Tactile vibration: Change of exponent with frequency[1]

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When cross-modality matches were made between a 60-Hz vibration and such other continua as electric current through the finger, number, force of handgrip, and both binaural and monaural loudness, the exponent of the power function for vibration was found to be about 1.0 at 60 Hz. The dependence of the exponent on frequency has been studied in a series of intramodality matching experiments. The exponent appears to reach its largest value in the vicinity of 30 Hz and its lowest value in the vicinity of 250 Hz. The highest value is roughly twice the lowest value. Over the low-frequency range, there is a suggestive similarity between the power functions for vibration and those for auditory loudness. As a vibration sensor, the ear may behave much like the finger.

Published studies have shown that the apparent intensity of a 60 Hz vibration applied to the fingertip increases as a power function of the amplitude of the vibration. The exponent for the 60 Hz vibration was found to be approximately 0.95 when numbers were matched to vibration under the method of magnitude estimation (Stevens, 1959b). Confirmation of approximately that value of exponent for the power function was obtained in other cross-modality matching experiments. Figure 1 shows examples of the results from studies in which the observers adjusted various stimuli, including number, to match preset levels of vibration.

The stimulus for "shock" was an electric current (60 Hz) passed through the finger (Stevens, 1959a). The equal sensation function rises very steeply, consistent with the high exponent of the function relating the sensation to the electric current. Since experiments with electric current have given rather variable results in different laboratories (Stevens, 1966a), it appears that cross-modality matches made with electric current may not provide a reliable basis for estimating precise values of other exponents. Nevertheless, the steep function in Fig. 1 is typical of results obtained in this laboratory.

The experiment in which observers squeezed a precision dynamometer in order to match the apparent force of handgrip to various vibration amplitudes gave results that confirm the exponent determined by magnitude estimation (J. C. Stevens, Mack, & Stevens, 1960). Thus the line labeled handgrip in Fig. 1 has a slope of 1.6. The line labeled number has a slope of 0.95 and represents the function determined by magnitude estimation in which each of 15 Os made two judgments of each stimulus. The ratio of the two slopes, handgrip and number, is about 1.7, which is the exponent measured directly for handgrip (J.C. Stevens & Mack, 1959).

In one of the earliest cross-modality experiments, the loudness of a band of noise centered at about 500 cps was matched to vibration on the fingertip (Stevens, 1959a). The equal sensation function had the exponent 0.6, which is close to the predicted value. In a replication of the experiment, the same exponent was reported by Geldard and Sherrick (1965). Additional functions are shown in Fig. 1 for the matching of loudness to vibration. They are from an experiment in

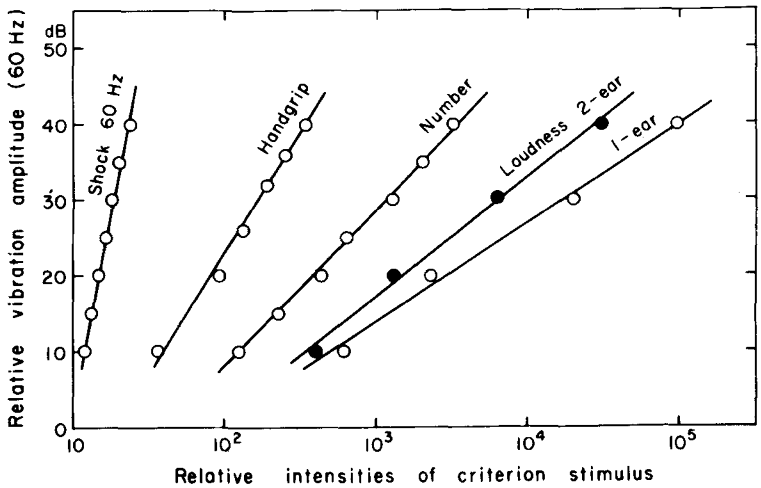

Fig. 1. Equal-sensation functions obtained by cross-modality matches between 60-Hz vibration on the fingertip and various other perceptual continua. Vibration amplitudes were set by the experimenter, and the observer adjusted the stimulus on another continuum to produce an apparent match. All data are from published experiments.

which the purpose was to determine the relation between the monaural and binaural loudness functions (Reynolds & Stevens, 1960). The auditory stimulus was a band of noise 250 to 2000 Hz. The values of the exponents were 0.78 for binaural and 0.66 for monaural listening. When the observers were allowed to adjust the vibration to match the loudness, the obtained slopes (exponents) were lower: 0.64 for binaural and 0.51 for monaural listening. These lower values provide another example of the ubiquitous regression effect that occurs when stimuli on one continuum are matched to those on another (Stevens & Greenbaum, 1966). The slope of the matching function depends on which stimulus the O adjusts.

The accumulated evidence from the experiments on cross-modality matching suggest that the psychophysical power law applies to sensed vibration and that the exponent for a 60 Hz vibration on the finger is not far from 1.0 Until greater precision is available, it appears reasonable to make the convenient assumption that the exponent at 60 Hz is unity.

EFFECT OF VIBRATION FREQUENCY

There are a few pieces of evidence to suggest that the exponent of the psychophysical function for sensed vibration on the finger decreases with frequency. The first experiment on vibration carried out in this laboratory employed a stimulus of 120 Hz, and the obtained exponent was 0.83 compared with 0.95 for 60 Hz (Stevens, 1959a). Some experiments at the University of Virginia (described by Hahn, 1960) suggested that the contours for equal apparent intensity, obtained by matching other frequencies to a standard frequency at 100 Hz, become more widely spaced at the higher frequencies. A wider spacing of the contours would mean that at the higher frequencies the value of the exponent is lower. Results obtained by R. H. Gibson (1960), who used magnitude estimation with seven Os, also showed that the exponent decreases with frequency. This decrease seemed to be lessened when the stimulus was measured as amplitude above a threshold value determined independently. Inspection of the functions suggests, however, that the dependence of the exponent on frequency would still be clearly evident if the stimulus were measured in terms of the effective threshold, as defined by the value that would serve to maximize the linearity of the function. In other words, a threshold measured independently may not give the most appropriate additive correction. A computer program for determining the effective threshold value that serves to maximize the product-moment correlation coefficient has been worked out by J. C. Stevens (1967). This curve-fitting procedure may or may not solve the problem.

MATCHING FUNCTIONS FOR VIBRATION

A purpose of the present experiments was to determine a family of equal-sensation functions for different frequencies of vibration. Intramodality matches were made for pairs of frequencies. The aim of the experiments was twofold: (1) to determine the form of the matching function when observers adjusted a vibration at one frequency to match the perceived intensity of a vibration at another frequency; and (2) to determine how the equal-sensation matching functions vary with the frequencies involved. Two principal experiments were run, one by the method of adjustment with nine Os, and one by the method of tracking with seven other Os. Exploratory experiments were also run by other methods with smaller groups of Os.

Apparatus

The O rested his middle finger on a button (6 mm diameter) fastened to a Goodmans Vibration Generator,

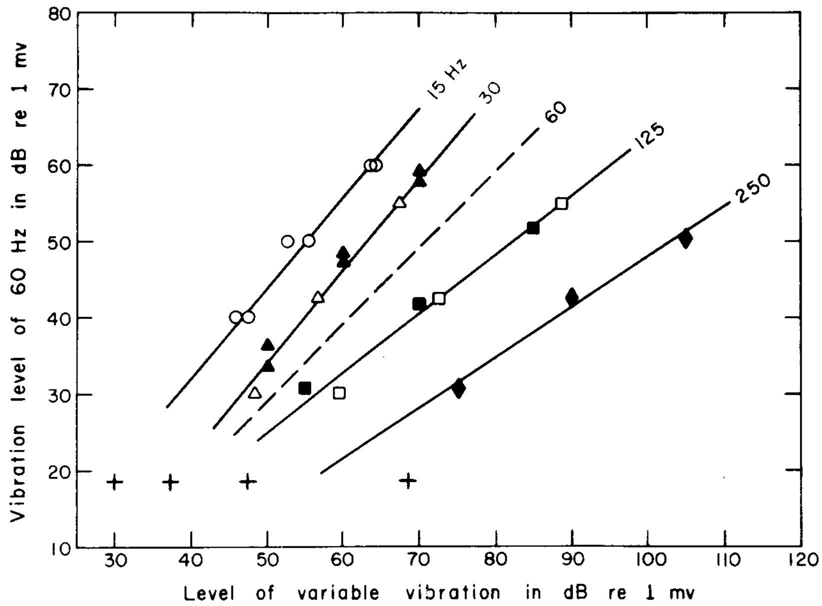

Fig. 2. Matching functions between a 60-Hz vibration and other vibration frequencies. The filled symbols indicate that the 60-Hz vibration was adjusted; the unfilled symbols indicate that the other frequency was adjusted. The crosses indicate the thresholds for the different frequencies averaged over the nine observers and all sessions. For clarity, the abscissa values for 30, 125, and 250 Hz have been shifted to the right by 10, 30, and 40 dB, respectively.

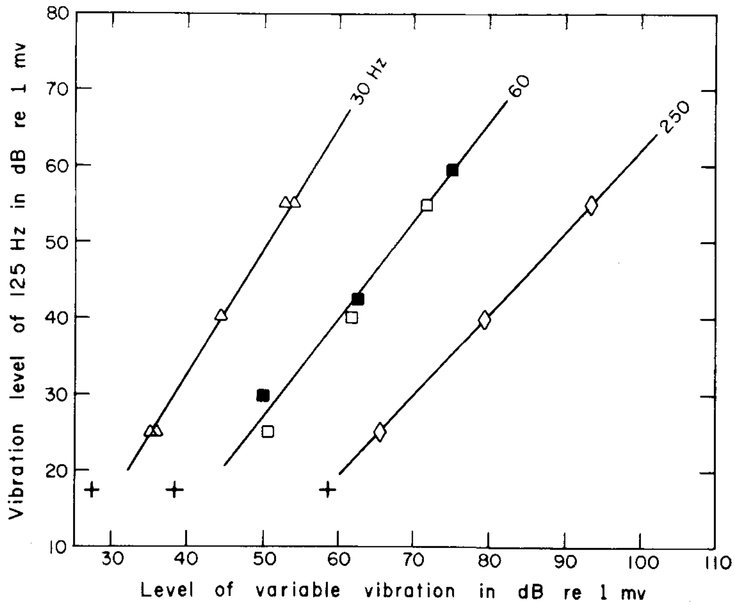

Fig. 3. Matching functions between a 125-Hz vibration and three other frequencies. The values for 60 Hz duplicate those shown in Fig. 2. The crosses are the averaged threshold values. The data for 60 Hz were shifted to the right on the abscissa by 20 dB, and those for 250 Hz by 30 dB.

Type 390A. This is a heavy-duty unit capable of an amplitude greater than 1 cm. In order to keep the steady pressure on the fingertip constant, the vibrator was mounted on one arm of a balance. The O held his finger on the button of the vibrator with just enough pressure to counteract a small excess in weight on the other arm of the balance.

The presentation of the stimuli was controlled by a motor-driven switch which in turn activated electronic switches designed to energize the vibrator alternately with current from one or the other of a pair of audio oscillators. The duration of each stimulus was 0.9 sec, and the interstimulus interval was 0.6 sec. The rise time of each vibration pulse was 0.05 sec, and the decay time 0.07 sec. These rise and decay times produced a rather pleasant sensation of instantaneous yet clickless onsets and offsets. In the adjustment experiment, the O adjusted the level of one of the vibrations by turning a sone potentiometer (a pair of 2000 ohm potentiometers ganged and cascaded). He was instructed to make the adjustable vibration appear equal to the fixed vibration and to approach the point of subjective equality by bracketing.

In the experiment in which the method of tracking was used, the level of the criterion vibration was slowly increased (about 20 sec/dB) from below threshold to the highest value available. As with the Békésy audiometer, the O pressed or released a switch in order to control the direction of movement of a recording attenuator. He thereby caused the level of the tracking vibration (100 Hz) to increase whenever it seemed less intense than the slowly changing criterion and to decrease whenever it seemed more intense. In other words, he tried to follow or track the level of the criterion stimulus by using the switch to raise or lower the level of the 100 Hz vibration. The recording attenuator was usually set to move 1 dB on each presentation of the variable stimulus.

For the method of adjustment, the O's right arm rested on the arm of a tablet-arm chair and the fingers protruded beyond the edge, so that the tip of the middle finger could rest on the button of the vibrator. The static pressure on the button was 50 g in the adjustment experiment. In the tracking experiment, only the first phalange protruded over the edge of the chair. The static pressure was 35 g, and in this instance the position of the fingers was secured by a strapping that held them in place during the tracking run.

In the experiments in which an audible tone was produced by the vibrator, the tone was masked by a steady noise through a pair of earphones.

Voltage levels across the vibrator were measured by means of a vacuum-tube voltmeter. Vibration levels are stated in terms of this voltage, specifically in terms of decibels re 1 mV. Over the ranges used, voltage was proportional to vibration amplitude, which was measured with the aid of a General Radio vibration pickup.

Matching by Adjustment

At the beginning of each session, the O made two threshold measurements for each of the three frequencies to be worked with. By adjusting the stimulus level, the O tried to bracket the threshold and to set the stimulus at a just detectable level. The thresholds measured in this manner are indicated by crosses in Figs. 2 and 3.

Following the threshold determinations, the O matched pairs of frequencies. One frequency was set by the experimenter at one of three amplitude levels, and the O adjusted the level of the other frequency to produce

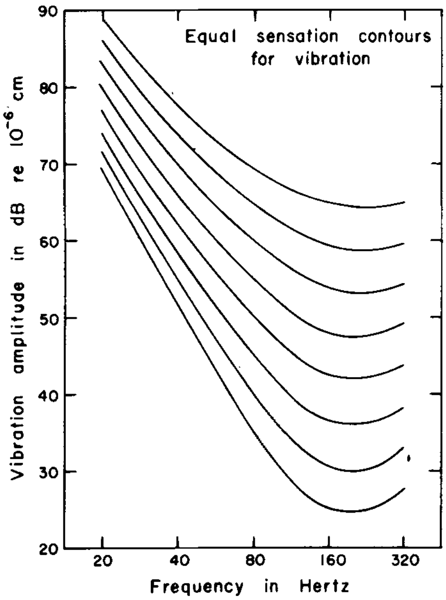

Fig. 4. Family of equal-sensation contours derived from vibration matches made by three observers. Matches were made between pairs of the octave frequencies designated on the abscissa. Contours for each observer were derived from the observer's matching functions. The three sets of contours were then combined and smoothed. The lowest contour corresponds approximately to measured threshold values.

an apparent match. The decibel averages of the matches by the nine Os are plotted in Figs. 2 and 3. The data in Fig. 2 represent all the matches that had 60 Hz in common. The 60 Hz stimulus served either as the standard fixed by the experimenter (unfilled symbols) or as the stimulus adjusted by the O (filled symbols). The matches that had 125 Hz in common are shown in Fig. 3. Note that some matches were repeated in two different sessions: 60 Hz matched to 30 Hz, and 15 Hz matched to 60 Hz (Fig. 2); also 30 Hz matched to 125 Hz (Fig. 3). The repeatability appears to be reasonably good. A stimulus at 15 Hz was matched to one at 30 Hz in two separate sessions, and the results confirm the suggestion in Fig. 2 that the functions for 15 and 30 Hz have very nearly the same slope (exponent). There is a suggestion that the exponent at 30 Hz is very slightly larger.

The matching functions in Figs. 2 and 3 indicate that, in order to preserve subjective equality, changes of amplitude by a constant ratio at one frequency require changes by a constant ratio at another frequency. In other words, the equal-sensation functions within the vibration domain turn out to be power functions, so that frequencies are related by straight lines in log-log or decibel coordinates.

Some of the measured threshold values lie close to the projection of the corresponding equal-sensation function; others do not. It seems apparent that the data, including the threshold, could be fitted reasonably well with a power function containing an appropriate additive constant, but it is not clear that the present uncertainties in the data warrant that attempt at refinement.

Taken together, the power functions in Figs. 2 and 3 confirm the indications from other experiments that the slopes (exponents) at the lower frequencies are larger than those at the higher frequencies. Between 30 and 250 Hz the exponent decreases by a factor of almost two. The slopes of the lines in Fig. 2 are 1.17, 1.20, 0.8, and 0.67 for the successive frequencies.

In a further study, three Os made matches among the octave-spaced frequencies 20, 40, 80, 160, and 320 Hz. The relative slopes of the matching functions agreed well with those in Fig. 2. The slopes (exponents) decrease with increasing frequency, but the data suggest that the value of the exponent may increase again when the vibration frequency becomes as high as 320 Hz. The smallest value of the exponent was found to lie somewhere in the vicinity of 250 Hz, but the exact location of the minimum, if there is one, remains uncertain.

On the basis of the matching functions for each of the three Os, three sets of equal-sensation contours were constructed. The similarity among the three sets of contours made it quite simple to average them into a smoothed consensus, the outcome of which is presented in Fig. 4. Although based on only a small number of Os, the smoothed contours show a reasonable agreement with all the foregoing matching results, including those in Figs. 2 and 3. The shapes of the contours in Fig. 4 accord also with the general form of the contours obtained by Goff and described by Hahn (1960). Contours for one O were later published by Goff (1967).

The lowest contour represents the approximate threshold. Published threshold measurements by various experimenters accord fairly well with the lowest contour, although some results suggest that over the lowest frequencies the curve may be concave downward rather than straight as drawn in Fig. 4. Thresh-

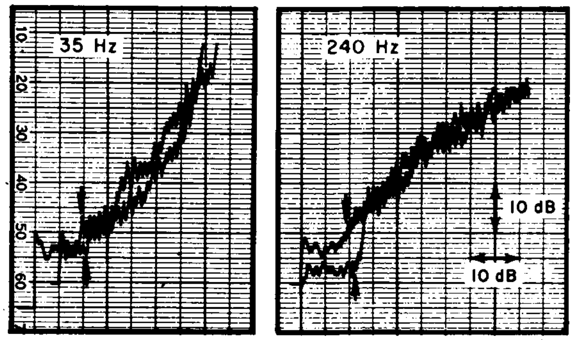

Fig. 5. Sample tracking records for one observer. By means of a motor-driven recording attenuator, the observer tried to maintain apparent equality between a 100-Hz vibration and a vibration at another frequency which increased slowly in amplitude. Each chart shows the tracks for two different runs. Each short arrow indicates the approximate threshold at which the slowly increasing amplitude was first detected. Note the greater steepness of the tracks for 35 Hz compared to those for 240 Hz.

Table 1. Slopes of the lines fitted visually by S.R. and S.S.S. to the graphs of the tracking data. The seven observers tracked an ascending vibration intensity by controlling the level of a 100-Hz vibrator. On the assumption that the slope for 60 Hz, had it been measured, would lie between the slopes for 50 and 75 Hz and have a value of about 1.4, the last column gives the slopes referred to the assumed value for 60 Hz.

Frequency	S.R.	S.S.S.	Average re 60 Hz
35	2.0	1.8	1.36
50	1.6	1.5	1.11
75	1.3	1.2	0.89
150	.9	.9	0.64
240	.8	.8	0.57

old measurements have been reviewed by Verrillo (1962, 1963). He also investigated many of the parameters that affect tactile sensitivity.

Matching by Tracking

Each of seven Os tracked the growth of apparent vibration intensity at least twice for each of five frequencies. Figure 5 shows examples of tracking records from one O. A line was drawn through the centers of each of the zigzag tracking paths, and all the lines for a given frequency were then plotted on a single graph. Although there are often twists and wiggles in any given tracking path, a bundle of 14 or more paths was found to define a clear general trend. The best straight lines defining the general trends were determined by eye independently by S. Ross and by the author. The slopes of the resulting lines are shown in Table 1.

The averages of the visually fitted slopes were referred to 60 Hz by means of the assumption that the value for 60 Hz could be found by interpolation between the values for 50 and 75 Hz. The last column in Table 1 gives the slopes re 60 Hz. These values may be compared with the slopes of the lines in Fig. 2. The same trend is evident in Table 1 and Fig. 2, but the tracking data suggest that the decrease in the exponent with increasing frequency may be somewhat greater than the decrease in slope exhibited by the data in Fig. 2. Between 35 and 240 Hz, the change in the exponent values in Table 1 exceeds a factor of two.

Comparison with Auditory Loudness

The frequency dependence of the exponent of the psychophysical function for vibration has an interesting parallel in hearing. A tabulation (Stevens, 1966b) of the data from four different studies shows that below a frequency of about 400 Hz the exponent of the power function for auditory loudness increases as the frequency is lowered. Furthermore, the exponent grows by a factor of about two, or a bit more, as the frequency decreases to the lowest values tested. Indeed, the similarity between hearing and vibration extends even to the approximate values of the exponents. Above 400 Hz the exponent for loudness may be assumed to have the standard value 0.6, but at 50 Hz it rises to a value between approximately 1.0 and 1.8, depending on whose data are considered. Roughly similar values hold for vibration on the fingertip.

Figure 6 shows the slopes (exponents) of the equal-sensation functions for auditory loudness and tactile vibration. All the experiments used one or another form of intramodality matching. Although the data from the four different loudness studies produced excellent power functions, as shown by the log-log plots (Stevens, 1966b), the differences among the exponents were sometimes large. The unfilled symbols show the measured values of the exponents referred to an assumed value of 0.6 for a tone of 1000 Hz. The filled symbols represent the exponents for vibration referred to an assumed value of 1.0 at 60 Hz. The diamonds are from the intramodality matching experiments, and the stars are from the tracking experiment.

The similarity between the perception of vibration on the fingertip and the perception of low-frequency tones in the ear leads directly to the hypothesis that

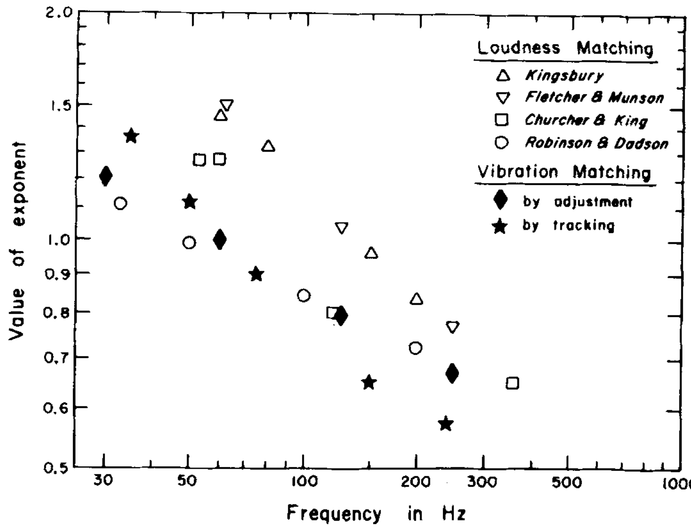

Fig. 6. Effect of frequency on the exponents of the power functions for auditory loudness (unfilled symbols) and tactile vibration (filled symbols). Each symbol represents the measured slope (exponent) of an equal-sensation function.

the two kinds of perception may be mediated by similar sensory processes. For tones up to about 400 Hz and for sound pressure levels up to about 80 dB above threshold, the ear responds to stimulus magnitude much as a vibration sensor. The available data indicate that at a sound pressure level of about 80 dB there is an abrupt transition, above which the exponent resumes the value 0.6, which is characteristic of the standard loudness function. No such transition has been observed with vibration on the fingertip, however. For one thing, vibratory stimuli more than 40 or 50 dB above threshold become impractical, because at large amplitudes the finger does not remain in contact with the vibrator.

Individual Functions

Although it seems well established that perceived intensity of vibration grows as a power function of stimulus amplitude when data are averaged over a group of Os, measures taken on a single O may show systematic, repeatable departures from a power function. Some of the curvatures of the records in Fig. 5, for example, were observed in both repetitions of the tracking procedure. The trackings made by other Os exhibited wobbles that had different, but sometimes quite repeatable, forms. Mostly, however, the wobbles on successive trackings assumed different forms. The paths generated by 14 or more trackings suggest that averaging over Os is an acceptable procedure.

Whether, in his matching functions, a given O exhibits stable departures from the power function can best be established, not by repeating a given procedure over and over, but by testing the implications of the departure by means of other kinds of matching procedures. On the basis of the present studies, the conclusion seems justified that, although individual matching functions obtained with a given procedure often show departures from linearity in log-log coordinates, the departures are relatively small and do not appear to contraindicate the averaging of data to obtain a more representative function.

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Note

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