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journal: STL-QPSR
volume: 10
number: 1
year: 1969
pages: 047-058

http://www.speech.kth.se/qpsr
IV. THE VIBROTACTILE SENSE

A. THE DEPENDENCE OF VIBROTACTILE THRESHOLD AND MAGNITUDE FUNCTIONS ON STIMULATION FREQUENCY AND SIGNAL LEVEL. A perceptual and neural comparison*

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A question of major concern in sensory psychology is the determination of the relationship between a certain physical input and the subjective response of an organism to this input. The method of magnitude estimation (Stevens, 1956, 1962) has proved a suitable technique for a direct assessment of perceived intensity. Stevens (1961) interpreted the form of the magnitude functions as reflecting the operating characteristics of the sensory transducer or, in less restrictive terms, inherent properties of sensory systems (Stevens & Stevens, 1963). Two recent studies in man reported by Borg, Diamant, Ström & Zotterman (1967) and by Franzén & Offenloch (1969) have given ample evidence for a close agreement between numerical scales constructed by direct scaling techniques and neuroelectric responses recorded under identical stimulation conditions. These investigations support the notion of a linear transmission along the perceptual pathway (de Reuck & Knight, 1966) as far as intensity is concerned.

The increasing interest for the mechanoreceptive system, in particular for its ability to transmit information of vibratory sinusoidal signals, is partly due to its exquisite usefulness as a vehicle to approach an understanding of neural mechanisms underlying sensory experience. The present investigation was mainly designed to characterize quantitatively the relation between signal intensity and apparent intensity for various stimulation frequencies.

Intensity functions for 60 cps and 250 cps stimuli delivered to the fingertip have been reported in previous work. The power law (Stevens, 1957) was descriptive of the translation of signal intensity into a perceptual magnitude with an exponent of 0.95 for 60 cps (Stevens, 1959), 0.60 for 250 cps (Stevens, 1960), and 0.56 for 300 cps (Franzén, 1969), - the latter study being germane to the present undertaking. These observations are compatible with those of Goff (1959) who mapped equal-vibness contours for two intensity levels (20 and 35 dB SL) over the range of 25-800 cps.


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(Subjective intensity in arbitrary units was denoted vib by Stevens, 1959. In analogy with loudness the concept of vibness is introduced.) From these curves one would expect the exponent of the power function to be about twice as large at e.g. 50-60 cps as at 200-250 cps. This kind of power transformation is of primary interest and an attempt will be made to correlate the present results with findings made in single-unit peripheral and central neurophysiology in monkey and cat. The subjective detection threshold as a function of stimulation frequency is compared with the neural displacement-frequency curve for sine-wave stimuli applied to the monkey foot. A dual mechanism of mechanoreception will be discussed.

Methods

Stimulation conditions

The signal generating system was manually trigged by a push-button. The rise and decay time of the gate was 10 msec and the constant portion of the pulse envelope lasted for 750 msec. The reference voltage was set to the desired level by means of an attenuator, Hewett-Packard. A mistuned stroboscope, Strobotac type 1531-A, was used to observe the sinusoidal motion of the stimulator through a binocular microscope. Displacement was found to be linearly related to the voltage across the vibrator, Pye-Ling, V-47, for the frequencies 50, 100, 150, 200 and 250 cps employed in the experiment. All amplitudes are specified in microns RMS. The plastic contactor with a diameter of 8 mm was moving perpendicularly to the fleshy pad of the index finger or the index toe. The vibrator was shock-mounted in a nearly soundproof wooden box. At the highest amplitudes, however, a faint hum could be perceived and therefore the subjects wore earmuffs during the whole experiment. The stimulator protruded into a hole of 12 mm and a clearance of 2 mm was thereby obtained. The whole arm supported comfortably on the box covered with rigid foam-rubber and on a table placed at the same level. The contactor was lowered about 2 mm relative to the top of the box coverage to assure a fairly constant position of the finger or toe tips.

Procedure

Two loci were chosen for stimulation: the index finger and index toe. First we will describe the experiments on the index finger tip of the right hand.
Detection threshold for a vibration applied to the finger tip was determined for 50, 100, 150 and 250 cps using a modified form of the method of limits with increments and decrements in 1-dB steps. Zero-signals were inserted at random to test for false alarms. Each subject made 5 threshold determinations per frequency. The subjective threshold gradually decreased with increasing frequency, a well-established observation (Verrillo, 1962).

The method of magnitude estimation with a fixed standard was employed for the construction of the intensity functions. The amplitudes covered a range of 30 dB for 50, 100 and 150 cps. The weakest intensity was about 10-12 dB SL. For 250 cps a larger range was used and the lowest level was about 5-6 dB relative to the threshold determined under liminal stimulation conditions. The step between the five lowest levels was 3 dB, and 6 dB above these levels.

The study on the index toe had its roots in an investigation dealing with the neural discharge from vibration-sensitive receptors in the monkey foot (Lindblom & Lund, 1966). The threshold was determined for 50, 100, 150, 200 and 250 cps. Two frequencies, 50 and 150 cps, were selected for the scaling experiments. Five intensities per frequency were examined with 5 dB between levels. The weakest intensity for 50 cps was about 6 dB SL and for 150 cps about 10-12 dB SL. In all the scaling experiments each subject delivered 6 estimates per stimulus with all stimuli presented in a random order. The standard was so chosen as to be in the middle of the actual range of stimuli and it was inserted once in each block of five trials.

Subjects

Five university students participated in the experiments. They had a training session before the main experiment started. Two of them had some previous experience of direct scaling methods. The data were collected in two sessions on the same day, each lasting about one and a half hour. The subjects had a break every ten minutes with a longer rest between sessions. All five subjects took part in the experiments on the finger; two of them participated in the experiments on the finger as well as those on the toe.
Results

All data will be presented in the form of arithmetic group means.

The magnitude functions

Each estimate is based upon thirty observations. In Fig. IV-A-1 subjective estimates of vibrations applied to the finger are plotted against displacement on log-log coordinates. Straight lines indicate that a power function \( \psi = c \varphi^B \) describes the relation of \( \psi \) to \( \varphi \), where \( \psi \) and \( \varphi \) are the perceptual and physical magnitudes, respectively, and \( c \) and \( B \) are empirical constants. It is interesting to note that the relation for 250 cps is best described by a two-limbed power function with a fairly steep rise at lower signal levels and a slower growth at higher intensities. Disregarding the lower branch of the 250 cps function for a moment it is easily seen that the functions get steeper with decreasing stimulation frequency. The best fitting power functions determined by least squares applied to the log-log plots are as follows:

\[
\begin{align*}
\psi_{50} &= 0.11 \varphi^{0.95} \\
\psi_{100} &= 0.35 \varphi^{0.81} \\
\psi_{150} &= 1.12 \varphi^{0.70} \\
\psi_{250} &= 2.04 \varphi^{0.58}
\end{align*}
\]

Now it turns out that sensation magnitude grows about linearly with stimulus magnitude as indicated by the power function \( \psi = 1.29 \varphi^{0.97} \) fitted to the lowest intensities, an interesting observation that will be dealt with in the subsequent discussion together with the successive decrease in the exponent with increasing frequency of stimulation. The experiments on the toe confirm the previous observations (Fig. IV-A-2). They differ, however, in one respect. The trend of data for each frequency was best described by the general form of the power function, \( \psi = c(\varphi - \alpha)^B \) (Ekman, 1958). This equation was first experimentally verified by Stevens (1959). The constant \( \alpha \) was thought by Ekman to represent a kind of threshold. The best fitting functions are for 50 cps, \( \psi = 0.03 (\varphi - 7.0)^{1.08} \), and for 150 cps, \( \psi = 0.48 (\varphi - 6.5)^{0.72} \).

The dependence of the exponent on carrier frequency as observed in this study and in other studies on the finger are summarized in Fig. IV-A-3. Talbot, Darian-Smith, Kornhuber & Mountcastle (1968) examined the intensity functions for 40 cps and 250 cps and Stevens for
Fig. IV-A-1. Family of magnitude functions for vibratory mechanical stimulation of varying frequency delivered to the finger tip.
Fig. IV-A-2. Magnitude functions for vibratory stimuli applied to the index toe.
Fig. IV-A-3. The psychophysical exponent as a function of frequency of sinusoidal mechanical stimulation applied to the finger tip.
60 cps (1959) and 250 cps (1960). A re-analysis of the data of Talbot et al. for 250 cps suggests a slope of about 0.6 in log-log coordinates which is fully compatible with the present observations and those of Stevens. It may also be mentioned that magnitude estimation of the apparent vibration of a metal rod held between the thumb and the fingers gave rise to a power function with an exponent of 0.83 for a driving frequency of 120 cps (Stevens, 1959). If we now slice the magnitude functions horizontally we would thereby be able to map a family of equal vibness-curves as shown in Fig. IV-A-4. One may question whether these curves really do represent equal-intensity contours as the unit of measurement could have been altered from one experiment to another. When all $\frac{n(n-1)}{2}$ combinations of frequencies are plotted against one another it is found that the prediction of exponents derived from the magnitude-estimation experiments are in close agreement with all pairs of matching functions. The contours in Fig. IV-A-3 are therefore a genuine description of equal vibness for the four frequencies under investigation. They are also very similar to the two curves reported by Goff (1959) with a kind of shift in the descending function at about 100 cps.

Detection threshold

In Fig. IV-A-5 triangles represent the subjective threshold for a vibration applied to the 'index' toe and circles represent the relation between threshold-amplitude and frequency upon sinusoidal stimulation of the glabrous skin of the monkey foot (Lindblom & Lund, 1966) as recorded from single afferent fibers in the dorsal root (L 7). The skin of the human and monkey foot have many characteristics in common and therefore a comparison is of particular interest. The two sets of data exhibit striking similarities. The descending slope is about $-1.40$ which indicates a decrease of about 8 dB per octave. This slope is somewhat less steep than what is reported for the thenar eminence (Verrillo, 1963).

Discussion

The displacement-frequency threshold function as determined by psychological and electrophysiological techniques

Recordings of the response of isolated and undissected Pacinian corpuscles (Sato, 1961) in the mesentery of the cat to sinusoidal mechanical stimulation of various frequencies evidenced that both the threshold-frequency relation and the receptor-potential-frequency relation
Fig. IV-A-4. Equal-vibness contours derived from the magnitude functions in Fig. IV-A-1.
Fig. IV-A-5. Triangles represent the subjective displacement-frequency threshold for a vibration applied to the volar aspect of the index toe. Circles denote the relation between threshold-amplitude and frequency upon sinusoidal stimulation of the glabrous skin of monkey foot as recorded from single afferent fibers in the dorsal root. (From Lindblom & Lund, 1966.)
have their optimal frequencies with respect to sensitivity at 150-200 cps. Since there is no anatomical differences between Pacinian corpuscles in different parts of the body, or in different species either, a comparison with threshold studies on human and monkey glabrous skin is highly opposite. In this connection it should be mentioned that the mechanical impedance of skin tissue is minimal at about the frequencies of greatest sensitivity of the receptor (Sherrick, 1953). The threshold curves in Fig. IV-A-5 are therefore fully comparable with those of earlier studies. However, they differ from Sato's in that they begin a sharp rise at 150 cps, especially the curve for the monkey foot. This discrepancy may be explained by inefficient transmission of high frequencies through the tissues beneath the skin.

A discontinuity in the threshold curve at about 20 cps was observed by von Békésy and was interpreted by him as an indication of the existence of a duplex mechanism of mechanoreception (von Békésy, 1959 a, 1965) in analogy with the break in the sensitivity of the eye found during dark adaptation (Riggs, 1937). Verrillo (1963) reached the same conclusion in his systematic studies on the influence of contactor area on the threshold. It is still puzzling that the point of break is continuously displaced toward the higher frequencies as contactor area is decreased and that the threshold is finally quite flat with contactor areas of 0.005-0.02 cm².

There is now neurophysiological evidence for receptors other than Pacinian corpuscles that are, to some extent, able to transmit vibratory stimuli. These are e.g. the intracutaneous touch receptors in the glabrous skin of monkey (Lindblom & Lund, 1966; Talbot et al., 1968). Their sensitivity maximum is at about 30-40 cps which means that this system may be at work at the lower end of the frequency scale. In the present study, however, no frequencies below 50 cps were explored.

Most investigations demonstrate (Sato, 1961; Hunt, 1961; Lindblom & Lund, 1966; Talbot et al., 1968; Jänig, Schmidt & Zimmermann,1968) that the Pacinian corpuscle is very suited for the mediation of high-frequency vibrations as far as the somatic system is concerned. At least one other receptor, namely the tactile pad receptor in hairy skin can follow high-frequency mechanical stimulation (Lindblom & Tapper, 1967).
Due to interaction between successive signals a drop in 'pitch' with increasing frequency should also be produced. On the basis of the data at hand we might expect the central nervous system to transmit signals up to about 50 cps with a rather high degree of fidelity. Single unit observations on postcentral gyrus of monkey lend some support to this notion. For 60 cps-300 cps the periodicity is not preserved any longer at the cortex and we would expect a successively increasing demultiplication or even disorganization. This phenomenon might be responsible for the observed decrease in the rate of growth of apparent intensity with increasing stimulation frequency. We may therefore assume that the power transformations are a reflection of the transmission capacity of the central nervous system. On the contrary it says very little about the receptor mechanism at work. The fact that the magnitude functions are displaced to the right in the graph (Fig. IV-A-1) is an indirect evidence for a decreasing sensitivity with a decreasing carrier frequency. The observations on the index toe confirm previous findings and do not add any new information in this respect.

Single unit activity in dorsal roots S₂, S₁ and L₇ was recorded in response to repetitive mechanical stimulation impinging upon a tactile pad in hairy skin of the monkey and cat (Lindblom & Tapper, 1967). Vibration frequencies up to at least 400 cps were portrayed with a high degree of precision. In contrast, postsynaptically the frequency of the signal was not preserved at about 50 cps (Tapper & Mann, 1968). Furthermore, neurophysiological recordings of responses in thalamus to electrical stimulation demonstrated that the system failed to follow repetition rates higher than 80 pulses per second (Rose & Mountcastle, 1959).

The process of demultiplication results in less and less recruitment of spikes per cycle which in turn would necessitate a larger increment in intensity for high-frequency functions than for low-frequency ones for the same subjective increment.

As was said, the psychophysical exponent is constant up to 60 cps and then begins to decrease in size above this frequency. It is therefore worthy of notice that frequency jnd, ΔF, (Goff, 1959) is practically constant up to 50 cps and then rises sharply and so does the Weber fraction though somewhat more irregularly. Goff's data demonstrate also that ΔF is very little effected by changes in intensity up to 50 cps as opposed to the great influence of intensity on higher frequencies. It was also
argued by von Békésy (1959 b) that the sensation of 'pitch' on the skin is a function of several variables as frequency, amplitude, locus of stimulation, nerve supply etc. In hearing, on the other side, $\Delta F$ is rather flat up to 2000 cps (Shower & Biddulph, 1931).

Since frequency and intensity are so intimately interrelated, at least above 50 cps, vibratory 'pitch' might therefore not be expected to behave as a metathetic continuum (Stevens, 1957).

The equal-vibness contours

As in audition (Kingsbury, 1927) the equal-vibness curves get flatter with increasing intensity. From Kingsbury’s curves one would expect the exponent for 100 cps to be about twice as large as that for 1000 cps. Analogous observations have been made by von Békésy (1955). The skin is not uniformly sensitive which is reflected in a decreasing threshold as the locus of stimulation is successively altered from, say, the forearm to the finger tip. It is particularly interesting that the equal-loudness curves for these loci are quite flat at high amplitudes. This circumstance is bound to lead to a steeper intensity function for less sensitive areas than for more sensitive ones.

Physiological studies on the auditory system (Katsuki, Suga & Kanno, 1962) demonstrated a correlation between sensitivity of first-order afferent neurons and the rate of growth of neural firing. The more sensitive the fibers are in terms of SPL, the slower the rate of increase in the neural discharge, a fact that might be interpreted as though the more sensitive fibers operate in a kind of demultiplicative mode as compared with the less sensitive fibers.

The psychophysical function at low signal levels

Despite the fact that the observers reported great difficulties in estimating the apparent intensity of stimuli at low signal levels, their performance shows great consistency as far as this can be judged from the fit to the data. A recent study of Ekman & Gustafsson (1968) was amenable to the same comments. The slope is 0.97 which means that subjective intensity is nearly linearly related to the physical input over this range of intensities. Beyond the point of transition the slope of the power function is 0.58. In their study on the visual system, Ekman & Gustafsson (1968) observed that the data approximated to a linear trend at weak intensities.
and that an abrupt shift then occurred to the cube-root power law that is usually well descriptive of the brightness function. It should be said at once that the general form of the power function would do well if only one or two levels were examined below the point of transition as was the case for the data on the toe. But as more points were collected below the break, a rectification of the function by introducing an additive constant appeared a less attractive solution.

It is far from certain that the shift from one function to another is so abrupt as indicated by the present data, since magnitude estimates are usually subject to considerable variability. Moreover, the linear trend has been observed only once before (Ekman & Gustafsson, 1968) and in a different sense modality.

Now, how does this sort of power transformation come about? It is well known that the nervous system is continuously operating against its own noisy background.

Masking experiments in audition suggest a straight-forward analogy (for an illustrative discussion of power transformations, see Stevens, 1966). The exponent of the masked function may sometimes turn out to be several times as large as the slope of the magnitude function in quiet. At the point of equal intensity of the masker and the 'maskee', the loudness function for the masked signal is transformed into its 'normal' and slower rate of increase. If this analogy holds, the point of transition of the double-limbed power function of the present study would then indicate that the internal noise and the external signal are of perceptually equal strength. It goes without saying that we enter here the realm of speculations, though instructive and stimulating.

More investigations by means of direct scaling methods are encouraged to establish the operating characteristics of sensory systems in the vicinity of their thresholds.

The present study was in part supported by research grants from the Swedish Council for Social Science Research.

Part of the experiments was carried out in the Department of Speech Communication, KTH, Stockholm. References, see next page
References:


