Electrocutaneous stimulation: Psychometric functions and temporal integration[1]

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Psychometric functions and psychophysical strength-duration curves were obtained with rectangular electrocutaneous pulses. The slopes of the psychometric functions were much steeper than corresponding functions in other modalities, with the standard deviation of the distribution only about 0.08 times the threshold. Precise monitoring of stimulus current showed that physiological rather than physical variability was involved. Psychophysical strength-duration curves support the contention that large A-fibers are directly stimulated. Data from this study, as well as from comparable I × t experiments in other senses, are well-fit throughout the range of durations by rectangular hyperbolas. The period over which complete temporal summation occurs is only about 0.5 msec.

Electrical stimulation of the skin has been used by psychophysicists since the late 19th century. This form of cutaneous activation has become increasingly popular as equipment has improved, but our knowledge of the mechanism of stimulation is still incomplete. Grundfest (1959) has presented evidence to suggest that electrocutaneous stimuli probably bypass the specialized receptors and directly excite the afferent axons. This view leads to two important expectations about psychophysical observations with rectangular electrocutaneous pulses. First, the slope of the psychometric function obtained by the method of constant stimuli should be very steep. Pecher (1936, 1939) and Verveen (1960) found that the probability of firing single axons in frog sciatic nerve went from zero to unity as the amplitude of stimulating pulses varied by 1 or 2% of threshold. If percutaneous electrical pulses need to excite a small number of axons for detection, then the resulting psychometric function should climb rapidly. Only Schmid (1961) and Green (1962) have determined psychometric functions with electrocutaneous stimulation, and their experiments were not aimed at studying the detection process for stimuli of low intensity. The few data obtained by Green and from my preliminary experiments, however, confirm the prediction. Indeed, the results suggest that all of the variance of the psychometric function could reflect a relatively small variability in the output of the stimulating system. This argument is clearly similar to the physical quantum theory of vision. The preliminary data had been obtained with oscilloscopic calibration, which is accurate to only a few per cent. Accordingly, Experiment 1 obtained psychometric functions while a special electronic system monitored stimulating current to at least 0.3% accuracy.

The second prediction from the thesis that electrocutaneous pulses directly excite the afferent nerves is that psychophysical strength-duration curves, which show how threshold varies with pulse width, should resemble the physiological strength-duration curves for mammalian A-fibers which innervate the skin. Electrocutaneous stimuli should fire the larger and, thus, more excitable A-fibers first. Hahn (1958) and Uttal (1958) have obtained such psychophysical curves. Hahn's data, however, do not go below 0.1-msec duration, where the strength-duration curve should be steepest. Furthermore, he used pulses of different frequencies rather than single rectangular pulses. Uttal did not use constant-current stimulation but corrected his data to compensate for selective filtering of various frequency components by the skin. Through this indirect method, he found reciprocity below 0.1 msec. Since no direct, complete examination of the relation of intensity and duration for electrocutaneous pulses of very brief duration is available, Experiment 2 obtained the necessary data.

EXPERIMENT 1

Apparatus

Stimulating equipment. The electrical stimuli were presented to the O through Grass silver electrodes, 8 mm in diam, filled with Grass electrode cream and applied over the left volar forearm in the region of the ulnar nerve. The center-to-center distance of the electrodes was about 2.5 cm. The O washed his arm prior to attachment of electrodes. A constant-current stimulation system was used, with the more proximal electrode connected to the cathode of a floating pentode unit gated by an Argonaut LIT-069 isolation transformer. Current was controlled by adjusting a variable resistor in the constant-current circuit. Tektronix Series 160 waveform and pulse generators controlled the duration of the rectangular pulse and the interval between pulses. A cathode ray oscilloscope constantly monitored the stimulus to ensure that the pulse was being presented. The output of the stimulator was determined on each trial by measuring the voltage drop across a precision resistor (1006 ohms) in series with the O. A system consisting of a sample-and-hold amplifier (Philbrick SPT & H) followed by a digital voltmeter (Hewlett-Packard Model 3440A with Model 3443A High Gain/Auto Range Unit) recorded the voltage. The amplitude during the stimulus pulse was "sampled" by the sample-and-hold amplifier, which was triggered during the plateau of the pulse. The amplifier "held" the voltage until the digital voltmeter could determine the value.

Calibrations. The Tektronix timing equipment was calibrated regularly on the oscilloscope to maintain correct pulse durations. A Ballantine Precision calibrator was used to calibrate the sample-and-hold amplifier, and the digital voltmeter was calibrated with a Muirhead Miniature Standard Cell (Model D-698A) and with a Hewlett-Packard Model 741A ac-dc Differential Voltmeter/dc Standard. The accuracy of the sample-and-hold system with the digital voltmeter was at least 0.3%, an order of magnitude better than the accuracy of an oscilloscope.

Stimulus indicators. The O rested his arm on a foam rubber pad. A pulse from a waveform generator closed a relay which turned on a red neon warning light for 1 sec and the electrocutaneous stimulus coincided with the offset of the light. Since the make and break of the relay produced audible clicks, the O could employ both visual and auditory warning cues. The E operated a two-position silent switch on some trials to prevent delivery of the pulse, although the warning signal still occurred. A large partition between the O and the E kept the former from observing experimental manipulations.

Subjects

The Os were three paid undergraduate students (two male

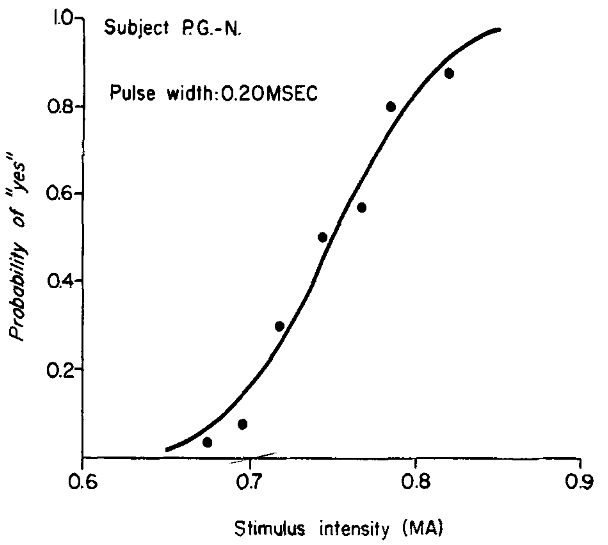

Fig. 1. Typical psychometric function.

and one female) who received extensive practice in psychophysical tasks.

Procedure

Preliminary exploration by the method of limits determined the approximate threshold. The E selected three intensities, each separated by 0.03 to 0.05 mA, above and below this value, yielding seven points spanning a range of 0.18 to 0.30 mA. An eighth setting of 0.0 mA was added to give an indicator of the false alarm rate. The order of presentation of currents was selected from a random number table; consequently, the number of trials at each setting was not exactly the same in each session. The usual session consisted of about 348 trials, with an average of 44 trials at each setting. Each S had 8 to 10 sessions. Pulse widths of 0.12 and 0.20 msec were employed, with four or five sessions at each. If O moved his arm during a session and shifted the threshold, E terminated the session and discarded the data.

Results

The data from the three Os were summarized as psychometric functions. Each session with each O was separately analyzed. The digital measuring system gave the currents presented on each trial, which allowed the data to be regrouped by using measured rather than ostensible current as the independent variable. In most sessions no regrouping was necessary. A few showed a slight amount of overlap between measured currents at adjacent nominal settings. Seven equal intervals of measured currents were used for each psychometric function; the median current value within an interval represented that interval. Figure 1 shows a typical function.

Each psychometric function underwent probit analysis (Finney, 1947) on an IBM 7040 digital computer. The program (UCLA Biomedical Program BMD-03S) yielded the parameters of the best fitting line, estimates of the mean and standard deviation of the underlying Gaussian function, and a chi square value to test goodness of fit. Tables 1 and 2 present the important values for the two pulse durations with no corrections for false alarms. They also show the false alarm rates. When the traditional correction was applied, some of the functions became slightly steeper. However, there was no consistent relationship between the magnitude of the false alarm rate and the steepness of the psychometric functions. Also, the standard deviations of the curves were not significantly different for the two pulse durations, a finding in agreement with Verveen's physiological results.

The chi square test examined the goodness of fit of the observed data points to a straight line in probit coordinates (which corresponds to a cumulative normal function in linear coordinates). Of the 23 probit functions, 10 had χ^2s which exceeded a conservative 0.10 level of significance. Six of these sets of data showed a severe displacement in the distribution of intensities. The current settings did not fall evenly over the range of the psychometric function, so that four or five of the seven stimuli were almost always detected or almost never detected. Very large or very small expected values of correct detections make unduly high contributions to the value of χ^2, exaggerating the significance of the total (Finney, 1947). Therefore, little importance attaches to the finding that some functions seem to differ from the cumulative normal function.

EXPERIMENT 2

For the purpose of obtaining psychophysical strength-duration curves, apparatus was the same as in Experiment 1. One female and one male served as Os.

Procedure

Thresholds were obtained by a two-alternative forced-choice staircase procedure (Cornsweet, 1962; Levitt, 1964; Wetherill & Levitt, 1965) for 15 pulse durations: 0.02-0.10 msec in 0.01-msec steps; 0.20-1.0 msec in 0.2-msec steps; and 3.0 msec. Each O participated in five sessions. Six or seven pulse durations were studied in random order in each session. Thresholds for every duration except 1.0 msec were determined on two occasions. The pulse duration of 1.0 msec was selected as a standard setting for every session.

A stimulus occurred after either one of two successive

Table 1
Results of Probit Analysis for Psychometric Functions, Pulse Width = 0.12 msec.

S	Session	Number of trials	False alarm rate	Mean (mA)	SD (mA)	χ^2	Mean/SD
CB	1	349	0.02	1.45	0.12	3.37	0.08
	2	348	0.05	0.85	0.17	6.54	0.20
	3	349	0.02	1.06	0.13	13.61*	0.12
	4	348	0.19	0.89	0.09	4.78	0.10
PG-N	1	348	0.19	2.08	0.19	43.06*	0.09
	2	348	0.00	1.19	0.05	9.05	0.04
	3	348	0.12	0.74	0.04	3.22	0.05
MB	1	290	0.08	0.94	0.07	3.21	0.07
	2	289	0.05	1.17	0.06	10.77*	0.05
	3	349	0.07	1.08	0.11	32.97*	0.10
	4	348	0.05	1.13	0.10	3.75	0.09

** significant χ^2 ($p \leqslant 0.10$)*

Table 2
Results of Probit Analysis for Psychometric Functions, Pulse Width = 0.20 msec.

S	Session	Number of trials	False alarm rate	Mean (mA)	SD (mA)	χ^2	Mean/SD
CB	1	347	0.00	0.91	0.16	17.97*	0.18
	2	342	0.00	1.11	0.08	8.09	0.07
	3	175	0.32	0.81	0.25	6.68	0.31
	4	343	0.05	0.93	0.18	6.81	0.19
PG-N	1	170	0.06	0.75	0.05	1.61	0.07
	2	81	0.00	1.11	0.06	6.85	0.05
	3	348	0.00	1.02	0.05	11.91*	0.05
	4	348	0.00	1.13	0.04	6.28	0.04
MB	1	259	0.03	0.72	0.04	14.41*	0.06
	2	322	0.16	0.71	0.06	41.75*	0.08
	3	326	0.07	0.69	0.07	39.32*	0.10
	4	319	0.08	0.80	0.06	24.14*	0.08

* *significant* χ^2 $(p \leqslant 0.10)$

warning lights, and the O had to indicate which light preceded the signal. Each warning light lasted 1 sec; 1 sec separated the offset of the first light from the onset of the second. If the O was correct, stimulus level was unchanged and then lowered after a second correct choice. If O was incorrect, intensity was raised one step. Step sizes of about 0.05 mA were used. Averaging the reversal points yielded a value which corresponds to the threshold for detecting a single stimulus with a probability of 0.71 in the two-alternative task, since the probability of detecting two successively was 0.50. The first two reversals were not included in the averages. Between 11 and 15 reversals contributed to the threshold for each pulse width.

Results

Figure 2 shows the strength-duration functions for the two Ss on linear coordinates. The ordinate is threshold as a multiple of the threshold for a 1.0-msec pulse in the same session. The points in Fig. 2 seem to lie on rectangular hyperbolas. The horizontal and vertical asymptotes were visually estimated and an approximation of the constant k of the equation $(t - a)(I - b) = k$ was calculated. The constant b is the rheobase while a represents the shortest pulse that is capable of exciting nerve. Figure 2 includes the theoretical curves. The equations of the hyperbolas with the abscissas expressed in milliseconds and the ordinates as a multiple of the threshold for a 1.0-msec pulse are: S CB, $(I - 0.8)(t - 0.001) = 0.30$; S SS, $(I - 0.6)(t - 0.001) = 0.40$.

The vertical asymptote, a, is difficult to estimate and might differ by as much as an order of magnitude, but the shape of the hyperbolas would be similar. A hyperbola is not the only function that describes the experimental points. Among others are: $(I - b)t^n = c$; $I = b/[1 - e^{-(t/d)}]$; and $I = g - [(t - h)/mt]$ where b is the rheobase, c, d, m, and n are constants, e is the base of natural logarithms, and g is the threshold value at the briefest pulse duration, h.

DISCUSSION

The typical electrocutaneous psychometric function displayed in Fig. 1 differs strikingly from similar curves from visual or auditory studies. Although their shapes are similar, the electrocutaneous function covers a much smaller range of stimulus magnitude. The threshold in this function is 0.75 mA and the detection rate changes from 0% at about 0.65 mA to 100% at about 0.85 mA. Thus the threshold value plus or

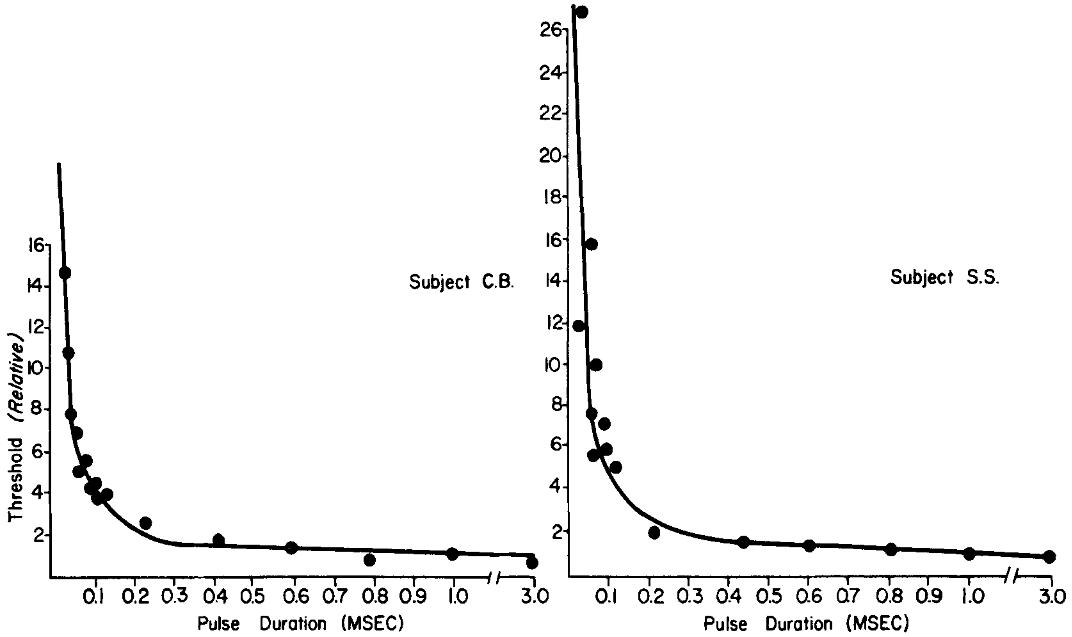

Fig. 2. Psychophysical strength-duration functions. The ordinate is the mean threshold expressed as a multiple of the threshold for a 1.0-msec pulse obtained in the same session.

minus about 0.10 mA spans the entire range. One standard deviation is 0.05 mA or about 0.07 times the threshold. The values for this ratio obtained in the present experiment range from 0.04 to 0.31, with a median of 0.08. In marked contrast, some typical visual functions yield a ratio of standard deviation to threshold of 0.30 (Heinz & Lippay, 1928), 0.311 to 0.539 (Blackwell, 1963), 0.42 (Hecht, Shlaer, & Pirenne, 1942), and 0.58 (Bouman & van der Velden, 1947). A two-alternative forced-choice study by Green (1960) yields a ratio of 0.70 or more for auditory detection.

Correction of data for measured current intensities effectively eliminates physical inconstancy of the stimulus as a source of this small variance in the psychometric function. Other sources of variability thus must operate in the detection process for low intensity electrocutaneous stimuli. Pecher's (1936, 1939) and Verveen's (1960) electrophysiological experiments indicate that changes in the sensitivity of peripheral nerve fibers can produce some variability. The ratio of standard deviation to threshold for a single impulse was about 0.01 to 0.02, which is less than the 0.08 obtained in the present experiment. Other possible sources of variability are changes in the distribution of subcutaneous tissue impedances or in responses of subcortical and cortical centers. No information exists on these factors.

In any event, the somatosensory system displays a remarkable sensitivity to slight alterations in the amplitude of an electrocutaneous stimulus. Considerably larger changes in visual or auditory stimuli are required to produce equal changes in detectability. The more shallow functions found in other modalities may result in part from the practice of Es to pool the data of several sessions, but curves obtained in single sessions are also considerably less steep than those reported here. A possible explanation of this difference goes back to the initial thesis that electrical pulses directly stimulate peripheral nerve, whereas "natural" or "adequate" signals impinge on receptors. Jones, Stevens, and Lurie (1940) placed electrodes in the middle ear cavity of patients lacking tympanic membranes and compared stimulation of nerve with natural stimulation of receptors in the other ear by a loudness-matching technique. The slope of the function of loudness against voltage was four times as steep with electrical as with acoustic stimulation. Exponents of cutaneous power functions derived by magnitude estimation go in a similar direction. Electrocutaneous stimulation gives exponents from 0.9 (Rosner & Goff, 1967) through 2.7 (Sternbach & Tursky, 1964) to 3.5 (Stevens, 1961). Other modes of cutaneous stimulation yield generally lower exponents of 0.6 to 1.2 for vibration and 1.1 for pressure (Stevens, 1961, 1968).

Strength-duration curves also indicate that electrocutaneous stimuli directly excite sensory fibers. The psychophysical functions in Fig. 2 closely resemble those obtained electrophysiologically by measuring currents required to initiate an action potential in peripheral nerve fibers. They are also very similar to those which Uttal (1958) obtained indirectly. The values of chronaxie for the two Ss from Fig. 2 are 0.25 and 0.35 msec, which correspond to values for large A-fibers. Chronaxie is not an absolute index of nerve excitability since it varies with such factors as kind of electrode (Brazier, 1958), but it does serve to indicate the type of nerve fiber excited.

Strength-duration data from experiments with visual flashes often appear as plots of log (I x t) against log t. The data points follow a positively accelerated course. Replotting the results of Fig. 2 in this way yields the same effect. Experimenters often try to fit two straight lines to such plots, intersecting at a "critical duration." The critical duration supposedly is the limit of the period of complete temporal summation, where I x t is constant, and above which threshold is independent of duration. The visual data and those of Fig. 2, however, deviate systematically above the two lines in the region of the critical duration, a finding which some interpret as indicating a period of partial summation. Furthermore, Kahneman (1966) has pointed out that the visual "critical duration" varies with the conditions of the experiment. The alternative approach of describing strength-duration data by a hyperbola, $(I - b)(t - a) = k$, gives a better fit to the results of this experiment and of such visual studies of temporal integration as Kam's (1936). As noted previously, other functions also fit better than the traditional one. Garner and Miller (1947) applied the equation $(I - b)t^n = c$ to describe the results of auditory temporal integration. This function is obviously close to a hyperbola, especially as n approaches unity as it did both in the auditory case and in the present study. Both functions predict receprocity for brief durations and constant threshold for long ones, but additionally they are able to fit intermediate points.

Whatever function is fitted to strength-duration data, the time over which summation occurs varies with modality and type of stimulus. Complete summation ends at about 0.5 msec for the data of Fig. 2. Over this range, the finding that threshold current varies inversely with duration indicates that the nerve is responding to stimuli of equal charge (coulombs). The duration at which the reciprocity of intensity and duration ceases for visual flashes is about 100 msec. For auditory sinusoids, complete integration occurs up to about 200 msec or beyond (Garner & Miller, 1947; Zwislocki, 1960) and similar values are reported for vibrotactile bursts (Verrillo, 1965) and for trains of electrical pulses (Gibson, 1967). The only form of stimulation which yields figures not very much larger than those reported here is transient tactile displacement (Hill, 1967). However, the limits on temporal integration for simple detection with most types of sensory activation are at least 200 times as long as when single electrocutaneous pulses are employed.

The mechanisms of temporal integration in different modalities may depend at least partly on peripheral factors. For example, visual physiologists have found temporal summation in studies of optic nerve discharges in Limulus (Hartline, 1934) and cats (Zacks, 1966). The results of the present study, moreover, suggest that the limits on temporal integration for single percutaneous electrical pulses are entirely peripheral. Further experiments are needed to delimit the contributions of central and peripheral mechanisms when natural stimulation of other modalities is employed and when the presentations consist of repetitive trains instead of single pulses.

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NOTES

1. This report is based on a portion of a dissertation submitted to the University of Pennsylvania in partial fulfillment of the requirements for the Ph.D. degree. The author is deeply indebted to Burton S. Rosner for his advice and criticism throughout the study and to Jacob Nachmias for his guidance. The research was supported by United States Public Health Service Grant MH-10848 from the National Institute of Mental Health to Burton S. Rosner.

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(Accepted for publication November 1, 1968.)