that the site of stimulation is not a factor in determining the effect of frequency upon the slope of the magnitude curves. The presence or absence of a limiting surround proved to be the decisive variable. When the surround was used at either body site, the slopes of magnitude-estimation curves were independent of frequency. Removal of the surround from the finger or thenar eminence resulted in lower thresholds and flatter curves at 250 Hz compared to measurements obtained at 60 Hz. The results are consistent with the data of Stevens (1959, 1968), who found frequency dependence without a surround, and with Verrillo et al. (1969), whose curves, obtained with a surround, were independent of frequency.

The hypothesis we suggest to explain the relationship between absence of a surround and frequency-dependent magnitude curves involves the frequency characteristic and the spatial sensitivity of receptors. Pacinian corpuscles are maximally sensitive at 250 Hz and may be activated by vibrations emanating from a remote source. Removal of the surround allows the vibrations to spread beyond the immediate region of the contactor, increasing the effective area of stimulation. The effective area is larger at 250 Hz than at 60 Hz in terms of the number of receptors activated since the sensitivity of the receptors is much greater at the higher frequency. It has been established that larger contactors produce flatter subjective-magnitude functions.

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(Received for publication February 22, 1974;
revision received June 25, 1974.)

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GREGORY, R. L., & HARRIS, J. P. Illusory contours and stereo depth. *Perception & Psychophysics*, 1974, **15** (3), 411-416. Figure 6 should have been labeled as you see it below.