Partial integration of single electrocutaneous pulses

HARVEY BABKOFF, RACHEL BRANDEIS, and YEHUDA BERGMAN

Bar-Ilan University, Ramat-Gan, Israel

Psychometric functions generated by single electrocutaneous stimuli yielded a median coefficient of variation (σ/μ) of 0.23. These data are consistent with other psychometric data recently reported by us which yielded σ/μ ratios of this size. The data are discussed and related to conflicting data reported in the recent literature indicating coefficients of variation for this mode of stimulation which are only 1/3 as large. Evidence is presented for partial temporal summation (time-intensity reciprocity) for electrocutaneous stimuli ranging from 175 to 610 microseconds. The data are best fitted by the equation $I \times t^a = k$, where a is approximately 0.57. This equation and exponent also fit summation data reported by the same authors who report finding steep psychometric functions. Clearly, then, the mechanism responsible for the very limited temporal summation found for electrocutaneous stimulation and the mechanism responsible for very steep psychometric functions are not identical. The discussion also includes speculation regarding possible mechanisms and suggestions for research.

The somatosensory system has been shown to display great sensitivity to small changes in the intensity of threshold electrocutaneous stimuli, whether measured by psychophysical (Babkoff, Bergman, & Brandeis, 1974; Green, 1962; Rollman, 1969a, b) or reaction time techniques (Babkoff, Bergman, & Brandeis, 1974). The extent to which the somatosensory system displays this sensitivity relative to other sensory system is controversial.

Rollman (1969a) has shown psychometric functions generated by electrocutaneous stimuli applied to the skin in the region of the ulnar nerve which display coefficients of variation (the ratio of the standard deviation to the mean threshold current, σ/μ) ranging from 0.04 to 0.31, with a median σ/μ ratio of 0.08. The implication drawn by Rollman is that electrical pulses stimulate peripheral nerves directly, whereas the other forms of cutaneous stimulation act via the receptor system, undergoing receptor transduction prior to nerve conduction.

In contrast, psychometric functions generated by brief tactile pulses applied to the dorsal forearm are one-third shallower than those generated by electrocutaneous stimuli, but are twice as steep as comparable visual or auditory psychometric functions (Rollman, 1973).

In contrast to these findings, we (Babkoff, Bergman, & Brandeis, 1974) observed psychometric functions to electrocutaneous stimuli whose coefficients of variation, although approximately one-half those reported for visual data, were, nevertheless, approximately three times as large as those reported by Rollman.

Another feature of electrocutaneous stimulation which differs from that of other sensory systems seems

to be the extent of temporal summation for threshold stimuli.

Several investigators (Green, Reese, Pegues, & Elliott, 1961; Rollman, 1969a, 1972) have reported very short time constants for the temporal summation of single electrocutaneous stimuli. Rollman (1972) reports the critical duration for electrocutaneous stimuli (i.e., that stimulus duration below which $I \times t = k$ and which $I \times t^a = k$, where $0 \leq a \leq 1$) to be around 100 μ sec, in sharp contrast to other sensory modalities and modes of stimulation for which critical durations of around 100 msec are reported. According to Rollman, this serves as further evidence that electrocutaneous stimuli bypass receptors and excite sensory fibers directly.

The question therefore arose, given the shallower slopes of psychometric functions to electrocutaneous stimuli reported under the conditions of our previous experiment, would the time constant of temporal summation also differ from that reported by investigators who report finding steep psychometric functions?

Because of the importance of Rollman's findings with respect to the role of receptor systems, we reinvestigated the temporal summation of single electrocutaneous stimuli, concentrating on durations for which partial summation is reported (between 100 and 600 μ sec) and used the same conditions and data analysis, which yielded relatively shallow psychometric functions (Babkoff, Bergman, & Brandeis, 1974). This design required the subject to respond as quickly as possible to stimuli of different intensities for three different stimulus durations, thus measuring reaction time by the same response which generated the psychometric functions.

METHOD

The apparatus and design of the concentric platinum electrodes

The authors would like to thank Jacob Gutgold of Bar-Ilan University, who is responsible for the equipment, and the Research Committee of Bar-Ilan University for funding this study.

are described in detail in a previous publication (Babkoff, Bergman, & Brandeis, 1974).

Pulse duration and the timing of a sequence within a trial were controlled by timing and logic circuits. Pulse shape, duration, and current were calibrated with a Tektronix P6042 current probe in series with a Tektronix Type 454A dual beam oscilloscope.

The electrodes were strapped to the underside of the left wrist in the vicinity of the ulnar nerve. The subject's response latency was measured from the presentation of a stimulus to the lift of the index finger of the right hand from a switch by a counter-timer. Reaction time was measured to the nearest 100 μ sec. All durations in the sequence, as well as the reaction time counter, were calibrated by a Monsanto Type 120 A electronic counter and were found to be accurate to within 0.1%.

Subjects were instructed to place the right index finger on the switch as soon as the warning light was lit and to lift it as quickly as possible if they felt anything. If 1 sec elapsed after a stimulus was presented without a response occurring, the trial was terminated and a "no" response (or miss) was recorded. Thus, only "yes" responses and their latencies were recorded. Intensity was randomized by trial. Three foreperiods, also randomized by trial, were used: 0.65, 1.30, and 1.95 sec. A stimulus was presented on every trial; no "blank" trials occurred. The randomized foreperiods allowed the recording of false positives if the subject anticipated the stimulus. Intertrial intervals were approximately 20 sec.¹ Approximately 125 stimuli were presented during each 1-h session. Stimulus durations were randomized over experimental sessions, with the condition that no duration was tested twice in succession.

Four subjects participated in this experiment. Two subjects generated psychometric functions for three different stimulus durations: 175, 350, and 610 μ sec.² Two other subjects generated psychometric functions for 175- μ sec pulses.

Five to seven intensities were used for each stimulus duration. The entire intensity range for each duration did not exceed 600 μ A.

There were an average of 240 presentations of each intensity to the two subjects tested with the 175- μ sec pulse alone. Those subjects tested at three stimulus durations received an average of 120 presentations per intensity. Data were collected over 15 sessions for each subject.

Several initial test periods were devoted to ascertaining the intensity range for each duration necessary to span the psychometric function from 15% to 99% before data were collected. During the period of the experiment, however, it became apparent that for several stimulus durations we had not chosen sufficiently low intensities, and that even the lowest energy stimuli were yielding response frequencies of 40% and higher. This did not affect the results, however, and no attempt was made to alter the experimental design.

RESULTS

Psychometric Functions

The psychophysical data were analyzed by probit analysis (Finney, 1947). The results are presented in Table 1.

The probit analysis (UCLA Biomedical Program BMD-03 S) yields the parameters of the best fitting line, estimates of the mean, the standard deviation of the underlying gaussian distribution, and χ^2 values to test goodness of fit of the data points to a straight line in probit coordinates.

The results indicate that when response frequency is plotted as a function of stimulus current in logarithmic units, five out of eight of the functions can be fitted by the cumulative gaussian distribution as indicated by nonsignificant χ^2 values. The small number of degrees of freedom for some functions

Table 1
Results of Probit Analysis for Psychometric Functions

Duration (μ sec)	Mean (μ) Micro- amp	SD Micro- amp (σ)	σ/μ	df	χ^2
Subject R 175	775	115	.15	(5)	22.69*
Subject E 175	617	154	.25	(5)	4.36
Subject A 175	1210	300	.25	(3)	7.147
350	699	163	.23	(2)	16.16*
610	541	144	.27	(3)	3.98
Subject B 175	860	168	.19	(2)	12.28*
350	623	107	.17	(3)	3.50
610	450	103	.23	(3)	7.79

* $p < .05$

occurred because one or two current levels were detected on 100% of the trials. These points were not included in the analysis. The median coefficient of variation across the different subjects and pulse durations is 0.23. This estimate is based upon data gathered over all the sessions, not on a session-by-session analysis.

This analysis supports the argument that the psychophysical data represent an underlying gaussian distribution when the independent variable is expressed in logarithmic units.³ A further indication of this is seen in Figure 1, in which two psychometric functions are drawn for Subjects R. and E. Each point is based on approximately 240 trials. Both functions

Figure 1. Psychometric functions are drawn for the two subjects, R. and E., stimulated with 175 μ sec pulses. Response frequency is plotted on a normal probability scale as a function of stimulus current on a logarithmic scale.

Figure 2. Threshold current is plotted in logarithmic units on the ordinate as a function of stimulus duration in logarithmic units on the abscissa. In the addition to the data, two theoretical functions are drawn. The upper curve, broken dotted line, represents the expected values based on probability summation hypothesis. The lowest curve, broken line, represents the expected values based on the hypothesis of complete summation, $I \times t = K$. (A) represents data for Subject A, while (B) represents data for Subject B. See text for explanation.

are clearly fitted by straight lines. The two functions differ in placement along the abscissa (mean) and in slope (variance), as reflected in different estimates of σ/μ (see Table 1).

The log current corresponding to 50% response frequency at each duration is taken as a measure of threshold and plotted separately for each subject in Figure 2. A and B, as a function of log stimulus duration.

In addition, two theoretical functions are drawn in Figure 2, one representing a predicted curve based on the probability summation hypothesis, the second representing a predicted curve based on the theory of complete temporal summation.

The probability summation hypothesis posits that the decrease in threshold current as a function of an increase in duration of electrocutaneous stimuli is due to an increase in the probability of reporting one of a series of independent events as the number of these events increases.

This hypothesis was presented by Pirenne (1943) to explain the results of two-pulse binocular data and has been tested in auditory (Zwislocki, 1960) and tactile (Craig, 1968) two-pulse studies. If applied to experiments using single pulses whose duration is increased, this hypothesis assumes that the decrease in threshold occurs as a result of the independent probability summation of detections due to an increasing number of segments (e.g., of 175 μ sec length) of a single pulse as its duration increases. Although the application of this hypothesis to single pulse data is questionable, nevertheless, since it assumes the absence of any physiological summation, it may serve as the null hypothesis, the converse of the hypothesis of physiological summation. For the sake

of argument, we assumed its relevance to the single pulse experiment and compared the experimental data with the predicted hypothetical functions (broken lines) drawn in Figures 2A and 2B. The hypothetical curves appear as negatively decelerating functions of pulse duration. The experimental data indicate a greater decrease in threshold than predicted by the probability summation hypothesis, indicating that the decrease in threshold cannot be due solely to the independent probability summation of detections, due to the increased number of segments of a single pulse.

The third function drawn in Figures 2A and 2B represents an alternative hypothesis, that of complete power summation. This hypothesis posits that up to some limiting duration, threshold current $\times$ duration is constant ($I \times t = k$). Accordingly, log I should decrease with a slope of -1 when plotted as a function of log t . The experimental data, however, indicate that the decrease in threshold current as duration increases is not as large as predicted by this hypothesis. Rather, the equation representing partial integration, $I \times t^a = k$, where $0 \leq a \leq 1$, seems to fit these data.

The data were tested by a least squares technique (Smillie, 1969) and indicate that for the conditions of this experiment, with durations of 175 to 610 μ sec, the linear component accounts for 98% of the variance when log current is plotted as a function of log duration. The slope is -0.64 for Subject A ($F = 49.49$, $p \leq .05$) and -0.52 for Subject B ($F = 232.19$, $p \leq .01$).

Reaction Time

The reaction time (RT) data are presented in

Table 2
Median Reaction Time to Electrocutaneous
Pulses of Three Durations

Intensity Microamp	RT (Msec) Duration		
	175 μ sec	350 μ sec	610 μ sec
Subject A			
500			242
600			227
700		260	232
800		233	241
900		233	226
1000		234	
1100		245	
1200	243		
1400	236		
1600	253		
1800	250		
2000	225		
Subject B			
400			279
500			274
600		288	264
700		280	269
800		269	264
900	231	254	
1000	264	231	
1100	237		
1200	252		
1300	227		

Table 2 for the two subjects tested with three stimulus durations. Although the general trend of the data shows clearly that reaction time decreases as stimulus intensity increases, the data are extremely variable, more so for Subject A than for Subject B. RT, as a function of intensity for a given duration, shows many reversals for Subject A, while for Subject B just one large reversal is found for the 610- μ sec stimulus. For the two subjects, there are eight overlapping conditions, i.e., in which RT is measured for different duration stimuli at the same current level. For six of the eight conditions, RT to the longer duration stimulus is shorter than RT to the shorter duration stimulus, as would be predicted if RT decreases as stimulus duration increases. In general, the RT-intensity functions for the shorter durations are displaced from the RT-intensity functions for the longer durations into the higher intensity regions. But the data are too variable to conclude whether these displacements produce parallel RT-I functions or not.

DISCUSSION

Psychometric Functions

The first comment regarding the data reported in this study and the data reported in a previous study (Babkoff, Bergman, & Brandeis, 1974), using the same methodology, relates to the shapes and slopes of the psychometric functions. Although all of the 19 psychometric functions generated by 10 subjects using different pulse durations (in this and in the previous

study) could be fitted by cumulative normal distributions when response frequency was plotted as a function of log stimulus current,³ the slopes of the functions are much shallower than those reported by Rollman (1969a), thus indicating more variance.

Rollman reports a median coefficient of variation, σ/μ , of 0.08, which is much smaller than the typical visual or auditory psychometric functions, such as 0.311 to 0.539 for vision (Blackwell, 1953, 1963) and 0.70 for auditory detection (Green, 1960). The median σ/μ ratio found for this experiment was 0.23; the median σ/μ found for this and the previous experiment (Babkoff, Bergman, & Brandeis, 1974) based on 19 psychometric functions generated by 10 subjects, was 0.24, lower than the coefficients of variation reported for vision and audition, but nevertheless 2.5 to 3 times as large as that reported by Rollman (1969a). In fact, this is almost exactly the coefficient of variation (0.26) reported by Rollman (1973) for tactile stimulation of the forearm.

There are several possible explanations for the discrepancy between the extreme sharpness of the electrocutaneous psychometric functions reported by Rollman and the relative shallowness of the slopes reported in this study. One possible explanation relates to the mode of stimulation, while a second relates to differences in methodology.

A possible explanation which merits discussion is that of the areal distribution of receptors stimulated, i.e., receptor density.⁴ Békésy (1960, 1967) reported results indicating that the density of innervation, the number of receptors stimulated (i.e., stimulus area), and the areal distribution (i.e., spatial configuration of the stimulus) are related to sensitivity to small changes in intensity for tactile as well as electrocutaneous stimulation, especially in the vicinity of threshold. Although absolute threshold is lowered as the number of stimulated receptors increases, the difference threshold is increased, especially at low intensity levels. This would lead to the prediction that the slope of the psychometric functions for stimuli delivered to densely innervated skin areas would be shallower than for functions determined for stimuli delivered to sparsely innervated skin areas.

The stimuli used by Rollman (1969a, b, 1972) were presented via Grass silver electrodes, 8 mm in diam, with a center-to-center distance of about 2.5 cm. The stimuli used in this study were presented via concentric electrodes; the diameter of the inner electrode was 4.9 mm and was separated from the edge of the outer electrode by 5.25 mm. As the diameter of the two electrodes, including the plastic ring separating them was 2.05 cm, current was spread over an area of at least 3.35 cm². The spatial configuration of stimulation using concentric electrodes of this nature is unclear. It is, therefore, possible that the spatial distribution of stimulation arising from differences in electrode configuration

between the electrodes used by Rollman and those used in this study might be considered a source of the differences found in the slopes of the psychometric functions.

This hypothesis, however, does not seem to be a reasonable means of explaining the differences between Rollman's studies and ours because the absolute threshold measurements reported by Rollman (1973) are nearly identical to those reported in this paper. This is discussed in detail below. If spatial configuration of stimulation were the basis for the differences in slope, reported by Rollman and in this paper, then one might expect different absolute threshold estimates as well. It seems, therefore, reasonable to reject differences in electrode configuration as a source of the difference in slope.

In the previous publication (Babkoff, Bergman, & Brandeis, 1974), we indicated that differences in methodology might also serve as a source of the discrepancy. One possibility which should be considered is that perhaps the constant stimulus method itself is the source of shallow psychometric functions. Studies using both forced choice and constant stimulus methods, however, indicate that this is not the source of differences in steepness of slope. Blackwell (1953) used several procedures, including the constant stimulus method (with 12% catch trials) and a forced-choice procedure. He reports that his subjects were extremely "cautious" and made few false alarms, so that only in rare instances was there "need to correct the raw data." His coefficients of variation for visual data are, therefore, based upon both a constant stimulus method, with conservative subjects yielding almost no false alarms, as well as upon forced-choice data. Rollman's (1973) data on tactile stimulation also indicate that the forced-choice procedure and the constant stimulus method produce the same coefficients of variation. The above-cited literature argues that the forced-choice vs. constant stimulus methods are most likely not the source of the difference in slope across modalities, or between our studies and those of Rollman.⁵

The method used in this study differed from that of other studies in that it was designed to obtain data on response frequency, as well as the subject's reaction time, in contrast to the method used by Rollman, which did not require the subjects to respond as quickly as possible to the stimulus. The reaction times to the threshold stimuli were well within the range of simple reaction times, thus indicating that subjects were, in fact, following instructions. The additional requirement to respond as quickly as possible to a stimulus in the vicinity of threshold may be the source of increased variance, which is reflected as a decrease in slope.

Temporal Summation

Another feature of electrocutaneous stimulation

Figure 3. Threshold current is plotted in logarithmic units on the ordinate as a function of stimulus duration in logarithmic units on the abscissa. Data from Rollman are plotted as filled circles (●), average data of the two subjects of this study are plotted as filled squares (■).

which differs from that of other sensory systems is the extent of time-intensity reciprocity. The threshold intensity (current) of a single electrical pulse applied to the skin in the vicinity of the ulnar nerve is inversely related to its duration (Green et al., 1961; Rollman, 1969a, b, 1972). The period of complete temporal summation, however, is extremely limited relative to other modalities. Rollman (1972) reports a value of critical duration (i.e., the duration below which $I \times t = k$ and above which $I \times t^a = k$) of approximately 100 μsec. Partial summation (i.e., those durations for which $I \times t^a = k$, and $0 \leq a \leq 1.0$) continues up to 1 or 2 msec. In contrast, the estimated critical duration (CD) for vision is around 100 msec (Graham & Margaria, 1935; Rouse, 1952), for audition, for vibrotactile trains of stimuli, and for trains of electrocutaneous stimuli, CD is estimated at around 200 msec (Garner & Miller, 1947; Gibson, 1968; Verillo, 1965; Zwilocki, 1960, 1969).

The results of this study indicate that for single electrocutaneous pulses of durations ranging from 175 to 610 μsec, the data are fitted by an equation representing partial integration, $I \times t^a = k$, with the exponent, a , estimated at 0.52 for one subject and at 0.64 for the other.

The average data of both subjects are plotted in Figure 3 together with the data presented by Rollman for durations extending from 80 μsec to 1 msec. First, the data of this experiment and that of Rollman fall along the same function, indicating not only the same trend (relation between stimulus current and duration) but also very similar thresholds despite different experiments, designs, and equipment.

Second, the data fall along a function with a slope of -0.57 ($F = 265.79$; $df = 1,6$; $p \leq .001$), indicating partial integration over this range of durations. Rollman's data plotted without the data of this study yield a slope of -0.55 . These data and those of Rollman are thus in excellent agreement and indicate partial summation for electrocutaneous stimuli extending over the range of $80 \mu\text{sec}$ to 1 msec , with the linear component (when log intensity is plotted as a function of log duration) accounting for 98% of the variance.

A final answer to the question of whether the equation $I \times t^a = k$ is the appropriate one to fit temporal summation data of this nature or not and a firmer estimate of the exponent await more detailed experimentation. What is important at this stage, however, is that despite the fact that the coefficient of variation reported for the data of this study is from 2 to 3 times the size of that reported by Rollman, and despite the use of different methods, electrodes, and equipment, the estimate of the extent of temporal summation is approximately the same. Clearly, then, the limit on temporal summation for single electrocutaneous pulses reported both in this study and in that of Rollman cannot be due to an especially steep psychometric function. Even when relatively shallow psychometric functions are generated, the estimate of temporal summation for single electrocutaneous stimuli remains the same.

The reaction time data indicated, in general, that the RT-intensity functions for the shorter durations were displaced from the RT-intensity functions for the longer durations into higher intensity regions. However, it is not possible to conclude on the basis of these data whether or not the displacement produced parallel functions. For those conditions in which RT was measured to stimuli of the same intensity but of different durations, in six out of eight cases, the RT to the longer duration was shorter than the RT to the shorter duration. Unfortunately, these RT data were too variable to allow analyses such as those performed for the visual system (Bruder & Kietzman, 1973; Grossberg, 1968; Hildreth, 1973; Kietzman & Gillam, 1972) or for the auditory system (Raab, 1962) designed to test the hypothesis of time-intensity reciprocity for latency data. Consequently, in contrast to the psychophysical data, no conclusions can be drawn from the RT data regarding intensity-time reciprocity for single electrocutaneous pulses.

What mechanisms may be responsible for the estimate of a short time constant for electrocutaneous stimulation? In a purely speculative manner, we suggest that the nature of the stimulus as well as certain features of the receptor (or neural unit) stimulated may contribute to the finding of short time constants.

As an alternative to the simple linear stimulus integration model, Zwislocki (1969) has presented a

detailed mathematical model of temporal summation for auditory threshold and suprathreshold phenomena. Zwislocki assumes that summation operates on neural rather than on stimulus energy and enumerates several variables contributing to the estimate of critical duration: (1) the exponent of the power function relating magnitude estimation (presumably related to integrated neural activity) to stimulus intensity; (2) the extent of adaptation in single neural units; (3) the time constant describing adaptation in single neural units; (4) the extent of statistical equilibration; and (5) the time constant describing statistical equilibration in neural populations. Perhaps the very short time constant found for the temporal summation of electrocutaneous stimulation reflects one or more of the parameters suggested by Zwislocki as contributing to estimates of critical duration, in which this mode of stimulation differs from other modes of stimulation. For example, in contrast to the exponent of the power function describing auditory magnitude estimation, 0.3 (Hellman & Zwislocki, 1961) estimates of the exponents reported for electrocutaneous stimulation when the data is not corrected for threshold extend from 1.0 to 3.5 (Rosner & Goff, 1967; Sternbach & Tursky, 1964; Stevens, 1961).

Zwislocki suggests that the rise time of a stimulus is an important variable in determining the equilibration time constant for auditory stimulation. The sharp rise time in electrical pulses applied to the skin may contribute to a decrease in the equilibration time constant for the cutaneous sense, thus reducing the time over which neural energy can be summated. In this regard, note that in contrast to single electrocutaneous stimuli, trains of electrical pulses do show summation over train-duration lengths of up to 200 msec (Gibson, 1968).

In addition, perhaps the nature of the neural unit stimulated by an electrical pulse limits temporal summation. Similar speculation has been raised regarding the visual system.

Although the reported limit of complete temporal summation for the visual threshold is approximately 100 msec when measured psychophysically as well as by physiological measures at lower neural levels such as the ERG (Babkoff & Sharpless, 1971) and optic tract potentials (Shevelev & Hicks, 1971), physiological recordings at higher neural levels indicate a much more restricted range of durations over which complete temporal summation occurs (Shevelev & Hicks, 1971). Shevelev and Hicks summarize their data on temporal summation at different levels in the visual system of cats as follows: "... the successive intensity duration curves from the retina to the visual cortex show a tendency to gradual transition from the law of complete summation to the Piéron law (from $n = 1.0$ to 0.5), i.e., from $I t = C$ to $I t^n = C$."

Shevelev and Hicks ascribe the apparent limitation on the summation of energy over time at higher levels in the visual nervous system to the greater synchronization of the neural activity found at higher levels. This results mainly from the fact that the percentage of phasic neurons, i.e., rapidly adapting neurons, found in central structures, is greater than the percentage of phasic neurons found in more peripheral structures. Phasic neurons require highly synchronized inputs in order to summate energy over time. They suggest, therefore, that an increase in the synchrony of the initial input may be an important variable for summation in this type of neural element.

Generalizing from the visual data presented by Shevelev and Hicks and from the theoretical considerations of Zwislöcki for auditory temporal summation leads to speculation regarding electrocutaneous stimulation. Perhaps the characteristics of temporal summation for single electrocutaneous pulses derive from (1) stimulation of rapidly adapting neurons at peripheral or receptor levels, and (2) the characteristics of rapidly rising electrical pulses which result in highly synchronized activity even at the periphery.

Since the characteristics of the electrical pulse may be contributing to the greatly truncated temporal summation reported for electrical stimulation, further examination should be made of the extent to which Zwislöcki's theory of auditory summation can predict the effects of various electrocutaneous stimulus manipulations such as, for example, rise time, on the course of temporal summation.

REFERENCES

- BABKOFF, H., BERGMAN, Y., & BRANDEIS, R. Response probability and response latency to threshold electrocutaneous stimuli. *Perception & Psychophysics*, 1974, **15**, 417-424.
- BABKOFF, H., & SHARPLESS, S. K. B-wave recovery: Conditioning pulse parameters. *Annals of Ophthalmology*, 1971, **3**, 467-476.
- BÉKÉSY, G. VON. *Experiments in hearing*. New York: McGraw-Hill, 1960.
- BÉKÉSY, G. VON. *Sensory inhibition*. Princeton: Princeton University Press, 1967.
- BLACKWELL, H. R. Psychophysical thresholds: Experimental studies of methods of measurement. *Bulletin of Engineering Research Institute*, University of Michigan, 1953, **36**, 1-209.
- BLACKWELL, H. R. Neural theories of simple discrimination. *Journal of the Optical Society of America*, 1963, **53**, 129-160.
- BRUDER, G. E., & KIETZMAN, M. L. Visual temporal integration for threshold, signal detectability, and reaction time measures. *Perception & Psychophysics*, 1973, **13**, 293-300.
- CRAIG, J. C. Vibrotactile spatial summation. *Perception & Psychophysics*, 1968, **4**, 351-354.
- FINNEY, D. J. *Probit analysis*. Cambridge: Cambridge University Press, 1947.
- GARNER, W. R., & MILLER, G. A. The masked threshold of pure tones as a function of duration. *Journal of Experimental Psychology*, 1947, **37**, 293-303.
- GIBSON, R. A. Electrical stimulation of pain and touch. In D. R. Kenshalo (Ed.), *The skin senses*. Springfield, Ill: Thomas, 1968. Pp. 223-260.
- GRAHAM, C. H., & MARGARIA, R. Area and the intensity-time relation in the peripheral retina. *American Journal of Physiology*, 1935, **113**, 299-305.
- GREEN, D. H. Psychoacoustics and detection theory. *Journal of the Acoustical Society of America*, 1960, **32**, 1189-1203.
- GREEN, J. B., REESE, C. L., PEGUES, J. J., & ELLIOT, F. A. Ability to distinguish two cutaneous stimuli separated by a brief time interval. *Neurology*, 1961, **11**, 1006-1010.
- GREEN, R. T. The absolute threshold of electric shock. *British Journal of Psychology*, 1962, **53**, 107-115.
- GROSSBERG, M. The latency of response in relation to Bloch's law at threshold. *Perception & Psychophysics*, 1968, **4**, 229-232.
- HELLMAN, R. P., & ZWISLOCKI, J. Some factors affecting the estimation of loudness. *Journal of the Acoustical Society of America*, 1961, **33**, 687-694.
- HILDRETH, J. D. Bloch's law and a temporal integration model for simple reaction time to light. *Perception & Psychophysics*, 1973, **14**, 421-431.
- KIETZMAN, M., & GILLAM, B. Visual temporal integration and simple reaction time. *Perception & Psychophysics*, 1972, **11**, 333-340.
- PIRENNE, M. H. Binocular and unocular threshold of vision. *Nature*, 1943, **152**, 698-699.
- RAAB, D. H. Effect of stimulus-duration on auditory reaction time. *American Journal of Psychology*, 1962, **75**, 298-301.
- ROLLMAN, G. B. Electrocutaneous stimulation: Psychometric functions and temporal integration. *Perception & Psychophysics*, 1969, **5**, 289-293. (a)
- ROLLMAN, G. B. Detection models: Experimental tests with electrocutaneous stimuli. *Perception & Psychophysics*, 1969, **5**, 377-380. (b)
- ROLLMAN, G. B. Temporal summation of threshold and supra-threshold electrocutaneous pulses. *University of Western Ontario Research Bulletin No. 226*, April 1972.
- ROLLMAN, G. B. Tactile stimulation: Psychophysical studies of receptor functions. *Perception & Psychophysics*, 1973, **13**, 81-86.
- ROSNER, B. S. Temporal interaction between electrocutaneous stimuli. *Journal of Experimental Psychology*, 1964, **67**, 191-192.
- ROSNER, B. S., & GOFF, W. R. 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.
- ROUSE, R. O. Color and the intensity-time relation. *Journal of the Optical Society of America*, 1952, **42**, 626-630.
- SHERRICK, C. E., JR. Effects of double simultaneous stimulation of the skin. *American Journal of Psychology*, 1964, **77**, 42-53.
- SHEVELEV, I. A., & HICKS, L. H. Characteristics of temporal summation at different levels in the visual system of the cat. In G. V. Gersuni (Ed.), *Sensory processes at the neuronal and behavioral levels*. New York: Academic Press, 1971. Pp. 57-68.
- SMILLIE, K. W. *Statpack 2: An APL statistical package* (2nd ed.). Edmonton, Canada: University of Alberta, February 1969.
- STERNBACH, R. A., & TURSKY, B. On the psychophysical power function in electric shock. *Psychonomic Science*, 1964, **1**, 217-218.
- STEVENS, S. S. The psychophysics of sensory function. In W. A. Rosenblith (Ed.), *Sensory communication*. Cambridge: M.I.T. Press, 1961. Pp. 1-33.
- VERILLO, R. I. Temporal summation and vibrotactile sensitivity. *Journal of the Acoustical Society of America*, 1965, **37**, 843-846.
- ZWISLOCKI, J. J. Theory of temporal auditory summation. *Journal of the Acoustical Society of America*, 1960, **32**, 1046-1060.
- ZWISLOCKI, J. J. Temporal summation of loudness: An analysis. *Journal of the Acoustical Society of America*, 1969, **46**, 431-441.

NOTES

1. Data on the masking of electrocutaneous stimuli applied to the same skin locus indicate that even for intensities very much higher than the highest intensity used in the studies reported in this paper no residual effect (measured by threshold shift) can be found at interstimulus intervals longer than $\frac{1}{2}$ sec (Rosner, 1964; Sherrick, 1964). An intertrial interval of 20 sec thus seems quite sufficient to eliminate residual stimulus effects.

2. Gibson (1968) measured tissue resistance, the voltage response, to constant current pulses ranging in duration from 0.5 to 50.0 msec. The rise times and peak resistance are inversely related to peak current. However, voltage rise and decay times do not vary with pulse duration over this range. We can, therefore, assume that voltage rise and decay times of the stimuli used in this study did not vary as a function of duration.

3. Seventy percent of the psychometric data plotted as a function of log current generate curves fitted by the cumulative gaussian distribution, while only 50% of these data plotted as a function of current in arithmetic units generate curves fitted by the cumulative gaussian distribution.

4. Rollman (1973) enumerates two other possible sources for the effect of skin type or skin locus on the steepness of tactile psychometric functions, involuntary tremor (finger greater than forearm) and receptor type (differing from one locus to another). These cannot be considered as possible sources of the differences in slope between the psychometric functions reported by Rollman for electrocutaneous stimulation and those reported in this paper, since

both studies involve the same type of stimuli applied to approximately the same skin surface (left volar forearm in the vicinity of the ulnar nerve).

5. The σ/μ ratios reported by Rollman are based on a session-by-session analysis, whereas those reported in this paper are based upon data generated across sessions. The question may be raised, therefore, that perhaps intersession variability is the basis for the relatively large σ/μ ratios reported in this study. At the suggestion of one of the reviewers, the data of each session were reanalyzed separately by probit analysis. The results indicate that the median σ/μ ratio of 48 sessions is 0.18, relative to the 0.23 obtained when the data is combined across sessions, indicating that a small portion of the variance may be due to intersession variability. However, this accounts for a very small portion of the variance, and a σ/μ of 0.18 is still approximately 2.5 times larger than that reported by Rollman. Furthermore, of the 48 σ/μ ratios calculated, 45 were larger than 0.08 (the median σ/μ ratio reported by Rollman). Clearly, then, the difference in data analysis techniques cannot account for the difference between the estimates of σ/μ ratios reported in this study and in that of Rollman. Since the number of trials per intensity per session is small ($N = 24$) relative to the number of trials across sessions ($N = 120$, or 240), the σ/μ estimate based on data combined across sessions may be a more stable estimate than that based upon data from each session.

(Received for publication October 7, 1974;
accepted November 18, 1974.)