Electrocutaneous psychophysical input-output functions and temporal integration

HARVEY BABKOFF

Bar-Ilan University, Ramat Gan, Israel

Electrocutaneous magnitude estimation functions were generated by stimuli ranging from 1.0 to 5.0 mA and from 100 to 6,400 msec in duration. The results indicate that when these functions are fitted by a two-parameter power function ($ME = aI^b$), the values of the constant, a , and the exponent, b , are altered by increases in stimulus duration, with a increasing and b decreasing. The exponent decreases from around 1.4 to 0.93 as duration increases from 100 to 6,400 μ sec. Equal magnitude estimation contours drawn for estimates ranging from "2" to "50" can be fitted by an equation representing partial integration, $I \times t^a = K$. The exponent a decreases as a function of the level of the magnitude estimation, indicating less partial integration at higher than at lower levels of estimated magnitude. The electrocutaneous data are compared to data in other sensory modalities.

Although the empirically derived psychophysical power law has been applied to magnitude estimation data in all sensory modalities, its application to electrocutaneous stimuli has been less successful.

Two major problems are encountered in an attempt to apply the power law to electrocutaneous data. One problem has been the justification for the use of the power law and the superiority of this equation over others in describing electrocutaneous input-output functions (Babkoff, 1976; McCallum & Goldberg, 1975). A second problem has been to determine the value of the exponent. S. S. Stevens, Carton, and Schickman (1958) reported exponents of 3.5, while later researchers reported exponents ranging from 1.6 to 2.7 (Sternbach & Tursky, 1964) and even as low as 0.7 if the data are corrected for threshold (Beck & Rosner, 1968). Bujas, Szabo, Kovacic, and Rohacek (1975) have reported exponents of 3.42 using a stimulation technique very similar to the one originally used by S. S. Stevens. Cross, Tursky, and Lodge (1975) recently presented a revised estimate of 2.26 as the value of the exponent. Rosner and Goff (1967) had suggested using double-limbed functions to fit electrocutaneous estimation data, but in a later paper (Beck & Rosner, 1968) this suggestion was withdrawn in favor of a correction for threshold. Rollman (1974) argued for the use of power functions uncorrected for threshold, since they represent the subjective impressions of the observer better and yield more information regarding the use of electrocutaneous stimuli in a somatosensory communications system. It has never been clarified what the stimulus parameters leading to such diverse estimates

of the exponent are, although it is possible that density of innervation and spatial configuration of the stimulus are important factors, as suggested by Babkoff, Bergman, and Brandeis (1974) with regard to threshold psychometric functions.

Stimulus parameters other than intensity also affect the exponent—for example, the number of electrocutaneous pulses in a stimulus train (Rollman, Note 1). As regards a single pulse, Beck and Rosner (1968) concluded that pulse duration was ineffective in altering the exponent. This would imply that electrocutaneous magnitude estimation functions are more similar to those generated by auditory stimuli than to those generated by visual stimuli (J. C. Stevens & Hall, 1966). The data of Beck and Rosner, however, were not analyzed in terms of the current-duration relationship necessary to obtain fixed levels of suprathreshold magnitude estimations, although those authors did present such data for threshold determinations.

Rollman (Note 1) reported an experiment in which the intensity of an electrocutaneous pulse of varying duration was matched to a 55-dB SL tone. These data were plotted in terms of the current-duration relationships for this match, and generate a function that is parallel to the threshold I - t function. This led Rollman (1974, Note 1) to conclude that the shape of the integration function and the critical duration for the suprathreshold electrocutaneous stimuli are the same as they are for threshold stimuli. However, since a systematic study of the electrocutaneous I - t relationship at various levels has not yet been performed, such evidence is not sufficient to warrant such a general conclusion.

In a previous publication (Babkoff, Brandeis, & Bergman, 1975), we presented evidence for partial temporal integration (time-intensity reciprocity) for a

This research and the preparation of this paper were supported by the Bar-Ilan Research Committee. The author would like to acknowledge the aid of B. Ben-Moshe.

threshold response to electrocutaneous stimuli ranging in duration from 175 to 610 μ sec. The data were found to be described best by the equation $I \times t^a = K$, where a is approximately 0.57. This equation and exponent were also found to fit electrocutaneous threshold summation data reported previously by Rollman (Note 1). Thus, as regards the threshold of electrocutaneous stimuli, there is partial integration of pulse durations ranging from 100 μ sec to approximately 2.0 msec.

This short review seems to point to the need of a systematic experiment designed to study the effects of the two stimulus parameters, pulse current and duration, on the estimated magnitude of electrocutaneous stimuli over a broad energy range. The present experiment was undertaken to fill that need.

METHOD

A pair of concentric platinum electrodes were constructed to fit into a plastic case which was strapped over the underside of the wrist in the vicinity of the ulnar nerve. The diameter of the inner electrode was 0.49 cm and was separated from the outer electrode by a radius of 0.525 cm. The diameter of the two electrodes, including the plastic ring separating them, was 2.065 cm.

A constant-current stimulator (local design), powered by a Heathkit Model IP-17 regulated H.V. power supply operated at 200 V, delivered square-wave pulses ranging from 100 μ A to 5 mA.¹ Pulse duration and the timing of a sequence within a trial were controlled by locally designed timing and logic circuits. Pulse shape, duration, and current were calibrated with a Tektronix P6042 current probe in series with a Tektronix Type 454A oscilloscope. Stimulus durations were calibrated by a Monsanto Type 120A electronic counter and were found to be accurate to within 0.1%.

The subject was seated, in an armchair facing a warning light, with the electrode strapped to the underside of his left wrist. The subject was instructed to respond by assigning a number reflecting the perceived magnitude of the stimulus. If 1 sec elapsed after a stimulus was presented without a response occurring, the trial was terminated and a miss was recorded. A trial sequence consisted of a warning light indicating trial onset, followed by a pulse to the electrodes after a foreperiod of 0.65, 1.30 or 1.95 sec. A stimulus was presented on every trial; no "blank" trials occurred. Pulse intensities and durations were randomized by trial. Foreperiods were also randomized by trial, independently of the pulse parameters. Because foreperiods were randomized, greater effort on the part of the subjects was required, thereby aiding in the maintenance of a high attention level throughout the session. Intertrial intervals were approximately 20 sec. The subject was given two short rest periods, evenly spaced over the session.

All subjects were practiced without feedback for a session prior to data collection.

Recent research has indicated that several nonsensory variables can affect the exponent of the magnitude estimation function. Among these are: regression, i.e., the tendency of the estimate to cluster around some central tendency, e.g., the mean estimate, the overall energy range (Cross et al., 1975; Teghtsoonian, 1973), and the instructions (Robinson, 1976). The possibility that nonsensory variables can alter the exponent is sufficient reason to design a parametric experiment so that subjects are presented with all values of the stimulus combinations during each of the experimental sessions. The effects of nonsensory factors can be distributed equally over all stimulus conditions, thus increasing control

over most contextual and range effects. The value of a counter-balanced magnitude estimation experimental design and its possible preference to a matching design are discussed by Marks (1974).

In this experiment, a group of nine subjects estimated the magnitude of 49 electrocutaneous pulses of current-duration combinations ranging in duration from 100 to 6,400 μ sec and from 1.0 to 5.0 mA. Peak tissue resistance is approximately constant at these current amplitudes (Gibson, 1968).² All current-duration combinations were presented during each session. Data are based on 15 presentations of each stimulus to each subject. Data were gathered during six sessions for each subject.

RESULTS

The median of the 15 magnitude estimations by each subject for each of the 49 stimuli was used as the measure of central tendency for each subject. These data were analyzed by a two-way analysis of variance for repeated measurements for both variables on an IBM 370 computer. The results of this analysis are presented in Table 1. The data indicate stimulus intensity and duration to be significant variables. In addition, significant interaction between these variables indicates that pulse duration affects the growth of perceived magnitude as a function of stimulus intensity.

Further analyses were performed using the average of the median magnitude estimation of the nine subjects. The data were analyzed by fitting three different two-parameter equations (linear, log-linear, and exponential) to the magnitude estimation-intensity functions for each of the seven pulse durations separately by a least squares technique. The analysis provides estimates of the parameters of the equation, a test of the linearity of the data (F), and the amount of variance accounted for by the fitted equation (R^2).

The data could be fitted equally well by either a two-parameter linear equation or a power function (two parameters) which account for 97% of the variance (average of the R^2). A linear-log function accounts for 94% of the variance on the average.

Table 1
Two-Way Analysis of Variance with Repeated Measurements:
Duration and Intensity of Electrocutaneous Pulses

Source*	SS	MS	df	F**
D	39,336.65	6,556.11	6	25.44
I	14,047.97	2,341.33	6	11.02
S	1,001.28	125.16	8	
I by D	5,305.64	147.38	36	6.35
D by S	12,368.53	257.68	48	
I by S	10,197.89	212.46	48	
D by I by S	6,679.10	23.19	288	
Total	88,937.06		440	

*D = duration; I = intensity; S = subjects.

** $p \leq .001$

Table 2
Least-Squares Analysis of Electrocutaneous Input-Output Functions Based on the Equation: $ME = aI^b$

Stimulus Duration†	Intercept (log a)	Slope b	Confidence Limits††	df	F	R ²
100	-3.928	1.299	.45	1,4	32.32*	.89
200	-4.2584	1.464	.13	1,5	493.74**	.99
400	-3.2676	1.25	.11	1,5	510.53**	.99
800	-2.9052	1.195	.11	1,5	420.09**	.99
1,600	-2.3804	1.079	.15	1,5	188.05**	.97
3,200	-2.2385	1.066	.11	1,5	342.92**	.99
6,400	-1.669	.928	.06	1,5	817.10**	.99

* $p \leq .01$

†Stimulus duration in microseconds.

** $p \leq .001$

††95% Confidence limits around slope ($\pm$ number given).

The results of the analysis for the two-parameter power function are shown in Table 2, as the remainder of the analyses are based on this treatment of the data.

These data are presented in Figure 1 as log magnitude estimation on the ordinate as a function of stimulus current on a logarithmic abscissa, with duration as parameter.

Reference to Figure 1 and Table 2 indicates that an increase in stimulus duration from 100 to 6,400 μ sec results in an increase in the intercept and a decrease in the slope (exponent of the power function). This is shown in Figure 2, in which the exponents of the power functions are plotted as a function of stimulus duration on a logarithmic abscissa.

Figure 1. Magnitude estimation in log units is plotted on the ordinate as a function of stimulus intensity (current) in microamps on a logarithmic abscissa. The parameter of the curves is stimulus duration. The position of the curves on the ordinate is ordered according to stimulus duration, such that the lowest curve represents data for the 100- μ sec stimulus, the next curve represents data for the 400- μ sec stimulus, and so on to the uppermost curve, which represents data for the 6,400- μ sec stimulus. See text for full explanation.

Figure 2. The exponent of the magnitude estimation function is plotted on the ordinate as a function of stimulus duration on a logarithmic abscissa.

The data plotted in Figure 1 appear as a convergent family of power functions. One of the properties of a family of convergent power functions is the inverse relationship between the log intercepts of the power functions and their exponents (Stevens, 1974). This is shown in Figure 3, in which the exponents of the power functions are plotted on the ordinate as a function of log intercept on the abscissa.

These data plot linearly with a slope of -0.1852 with a 95% confidence limit of ± 0.03 . A least squares analysis indicates that 96% of the variance is accounted for by the linear component. The implications of the slope of this function are discussed below.

The fitted functions plotted in Figure 1 were used to generate equal electrocutaneous magnitude-estimation contours that relate the required current-duration parameters needed to generate equal magnitude-estimation levels. The fixed magnitude-estimation levels were chosen so as to cover a range from close to threshold to approximately the highest levels of estimation used ("2" to "50").

The equal magnitude estimation contours are plotted in Figure 4 in terms of the log stimulus current as a function of log stimulus duration needed to produce the given magnitude estimate. In addition, the

Figure 3. The exponents of the magnitude estimation-intensity functions are plotted on the ordinate as a function of the intercepts in log units on the abscissa. See text for full explanation.

Figure 4. Equal magnitude estimation contours. Log intensity (microamps) is plotted on the ordinate as a function of log duration (microseconds) on the abscissa. The parameter is the level of the magnitude estimate. Curve A represents the intensity-duration relationships for a threshold response (see text). Curve B represents an estimation level of "2," Curve C represents an estimation level of "5," Curve D represents a level of "10," Curve E represents a level of "20," and Curve F represents a level of "50."

log current-log duration parameters generated in a previously reported experiment on electrocutaneous threshold (Babkoff et al., 1975) are also plotted in Figure 4 for comparison.

The equation representing partial stimulus integration, $I \times t^a = K$, $a < 1$, was fitted to the equal magnitude estimation contours, and the constants of this equation were estimated by the least squares technique (Smillie, Note 2). The results of the analysis are shown in Table 3, which indicates that this equation accounts for 95% to 99% of the variance (R^2).

The analysis indicates that the exponent a decreases from a value of approximately 0.6–0.7 at a low magnitude estimate ("2" or "5") to around 0.4 to 0.25 at a high magnitude estimate ("20" and "50"). This is shown more clearly in Figure 5, in which the value of the exponent is plotted as a function of the level of the estimated magnitude on a logarithmic abscissa. The exponent of the $I \times t^a = K$ equation describing the current-duration parameters for an electrocutaneous threshold response (Babkoff et al., 1975) is also shown in Figure 5 for comparison.

DISCUSSION

In summary, our results indicate that when electrocutaneous magnitude estimation data are fitted by

Table 3
Constants of the Equation $I \times t^a = K$ for Different Levels of Magnitude Estimation

	Intercept (K)	Slope (a)	Confidence Limits†	df	F	R ²
Threshold	4.324	-.586	.078	1,1	217.495*	.99
"2"	4.732	-.69	.09	1,5	240.073**	.98
"5"	4.8604	-.618	.12	1,5	104.446**	.95
"10"	4.6218	-.459	.047	1,4	358.88 **	.99
"20"	4.638	-.377	.04	1,4	313.27 **	.99
"50"	4.593	-.25	.03	1,3	204.60 **	.99

* $p \leq .05$

†95% Confidence limits ($\pm$ number given).

** $p \leq .001$

a two-parameter power function ($ME = at^b$), the values of both the constant a and the exponent b are altered by increasing stimulus duration from 100 to 6,400 μ sec, with a increasing and b decreasing from around 1.4 to 0.93. Equal magnitude estimation contours drawn for estimates ranging from "2" to "50" can be fitted by an equation representing partial stimulus integration, $I \times t^a = K$ (Babkoff et al., 1975). The exponent of this equation decreases as a function of magnitude estimation level, indicating decreased partial integration as a function of increased magnitude level.³ None of the data indicate total integration of stimulus duration over the range of 100 to 6,400 μ sec at any magnitude estimation level from threshold to the highest empirically obtained estimate.

These results are relevant to a discussion of several aspects of electrocutaneous stimulation.

Exponent of the Power Function

The value of the exponent of the electrocutaneous magnitude estimation function is, as noted above, also a controversial subject. The estimates reported in this paper are lower than those reported in the

literature except for the estimates reported by Beck and Rosner after correction for threshold (Cross et al., 1975; Beck & Rosner, 1968; Bujas et al., 1975; Rosner & Goff, 1967; Sternbach & Tursky, 1964; S. S. Stevens et al., 1958). One possible explanation for the lower estimates reported in this study reflects the role of regression and range effects in determining the value of the exponent (Cross et al., 1975). The tendency of subjects to regress toward a mean level would lead to an overestimating of low intensities and to an underestimation of high intensities. As a result, the larger the range of energies to which the subject is exposed, the lower the exponents when using magnitude estimation procedures (Cross et al., 1975; Marks, 1974; Poulton, 1968). As noted by Marks (1974), the results of a scaling experiment in which all stimulus parameters are counterbalanced provide a better measure of sensory-physical relations than a matching experiment in which stimulus parameters are not counterbalanced even when the degree of regression is large. In matching, regression influences the sensory physics, whereas in scaling, regression influences the psychophysical procedure, leaving the sensory physics relatively unaffected (Marks, 1974). In the experiment reported in this paper, subjects were exposed to currents ranging from 1 to 5 mA combined with durations ranging from 100 to 6,400 μ sec, an energy range of 2.51 log units. In contrast, in previously reported experiments on electrocutaneous stimulation in which only a single duration was used (e.g., Cross et al., 1975), the energy range to which subjects were exposed did not exceed 0.7 to 0.8 log units. The experimental design thus may have led to an overall lower estimate of exponents. However, since all of the stimulus parameter combinations were presented within all sessions, regression, if operable, could not differentially influence the effect of duration in reducing the value of the exponent. This reduction is therefore not due to contextual, but rather to stimulus, properties.

Figure 5. Exponent a of the partial integration time-intensity function ($I \times t^a = K$) is plotted on the ordinate as a function of the magnitude estimation level. The exponent of the partial integration function for threshold is shown for comparison. See text for explanation.

Family of Convergent Electrocutaneous Power Functions

The power functions plotted with stimulus duration as parameter appear as a family of convergent

lines. J. C. Stevens (1974) recently examined a series of psychophysical power functions from auditory, visual, proprioceptive, warm, and cold modalities plotted with various parameters, e.g., areal extent, duration, frequency, etc., and noted that they seem to have the property that the members of each family intersect at a common point. Stevens concludes: "In some cases this point corresponds to a very strong stimulus level that approximates the threshold of pain and may be the ceiling level for the modality." Given the results reported in this paper, one can add to such families of convergent power functions, electrocutaneous magnitude estimation functions plotted with stimulus duration as the parameter.

One of the properties of a family of convergent power functions is that the exponents plot as a negative linear function of the intercept of the power function in log units. Such a plot is shown above in Figure 3. Furthermore, J. C. Stevens (1974) proves that the slope of the function relating the exponent of the power function to its intercept in log units can furnish an estimate of the intersection point by taking the antilogarithm of the slope of the line. The slope of the line plotted in Figure 3 is -0.1852 with 95% confidence limits of ± 0.03 . This yields an estimated 668 mA with a range of 610 to 716 mA as the estimated intersection point of conversion for the family of electrocutaneous power functions.

J. C. Stevens (1974) argues that in many cases convergence occurs at the threshold of pain. For the data reported in this paper, however, that does not seem to be the case. The pain threshold for electrocutaneous stimuli is very much lower. Tursky (1974) and Tursky and O'Connell (1972) report average threshold to pain tolerance of 8 to 10 mA for a 1-sec-duration 60-Hz constant current stimulus. This estimate is almost two orders of magnitude lower than the estimated point of convergence for the electrocutaneous data reported in this paper. As noted by J. C. Stevens (1974), although convergence of power functions seems to be a general psychophysical phenomenon when modalities are investigated parametrically, the meaning of convergence remains partly a matter of speculation. This is the case of electrocutaneous power functions.

Electrocutaneous Power Functions and Integration

The exponent of the equation relating magnitude estimation to intensity decreases as stimulus duration increases. Equal magnitude estimation contours can be fitted by the equation, $I \times t^a = K$, the exponent of which decreases as a function of increases in the level of the estimated magnitude.

If these data are compared to the visual and auditory modalities, one notes differences as well as similarities. In contrast to both the visual and audi-

tory modalities, none of the electrocutaneous data indicate total intensity-duration reciprocity. The absolute values of stimulus duration which affect electrocutaneous psychophysical functions differ by a factor of 20 to 50 from those which affect visual and auditory functions (100 to 6,400 μ sec as compared to 2 to 500 msec). On the other hand, with respect to the effect of magnitude estimation level on the extent of integration, the electrocutaneous data are more similar to the visual and quite different from the auditory data.

For visual data, the critical duration decreases from around 100 to 10 msec as a function in increased levels of magnitude estimation (Raab, 1962; S. S. Stevens, 1966a, 1966b; J. C. Stevens & Hall, 1966). In contrast, auditory equal-loudness contours yield equivalent slopes for durations shorter than 150 msec at all levels of magnitude estimation. The extent of complete reciprocity for vision and of the magnitude of the partial integration for electrocutaneous stimulation are reduced as the level of magnitude estimation is raised.

The fact that both visual and electrocutaneous magnitude estimation functions are affected in terms of the extent of possible integration in a similar manner by increases in duration, although the absolute ranges are quite different, makes it unlikely that this aspect of the dynamics is determined by receptor characteristics but rather by more central nervous system mechanisms.

Uttal and Kirsoff (1968) concluded that the code for stimulus quantity is a function of the number of impulses in a single fiber and the number of responding fibers collectively within some critical period of time.

Rollman (Note 1) surmised that at threshold there is an activation of a critical number of nerve fibers. The activity of these fibers does not alter as intensity rises further, that is, they still produce the same number of impulses. What does occur is that with increases in signal strength, more fibers are excited, that is, stimulus intensity is coded in terms of the number of fibers activated. Rollman concluded that the form of the $I \times t$ function will be unaltered at threshold and suprathreshold levels.

Our data indicate that, on the contrary, the extent of integration decreases as the subjectively perceived level of stimulation is increased. Perhaps as current is raised several events occur, an increase in responding fibers as well as an increase in the synchrony of response across fibers. Perhaps the intercept of the $I \times t$ functions represents the maximum intensity for a requisite number of fibers to generate a perceived magnitude, while the slope represents the effective time over which synchrony of firing can produce a fixed effect. The data would then imply that, as perceived magnitude rises, the required synchrony of

responding fibers becomes compressed into smaller units of time.

In conclusion, it appears that input-output psychophysical functions relating magnitude estimation to intensity of electrocutaneous stimuli can be fitted by power functions, the exponents of which decrease as a function of changes in pulse durations from 100 μ sec to 6.4 msec. Equal-magnitude estimation contours drawn for these data indicate that $I \times t$ functions for fixed-level suprathreshold stimuli can be fitted by exponential functions indicating partial integration. The extent of the partial integration, i.e., the value of the exponent a in the equation, $I \times t^a = K$, is inversely related to perceived magnitude of stimulation.

REFERENCE NOTES

1. Rollman, G. B. *Temporal summation of threshold and supra-threshold electrocutaneous pulses*. Paper presented at the Eastern Psychological Association, Boston, Massachusetts, April 1972.
2. Smillie, K. W. *Statpack 2: An APL statistical package* (2nd ed.). University of Alberta, Edmonton, Canada, February 1969.

REFERENCES

- BABKOFF, H. Magnitude estimation of short electrocutaneous pulses. *Psychological Research*, 1976, **39**, 39-49.
- BABKOFF, H., BERGMAN, Y., & BRANDEIS, B. Response probability and response latency to threshold electrocutaneous stimuli. *Perception & Psychophysics*, 1974, **15**, 417-424.
- BABKOFF, H., BRANDEIS, B., & BERGMAN, Y. Partial integration of single electrocutaneous pulses. *Perception & Psychophysics*, 1975, **17**, 285-292.
- BECK, C., & ROSNER, B. S. Magnitude scales and somatic evoked potentials to percutaneous electrical stimulation. *Physiology and Behavior*, 1968, **3**, 947-953.
- BUJAS, E., SZABO, S., KOVACIC, M., & ROHACEK, A. Sensory scales for electrical stimuli in three sense modalities. *Acta Instituti Psychologici*, University of Zagreb, 1975, **75**, 17-23.
- CROSS, D. V., TURSKY, B., & LODGE, M. The role of regression and range effects in determining the power function for electric shock. *Perception & Psychophysics*, 1975, **18**, 9-14.
- GIBSON, R. H. Electrical stimulation of pain and touch. In D. R. Kenshalo (Ed.), *The skin senses*. Springfield, Ill: Thomas, 1968. Pp. 223-261.
- MARKS, L. E. *Sensory processes*. New York: Academic Press, 1974. Pp. 57-58.
- MARKS, L. E., & STEVENS, J. C. Temporal summation related to the nature of the proximal stimulus for warmth. *Perception & Psychophysics*, 1973, **14**, 570-576.
- MCCALLUM, P., & GOLDBERG, H. Magnitude scales for electrocutaneous stimulation. *Perception & Psychophysics*, 1975, **17**, 75-78.
- POULTON, E. C. The new psychophysics: Six models for magnitude estimation. *Psychological Bulletin*, 1968, **69**, 1-19.
- RAAB, D. Magnitude estimation of the brightness of brief foveal stimuli. *Science*, 1962, **135**, 42-43.
- ROBINSON, G. H. Biasing power law exponents by magnitude estimation instructions. *Perception & Psychophysics*, 1976, **19**, 80-84.
- ROLLMAN, G. B. Electrocutaneous stimulation. In F. Geldard (Ed.), *Cutaneous communication systems and devices*. Austin, Tex: The Psychonomic Society, 1974. Pp. 38-51.
- ROSNER, B. S., & GOFF, W. B. Electrical responses of the nervous system and subjective scales of intensity. In W. D. Neff (Ed.), *Contributions to sensory physiology* (Vol. 2). New York: Academic Press, 1967. Pp. 169-221.
- STERNBACH, R. A., & TURSKY, B. On the psychophysical power function in electric shock. *Psychonomic Science*, 1964, **1**, 217-218.
- STEVENS, J. C. Families of converging power functions in psychophysics. In H. R. Moskowitz, B. Scharf, & J. C. Stevens (Eds.), *Sensation and measurement*. Dordrecht, Holland: Reidel, 1974. Pp. 157-165.
- STEVENS, J. C., & HALL, J. W. Brightness and loudness as functions of stimulus duration. *Perception & Psychophysics*, 1966, **1**, 319-327.
- STEVENS, S. S. Matching functions between loudness and ten other continua. *Perception & Psychophysics*, 1966, **1**, 5-8. (a)
- STEVENS, S. S. Duration, luminance and the brightness exponent. *Perception & Psychophysics*, 1966, **1**, 96-100. (b)
- STEVENS, S. S., CARTON, A. S., & SHICKMAN, G. M. A scale of apparent intensity of electric shock. *Journal of Experimental Psychology*, 1958, **56**, 328-334.
- TECHTSOONIAN, R. Range effects in psychophysical scaling and a revision of Stevens' law. *American Journal of Psychology*, 1973, **86**, 3-27.
- TURSKY, B. Physical, physiological and psychological factors that affect pain reaction to electric shock. *Psychophysiology*, 1974, **11**, 95-112.
- TURSKY, B., & O'CONNELL, D. Reliability and interjudgment predictability of subjective judgments of electrocutaneous stimulation. *Psychophysiology*, 1972, **9**, 290-295.
- UTTAL, W. R., & KIROFF, M. Response of the somesthetic system to patterned trains of electrical stimuli. In D. R. Kenshalo (Ed.), *The skin senses*. Springfield, Ill: Thomas, 1968. Pp. 262-303.

NOTES

1. The subject was protected from equipment failure and shocks by an electronic safety-fuse system which would automatically isolate the subject from the electric circuit with the passage of a 10-mA current of 50- μ sec duration.
2. Gibson (1968) reported a series of studies on the electrical properties of tissue, including the development of voltage in hairy and hairless tissue as a function of peak current amplitude and pulse duration. The time constant of voltage growth is an inverse function of current amplitude. The time constant of voltage onset time does not vary with pulse duration. Peak tissue resistance decreases as an approximately exponential function of current amplitude. In a parallel manner, the voltage time constant decreases as a function of peak current. Neither is affected by pulse duration. The voltage rise time constant and the drop in peak resistance of the skin are related to current amplitude as an exponential decay function with an asymptote around 1.0 to 2.0 mA, i.e., no further apparent change is seen with current amplitudes greater than 1.0 to 2.0 mA. The lowest current levels used in this study were 1.0 and 2.0 mA. Therefore, the possible effects of the stimulus levels in this study on altering skin resistance appear to be minimal.
3. The decrease in the exponent of the $I \times t^a = K$ trading relation as a function of increased magnitude level resembles the results reported by Marks and J. C. Stevens (1973) for thermal stimulation. They report that the degree of summation decreases from complete reciprocity at low warmth to square root summation at higher levels. However, further comparison with the thermal sense is difficult, given the complexity of the psychophysical functions presented by Marks and Stevens and the difficulty in interpretation as noted by those authors.

(Received for publication March 11, 1977;
revision accepted November 2, 1977.)