Algebraic models for integration of painful and nonpainful electric shocks

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Subjects rated the average intensity of two sequentially presented electric shocks, which were either painful (intensity range from 1 to 4 mA, Experiment 1) or nonpainful (intensity range from .6 to .9 mA). In both experiments, stimuli were presented in a 4 by 4 factorial design to allow tests of algebraic models of the integration process under analysis of variance (Anderson, 1970, 1974). Both sets of data were fit by the equation $R_{ij} = w_1s_1 + w_2s_2$, ($w_1 + w_2 = 1$), where R_{ij} is the rating scale response, s_1 and s_2 the scale values for the first and second stimuli, respectively, and w_1 and w_2 associated weights. When stimuli were painful, $w_1 = w_2$, and when stimuli were nonpainful, $w_1 < w_2$. Subjective scale values as a function of stimulus intensity appear to increase nonlinearly for painful stimuli and linearly for nonpainful stimuli. Some implications of the results for pain research are discussed.

Since the study by Stevens, Carton, and Shickman (1958), a number of investigators have attempted to generate psychophysical functions for responses to electrocutaneous stimulation. In the main, experimenters have used the technique known as magnitude estimation in which subjects are required to give a number in response to changing current (e.g., Babkoff, 1976, 1978; Beck & Rosner, 1968; Cross, Tursky, & Lodge, 1975; McCallum & Goldberg, 1975; Rollman, 1969; Rosner & Goff, 1967; Sternbach & Tursky, 1964). It is commonly argued that the data are best fit by power functions, in simplified form,

$$R = aI^b, \quad (1)$$

where R represents psychological scale values for I shock intensities, b is a rate parameter, and a an arbitrary constant representing choice of units.

Stevens (e.g., 1957) originally argued that the exponent, b , represents rate of sensory transduction for a particular modality, and Cross et al. (1975) have argued that it is therapeutically important to establish the true value of b for various painful stimuli. One might argue, for example, that a decline in the value of the exponent might be associated with the use of some analgesic technique. Unfortunately, the exponent for electric shock has shown considerable variability from study to study. The reported high seems to be 3.50 (Stevens et al., 1958), with a low of .70 (Beck & Rosner, 1968). Some of the variability probably reflects changes in the range of intensities presented to the subject (cf. Poulton, 1968). Choice

of the anatomical site to be stimulated may also be a factor (Stevens et al. stimulated the fingertips, while Babkoff, 1978, obtained a low estimate of $b = 1.3$ after stimulating the underside of the wrist). Intensities of around 1 mA certainly induce strong sensations of pain in the fingertips (e.g., Stevens et al., 1958), whereas in the present work, a shock 1 mA in intensity on the volar surface of the forearm is typically experienced as only moderately painful. How investigators choose to fit Equation 1 and what additional parameters are assumed will also affect the value of b . Beck and Rosner (1968), for example, made the traditional correction for threshold in estimating an exponent equal to .7.

Moreover, the power function rule for electric shock is questionable in itself. McCallum and Goldberg (1975) found that magnitude estimation data for shock are as well fit by linear as by power functions (see also Babkoff, 1976, 1978). It may be, as Anderson (1970) has suggested, that the usefulness of power functions is often largely formal; they provide good fits to a class of monotone functions. Equation 1 need not reflect, therefore, the underlying psychological scale.

Starting with the truism that perception is some form of information integration, Anderson (e.g., 1970, 1974) has argued that we must distinguish between psychophysical laws, of which Equation 1 is a possible example, and psychological laws that reflect both an integration process and a valuation process for particular judgments. Anderson (1974) has discussed a wide range of algebraic integration models. For example, if the subject is required to combine two sequentially presented stimuli, some simple models of the integration include adding

$$R_{ij} = w_1s_1 + w_2s_2 + e, \quad (2)$$

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averaging,

$$R_{ij} = w_1 s_1 + w_2 s_2 + e, (w_1 + w_2 = 1), \quad (3)$$

or multiplying

$$R_{ij} = s_1 s_2 + e, \quad (4)$$

where the R_{ij} are responses on a rating scale, s_1 and s_2 are subjective values for the first and second stimuli, respectively, w_1 and w_2 are associated weights frequently representing order effects, and e is an error term with zero expectation, which for convenience will be omitted from this point. Tests of goodness of fit for these models may be obtained graphically and through the analysis of variance. The averaging model, for example, implies that ratings for the second stimuli plot against the intensity of the first stimulus as a set of parallel linear curves. If responses are cast in a Row by Column matrix with row vectors representing the first stimulus and column vectors the second, the analysis of variance provides a statistical test of parallelism as a zero (or, in practice, statistically insignificant) interaction. The importance of parallelism for the representation of psychological values is clear, since parallelism provides an equivalence relation (reflexive, symmetric, and transitive). Given a correct model, parallelism would allow a simple determination of subjective values on an interval scale. Best least squares estimates of s_1 and s_2 are available from the marginal means of the Row by Column matrix (Anderson, 1970, 1974).

The present work was designed to investigate the possibility that simple and psychologically meaningful algebraic models might describe the integration of electric shocks both when the shocks are judged to be painful and when they are not. There is general agreement that judgments of painfulness are complex, reflecting both sensory and cultural or situational factors (e.g., Tursky, 1974). Perceived painfulness may also change qualitatively with increasing stimulus intensity (e.g., Melzack & Torgerson, 1971). In Stevens' term, pain scales may be a mixture of meta-thetic and prothetic continua (cf. his argument about pitch scales, Stevens, 1957). Little seems to be known about the integration process of painful stimuli. Negative time-order errors (TOEs) may occur when subjects rate the painfulness of shocks (Geertsma, 1958); that is, subjects would show a tendency to judge the second of a pair of intensities as the more painful of the two. This might suggest an averaging model with $w_2 > w_1$ or perhaps a differential weighted averaging model in which w_2 increases monotonically as a function of s_2 . In the latter case, parallelism would be violated and curves would converge to the right. This pattern has, in fact, been observed for judgments of average line length (Birnbau, Parducci, & Gifford, 1971).

In the following experiments, subjects were asked to judge the average intensity of two sequentially presented electric shocks along a 20-point rating scale. In Experiment 1, the shocks were judged to be painful and in Experiment 2, to be nonpainful. Factorial designs were used to allow tests of algebraic integration models under the analysis of variance.

EXPERIMENT 1

Method

Subjects. The subjects were 14 graduate and undergraduate students paid for their participation at a rate of \$10/h. All agreed to participate after being forewarned that the experience would be painful. All were free to withdraw participation at any time during the experiment.

Apparatus. A Lafayette device delivered ac pulses for a fixed duration of 500 msec through concentric electrodes (Tursky, Watson, & O'Connell, 1965) into an electric skin circuit that maintained impedance at $5,000 \pm 500 \Omega$. The equipment had been carefully tested to ensure that it met CSA standards for safety to the subject.

Procedure. The subject was seated on a stool and either one (pretest) or two (experimental session) electrodes were attached to the volar surface of the left forearm. In the pretest, subjects were exposed to single electric shocks ranging in intensity (rms mA) from 0 to 5 mA and had rated the sensation along a 10-point scale from 1 (no sensation) through 5 (mild pain) to 10 (intolerable pain). The session was always terminated when the subject rated the sensation as 10. All subjects used in the experiment had judged that the intensity range of 1 to 4 mA lay in the region from mild pain to just below the level of tolerance.

In the experimental session, the two electrodes were attached such that one was approximately one-third the distance from wrist to elbow and the other was about two-thirds the distance. On each trial, two shocks were presented sequentially, one through each electrode, with a 1,000-msec interval between the two. The order in which the electrodes were used was randomized over trials. This procedure was used to minimize the possibility of local enhancement or summation effects, which are known to occur when pairs of vibrotactile stimuli are presented in sequence (e.g., Verillo & Gescheider, 1975).¹

Subjects were instructed to rate the average intensity of each pair of shocks along a scale from 1 to 20. Anchor points were provided before the experimental session. The subject received a pair of shocks, each .75 mA in intensity, and was instructed to call the average intensity "1." Similarly, a pair, each 4.25 mA in intensity, was called "20." Each of the intensities—1, 2, 3, and 4 mA—was presented as the first and as the second intensity in a 4 by 4 factorial design with four replications in each cell. The order in which pairings were presented was randomized over the 64 trials. The interval between trials was 7 sec.

Results

The main data are presented graphically in Figure 1, which shows mean ratings over subjects for each column (second stimulus) intensity as a function of each row mean. The curves are linear and exhibit parallelism. Moreover, the distances between pairs of adjacent stimuli clearly increase as stimuli intensity increases (increasing vertical separation of curves in the graph). Under analysis of variance, the main effects of row [$F(3,39) = 220.48, p < .001$] and column [$F(3,39) = 135.30, p < .001$] were highly significant, and the interaction was statistically nonsignificant [$F(9,117) < 1$].

Figure 1. Mean rating-scale values over subjects for each of the second-presented stimulus intensities as a function of the mean scale values for the first stimulus (Experiment 1).

Figure 2. Combined means for rows and columns as a function of stimulus intensity (Experiment 1).

Given linearity and parallelism, Equation 3 seems to provide a reasonable model of the integration process. Anderson (1970, 1974) has suggested averaging the two sets of marginal means and plotting row and column means against the overall means. The slopes of the resulting plots then provide estimates of row and column weights. In the present case, this procedure yielded estimates of $w_1 = .52$, $w_2 = .48$. In other words, the weights assigned to the two stimuli

are approximately equal, and Equation 3 reduces to the arithmetic mean of the two scale values, that is,

$$R_{ij} = (s_1 + s_2)/2. \quad (5)$$

In Figure 2, the overall means are plotted as a function of stimulus intensity in milliamperes to illustrate the psychophysical law for the data. The function appears positively accelerated, and the best fitting two-parameter function is exponential ($r^2 = .9994$). A three-parameter power function of the form

$$\bar{X}_{ij} = aI^b + c \quad (6)$$

also provides an excellent fit ($r^2 = .9987$) with $b = 2$, where $\bar{X}_{ij}$ is the mean of the i^{th} row mean and the j^{th} column mean ($i = j$). This is an interesting result since power in the circuit increases as the square of the current. Hence, mean subjective values were linearly related to output power (cf. Cross et al., 1975).

EXPERIMENT 2

In this experiment, the procedure of Experiment 1 was followed precisely with nine subjects except that the four shock intensities were .6, .7, .8, and .9 mA. All the subjects tested in Experiment 2 had judged that all four intensities did not elicit painful sensations. Anchor points were provided at .55 and .95 mA.

Results

The main data are presented in Figure 3 as a plot of mean ratings for column stimuli against row means. Again, the curves are linear and parallel, although the vertical separation of curves now appears to be roughly constant. Analysis of variance showed significant main effects for row [$F(3,24) = 65.79$, $p < .001$] and column [$F(3,24) = 104.15$, $p < .001$], and a non-significant interaction [$F(9,72) < 1$].

Estimation of w_1 and w_2 showed that the second stimulus tended to be weighted more heavily with $w_1 = .42$ and $w_2 = .58$.

Figure 4 shows the linear relationship ($r^2 = .9980$) between overall means and stimulus intensity. It is clear, therefore, that the form of the psychophysical law may change according to judgmental context—in this case, whether stimuli are felt as painful or not.

DISCUSSION

The present results provide a preliminary but encouraging differentiation between subjects' judgments of painful and of nonpainful electrical stimuli. In both cases, Equation 3 appears to be a reasonable description of the integration process. When shocks were painful, the weights were roughly equal and the model becomes a special case of Equation 3; rating scale responses were a monotone function of the arithmetic mean of scale values. In the non-

Figure 3. Mean rating-scale values over subjects for each of the second-presented stimulus intensities as a function of the mean scale values for the first stimulus (Experiment 2).

Figure 4. Combined means for rows and columns as a function of stimulus intensity (Experiment 2).

painful case, the weight associated with s_2 is greater by a factor of about $1\frac{1}{3}$ than the weight accorded s_1 . Such weighting could result in a strong recency effect (negative TOEs) if subjects were asked to judge, for example, the serial position of the stronger shock. Painful and nonpainful conditions also differ in the relationship between scale values and stimulus intensity. Subjective distances were linearly related to

current when shocks were nonpainful and nonlinearly related when shocks were painful.

Recency effects are typical of many, perhaps most, psychophysical judgments when stimuli are sequentially presented (e.g., Jamieson & Petrusic, 1975). Jamieson and Petrusic argued that TOEs are a memory-perceptual phenomenon rather than a decision bias. On this basis, equal weighting of two closely spaced painful stimuli may be psychologically meaningful. A painful first stimulus may persist in memory and hence be accorded equal weight with the second stimulus. Moreover, the subject may regard both stimuli as qualitatively the same. Both stimuli can be described as "tolerably painful." It should follow for future work that increasing the temporal separation of the two painful shocks should result in increased weighting of s_2 .

Stevens et al. (1958) spoke of "the process of expansion" for electrical shock; that is, subjective magnitude grows more rapidly than the stimulus magnitude. The present data suggest that "expansion" characterizes subjective values only when the shocks are judged to be painful.² Accelerating scale values for painful stimuli seem biologically plausible since pain signals possible tissue damage. On the other hand, nonaccelerating functions might be expected for nonpainful stimuli. Rollman (1969) has argued that electrical stimuli have neural consequences different from those following, say, visual or auditory stimulation since shocks may bypass cutaneous receptors and directly excite afferent nerves. He further suggests that psychometric functions will accelerate more rapidly when stimuli are not mediated by receptors. One may speculate that psychophysical functions follow the same principle. Higher energy (painful) stimuli may affect sensory nerves without receptor transduction resulting in the acceleration of subjective values that we observe in Experiment 1. Lower intensity (nonpainful) shocks may be mediated by skin receptors resulting in the zero accelerated functions of Experiment 2.³

The present data support the general contention of Rosner and Goff (1967) that psychophysical functions for shock may be best fit by double-limb functions. They argued that the following model provided a better fit than a log function of a single power function,

$$\left. \begin{aligned} R &\propto I^{b_1}, I \leq T_i \\ R &\propto I^{b_2}, I \geq T_i \end{aligned} \right\}, \quad (6)$$

where T_i is some cutoff value of I that varied between subjects. They found median values of $b_1 = 1.8$ and $b_2 = .9$; that is, the lower limb of the psychophysical function was positively accelerated and the upper limb nearly linear. The data reported here suggest the reverse relationship. How may we resolve the discrepancy? Rosner and Goff also argued that

physiological responses, P , were related to I by power functions,

$$\left. \begin{aligned} P &\propto I^{r_1}, I \leq T_i \\ P &\propto I^{r_2}, I \geq T_i \end{aligned} \right\} \quad (7)$$

It follows, therefore, that R is functionally related to P by

$$\left. \begin{aligned} R &\propto P^{b_1/r_1}, I \leq T_i \\ R &\propto P^{b_2/r_2}, I \geq T_i \end{aligned} \right\} \quad (8)$$

Rosner and Goff (1967) estimated b_1/r_1 to be about 1.2, and b_2/r_2 to be about 4.5. In other words, subjective values as a function of physiological changes were nearly linear on the lower limb and positively accelerated on the upper limb in conformity to the present data. Assuming the validity of the psychophysical law suggested by Rosner and Goff, one may argue that the present averaging task directly illustrates the relationship between subjective scale values and physiological responsiveness.

Finally, it is worth commenting on the practical value of the results of Experiments 1 and 2. Cross et al. (1975) argued that demonstrating the true value of the exponent for a power function fit to magnitude estimation for shock would allow pain researchers and therapists to "select levels of stimulation with known subjective magnitudes" (p. 14). The present results suggest that we may be able to avoid altogether the problem of fitting psychophysical functions. Consider the problem of evaluating some analgesic technique. The success of the technique in alleviating the painfulness of stimuli may be reflected in a change in the relative weighting of s_1 and s_2 , in a change in scale values, or in both. It would be a simple matter to examine scale values and weights in a control condition similar to Experiment 1 and in a treatment condition using the analgesic.

In sum, the present results converge with some magnitude estimation data in suggesting that no single function provides a psychophysical law for electric shock (cf. Rosner & Goff, 1967) and in demonstrating an exponent of 2 for a power fit to shock data, at least for more intense stimuli (cf. Cross et al., 1975). However, the main value of these results is that the integration process for sequentially presented shocks is simple. Integration models, rather than psychophysical models, could therefore allow us to gather important practical information in pain research.

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NOTES

1. Pilot work in which both shocks were delivered sequentially over a single electrode resulted in complicated interactions between row and column values, which were perhaps due to local enhancement or inhibition.
2. Stevens et al. (1958) did not have subjects rate the painfulness of stimuli. However, they reported that higher intensity stimuli (around 1 mA at the fingertips) were "very disagreeable."
3. McCallum and Goldberg (1975) argued, reasonably enough, that experimenters should use the widest possible stimulus range in order to fit psychophysical functions. However, the experimentally useful range of electric shock is extremely restricted compared with the possible stimulus range in other modalities. Moreover, the part of the range that is experienced as nonpainful is even further restricted. In the present experiments, shocks ranged from .60 to 4 mA so that the nonpainful part of the range is less than one-fifth the total range.

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