Integration of Noxious Stimulation Across Separate Somatosensory Communications Systems: A Functional Theory of Pain

Daniel Algom, Nehama Raphaeli, and Lior Cohen-Raz
Bar-Ilan University, Ramat-Gan, Israel

Functional measurement analyses and psychophysical techniques were used to assess how separate, cross-modal, aversive events are integrated in judgments of pain. Subjects made magnitude estimations of noxious stimuli produced by a 6 × 6 factorial design of electric shocks and loud tones. Group data and most of the individual results were consistent with a model of linear pain summation. The estimates of pain approximated the linear sum of the pain estimates of the individual electrorotcutaneous and auditory components. The relation between painful sensation and current intensity could be described by a mildly expansive power function with an exponent of about 1.1. Auditory produced painful sensation related to sound pressure level by a mildly compressive power function with an exponent of about 0.90 as a representative figure. Results are interpreted in terms of a functional theory of pain. Noxious events are first transformed to psychological scale values via stimulus-specific psychophysical transfer functions. The outputs of these functions are then combined with other pain-related internal representations of either sensory or cognitive origin, according to simple algebraic models.

Suppose you are suffering from an acute toothache. Then another painful sensation appears, that one resulting from an upset stomach. What is the overall level of pain you are feeling now? Is it more severe than having either of the painful components alone? And if it is, how much so? Of special interest is the question whether pain summation—if it exists— is perfect: Is overall pain equal to the simple sum of the component painful sensations?

To answer these questions requires that one has a means for quantifying pain. Pain, however, is a complex phenomenon, depending, among other things, on the mode and nature of the noxious stimulation. Electrocutaneous pulses have become a popular pain-inducing method in the experimental literature. Uncomfortably loud tones, though less popular, seem to provide an equally controllable experimental method. Both procedures enable the experimenter to control carefully the spatiotemporal characteristic of the aversive stimuli. These two types of noxious stimulation were used in the present study to investigate the rules by which painful information combines in perception and to simultaneously evaluate the psychophysical relations involved.

Electrocutaneous Stimulation

Various investigators have reached different conclusions about the form of the psychophysical function for the mostly painful responses to electrocutaneous stimulation. Most of the studies used direct procedures, notably magnitude estimation (Marks, 1974a, 1974b; Stevens, 1975), for a response measure and various versions of the power function as the main means of data reduction. Stevens, Carton, and Shickman (1958) found simple power functions adequate to describe the growth of electrically produced intensity, the stronger values of which were "very disagreeable." However, even the weak shocks were found aversive by the subjects. The authors reported exponents of about 3.5, more than twice the value for the next steepest psychophysical function examined until that time (Stevens, 1961; see Rollman, 1974).

Later researchers generally reported somewhat lower exponents ranging from 1.3 to 2.7 (Babkoff, 1976, 1977, 1978; Cross, Tursky, & Lodge, 1975; Ekman, Frankenhauser, Levander, & Mellis, 1964; Sternbach & Tursky, 1964), although Bujas, Szabo, Kovacic, and Rohacek (1975) obtained exponents of 3.42 using stimulation techniques very similar to those originally employed by Stevens et al. (1958). Other researchers obtained values even as low as 0.70 or 0.93 (Babkoff, 1978; Beck & Rosner, 1968) if the data are corrected for threshold or if durations are parametrically varied. Linear psychophysical functions have also been suggested as a viable alternative to the nonlinear descriptions (Babkoff, 1976; Jones, 1980; Jones & Gwynn, 1984; McCallum & Goldberg, 1975). As a result, the superiority of the power equation over others in describing electrocutaneous input–output functions has been questioned (Babkoff, 1976; Jones & Gwynn, 1984; McCallum & Goldberg, 1975; Rosner & Goff, 1967).

Some of this vast variability probably reflects rather large range effects (e.g., Poulton, 1968; Teghtsoonian, 1971, 1973). An additional portion is probably accounted for by the influence of stimulus parameters that have yet to be systematically clarified. Yet another source of variation, both within and across studies, may stem from differences in the ways that subjects use numbers to describe sensations (Algom & Marks, 1984). Hence, validity is at issue, implying that at least some of the direct estimation results may not faithfully reflect the underlying scale values. The

The present study makes use of a substantive, multifactor model of sensory and cognitive processes that contains pain scales as its natural derivative. The validation of the model entails simultaneous validation of the scales, too. Thus, scaling becomes an integral part of the psychophysics and cognition of sensory processes (see Marks, 1978b). The present approach makes use of the theory of scaling proposed by Anderson (1981, 1982), designated “functional measurement,” as the main analytic device for both data reduction and theoretical interpretation. The main purpose of analysis in terms of functional measurement methodology is to determine the integration function that combines separate stimulus components into a unitary response. At the same time, the theory also provides unique and validated functional scales to each of the component stimulus dimensions.

As mentioned earlier, loud tone bursts were chosen as the complementary aversive continuum to serve in the present factorial design.1

Aversive Auditory Stimulation

The aversive, indeed harmful, properties of exposure to massive auditory stimulation need no documentation here. Temporary and permanent threshold shifts, hearing losses at particular bands of frequency, and loudness recruitment constitute but a sample of well-known pathologies within clinical acoustics that may result from powerful and prolonged auditory stimulation. However, even short sounds may feel aversive and painful if presented at sufficiently high levels. It is little wonder, then, that loud auditory pulses serve as a convenient experimental substitute to (the more ethically problematic?) electrical shock in many learning and social psychology experiments (e.g., Feshbach, 1972; Hiroto, 1974; Hiroto & Seligman, 1975).

Overloading of the auditory mechanism gives rise to subjective impressions of “feeling, tickle, touch and pricking” as well as “discomfort” (Licklider, 1951, pp. 997–998). Thus, the painful sensations induced have tactile as well as auditory characteristics. These sensations arise fully at intensities of at around 110 dB SPL and beyond, but as Licklider notes, complaints of discomfort and tickle begin at levels 5 to 10 dB lower. Note, however, that the above values were obtained for subjects who had become used to intense acoustic stimulation for an extended period. Much lower thresholds of discomfort are expected with inexperienced subjects stimulated with abrupt sound bursts (the popular method in the learning and social psychology literature). Recently, Cohen, Naliboff, Schandler, and Heinrich (1983) obtained thresholds of discomfort for a 4-s, 500-Hz tone burst with a group of chronic low back pain patients as well as for healthy nonpatient controls. The average uncomfortable threshold (dB) obtained for the group of patients was 71.5 ($SD = 8.5$), whereas the normal controls had an even lower value of 56.9 ($SD = 6.2$).

Although the aversive effects of intense auditory stimulation are well recognized, no data regarding the functional relation involved have been reported in the literature. An aim of the present investigation was to functionally relate levels of induced discomfort to levels of auditory physical magnitude to arrive at a quantitative appraisal of the psychophysical contingency.

Integration of Painful Sensations

A significant feature of the present experiment is the composition of stimuli. It used a matrix of energy inputs in which each of several electric shocks was combined simultaneously with each of several loud auditory pulses to produce a factorial set of noxious events. Assuming (a) a separate and independent transduction process for each of the noxious dimensions and (b) some equivalent internal representation for the two types of stimulation, an additive model of integration seems a natural prediction. At the least, linear addition of pain may serve as a useful working hypothesis. Jones (1980) and Jones and Gwynn (1984) have indeed demonstrated that electrocutaneous data conform to linear combination models (in particular weighted averaging). Note, however, that their results relate to integration rules within a sensory communication system, whereas the present study examines composition rules across completely separate systems. Moreover, as Marks (1978b) has pointed out, superimposing complex cognitive operations (such as judgments of averages of stimulus sequences in Jones’ studies) on sense perception may actually add more nonlinear transformations onto the data and thus complicate the solution. Gracely and Wolskee (1983) showed an additive structure to operate on sensory signals (electrical tooth pulp stimuli) and verbal symbols of pain. The present research employed a most elementary judgmental task (subjects were asked simply to report the degree of pain or discomfort felt) relating to the intensity of concurrent, quantitatively controllable, noxious stimuli to arrive at the specification of the appropriate integration model.2

1 The choice of an auditory noxious stimulus in the present study may seem interesting in view of an earlier literature that dealt with intense noise as an analgesic agent (e.g., Gardner & Licklider, 1959; Gardner, Licklider & Weisz, 1960). However, as later work has shown, “audio analgesia” largely depends on suggestion, expectation, and placebo effects (e.g., Melzack, Weisz, & Sprague, 1969; see Melzack, 1973; Weisenberg, 1977). Even in their original report, Gardner et al. concede that “If the subjects pay attention to the nociceptive stimulus and report upon the magnitude of the resulting subjective pain, the effect of acoustic stimulation is usually small” (p. 32). In contrast to these studies, the present experiment called for an explicit (and to some extent exclusive) concentration on the nociception of the stimuli presented.

2 There are two analytical approaches that allow an investigator to test composition rules of independent variables from unitary judgments based on their compound presentations. The one chosen in this study was the functional measurement approach (Anderson, 1981, 1982) because (a) of the ease of obtaining direct magnitude estimations (rather than rank-order responses), (b) utilizing more of the metric properties of the experimental data, and (c) the availability of relatively straightforward analytic techniques for both model diagnosis and derivation of psychophysical functions. The other approach, conjoint measurement (Krantz, Luce, Suppes, & Tversky, 1971), suffers from a major shortcoming, namely, the lack of an error theory or an analytic way of handling response variability in real data. The axiomatic model assumes error-free, rank-order responses, thereby seriously limiting its applicability to empirical research (e.g., Falmagne, 1976). Although several strategies have been suggested to deal with random error (e.g., Coombs & Huang, 1970; Coombs & Lehre, 1981; Falmagne, 1979; Person & Barron, 1978), so-
Besides its intrinsic interest—reflecting on important theoretical and practical issues—the specification of the integration model makes other, perhaps equally intriguing, points. It entails procedures allowing for validated estimations of the underlying psychophysical functions. For electrical shock, the to-be-extracted parameters bear heavily on the question of the form of electrocutaneous psychophysical input-output function. For loud tones, we hoped to uncover the functional form of the dependency between degrees of discomfort and sound pressure level.

Method

Subjects

Ten young men and women (7 males and 3 females), all volunteers from the Bar-Ilan University community, served as subjects. Their ages ranged from 22 to 31 years, and four of them had previous experience with the method of magnitude estimation, though not necessarily in judging auditory or electrocutaneous stimuli. Each of the observers was tested over two sessions separated by 1 day or more. All had been advised that the experiment would comprise painful stimuli and were free to withdraw participation at any time during the experiment.

Apparatus

A constant current stimulator (local design), powered by a Heathkit Model IP-17 regulated H.V. power supply, delivered square-wave pulses for a fixed duration of 3.2 ms through concentric electrodes. Pulse shape, duration (controlled by locally designed timing and logic circuits), and current were calibrated with a Tektronix PM6424 current probe in series with a Tektronix Type 454A oscilloscope. The pair of concentric platinum electrodes 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 0.524 cm).

Tone stimuli were produced by a Coulbourn precision signal generator, gated and timed with additional Coulbourn modules. The output was amplified (Shure mixer-amplifier unit) and then attenuated before being fed to the AKG(Z50A) headphones. The binaural stimuli had abrupt rise and decay times (i.e., 100 μs) and lasted 3.5 s.

A common trigger activated both electrical and auditory stimulus production systems. The electrical shock appeared 450 ms after the onset of the tone stimulus in each trial.

Shock durations of 3.2 ms, and tone durations of 3.5 s were determined so as to be beyond the ranges of even partial temporal integration reported for the respective stimulus dimensions (see Algom & Babkoff, 1978, 1984; Algom, Babkoff, & Ben-Uriah, 1980; Babkoff, 1978; Babkoff, Brandeis, & Bergman, 1975; Rollman, 1969a, 1969b). Of course, temporal integration of pain reactions may well exceed the values of critical duration usually obtained for loudness or weak electric intensity. Nevertheless, pilot data showed all stimuli to be uncomfortable or painful.

Procedure

Six different levels of electrical current (0, 1, 2, 3, 4, and 5 mA) were combined factorially with six levels of sound pressure (77, 81, 85, 89, 93 dB, and a "zero," well below threshold stimulus), making 36 different noxious stimuli in all. Stimuli were presented one at a time to the subject for judgment. Each stimulus was presented and judged three times in the course of the first experimental session and three times at a second session, making six judgments per stimulus in all. The initial part of the first session, prior to data collection, comprised a preliminary practice phase for all subjects to become familiar with both the stimulus setting and the method of magnitude estimation. Order of presentation of stimuli was irregular and different for each subject.

The experimental sessions took place in a booth removed from the equipment. The subject was seated in an armchair, with the electrodes strapped to the underside of his or her right wrist and the earphones on the head.

The method was magnitude estimation. Subjects were instructed to assign to the first stimulus whatever number seemed most appropriate to represent the discomfort or pain it caused; then to succeeding stimuli they were to assign numbers in proportion. If no pain was felt, subjects were to assign the number zero. Subjects were told that they could use whole numbers, decimals, and fractions as needed.

Results and Discussion

Pooled Data

Group results are presented first. The magnitude estimates of pain given to each stimulus were averaged geometrically, and these means are plotted in Figure 1 as a function of current intensity in milliamperes. The parameter is sound pressure level; each contour represents a different constant level of sound delivered to the two ears.

Perhaps the most salient characteristic of this family of curves is their roughly equal spacing in the vertical dimension, though a slight trend toward divergence at the upper right is evident. Because the pain estimates are plotted on a linear scale, the hypothesis of linear pain summation may be assessed by visual inspection. The parallel spacing implies linear additivity of the overt numerical responses. Apparently, the aversiveness of an electric shock and of a massive tone burst presented simultaneously at various intensities to the skin of the wrist and to the ears, respectively, approximates the linear sum of the individual painful components. This additive structure is evident in the even spacing of the curves in Figure 1. The slight deviation from additivity is probably attributable to the fact that the data sets of at least some of the subjects did not follow a rule of exact addition (see the section on individual analyses below).

Analysis of variance of the judgments of painful sensations (performed on the geometric means of the various subjects) confirmed the linear addition rule drawn from the visual inspection of the graphic display. Interaction variance is the critical term to assess, because failure of additivity will appear as a significant
INTEGRATION OF NOXIOUS STIMULATION

Figure 1. Average magnitude estimates of pain, plotted as a function of current intensity delivered to the wrist. (Each curve represents a constant SPL delivered to the two ears.)

interaction (Anderson, 1970, 1974, 1982). The data showed a nonsignificant overall interaction at the 1% significance level, but not at the 5% level, \( F(25, 225) = 1.73, .01 < p < .05 \). However, a major part of this rather small interaction variance resided in the bilinear component (47%). The bilinear component was highly significant, \( F(1, 25) = 20.34, p < .01 \), whereas the residual was not, \( F < 1 \).

Graphically, a significant bilinear interaction appears as a tendency for the family of functions to converge or diverge at the upper right. And divergence (or convergence) is the hallmark of many nonlinear numerical response biases where the underlying metric is additive (e.g., Algom & Marks, 1984; Marks, 1979b). Nonlinearity of this type can be eliminated by rescaling the numerical values to obtain a theoretically prescribed criterion such as complete elimination of the divergence (e.g., Marks, 1979a, 1979b) or removal of any significant interaction variance (see Anderson, 1970). We used the class of power transformations (in which the original estimates \( R \) were transformed by the equation \( R' = R^m \)) and, by iteration, found the value of \( m \) that reduced interaction variance beyond the 5% significance limit. This procedure entailed a mild, negatively accelerated transformation, raising the magnitude estimates to the 0.90 power. (Complete elimination of observed divergence involved raising estimates to the 0.85 power.) Considering the transformed data, the additivity of components is even more evident.

The data were subjected to analysis of variance by yet another procedure because, as Anderson (1982) points out, the interaction in a within-subject data matrix like this might be biased by individual differences. In order to eliminate any subject effect (and to make the error term the Shock × Tone × Subject interaction), each subject's numbers were multiplied by the constant needed to make that subject's mean equal to all other means (i.e., to the overall mean) (see Lane, Catania, & Stevens, 1961; Marks, 1980).

Results of this analysis showed a nonsignificant overall interaction, \( F(25, 225) = 1.50, p > .05 \), substantiating once again the results of the graphic test of parallelism: linear addition of painful sensations across separate somatosensory systems.

As Anderson (1970, 1974) has pointed out, given a factorial design of the type used in this investigation and results consistent with additivity in the response domain, the marginal means provide estimates of the scale values. The lower portion of Figure 2 gives these calculated scale values for electrical shock, produced by averaging across the rows of the data matrix (i.e., across the different SPLs), and then setting to zero the scale value at zero stimulus intensity.

However, the present design entails yet another indicant of the underlying scale values. These derive from only a subset of the results, namely, data for presentations that were electrocutaneous only or auditory only (i.e., data from either the first column or the first row of the factorial design). Because they derive from the entire response matrix, the marginal means have, of course, a fuller basis than do the unifactor pain judgments. Nevertheless, both derivations are valuable in providing converging evidence for a validated psychophysical function characterizing a specific pain experience. The upper part of Figure 2 plots the unifactor function for electrocutaneous pain, based on judgments of shock-only presentations (i.e., derived from trials on which tones had a value of "zero"—well below the threshold of audibility).

The electrocutaneous psychophysical functions—both the

Figure 2. Psychophysical functions for electrocutaneously induced pain. (Top: average magnitude estimates of pain as a function of shock intensity. Bottom: same, but the estimates represent adjusted marginal means, calculated from the entire 6 × 6 data matrix. Note that both the ordinate and the abscissa are shown in logarithmic units.)
magnitude estimates and the marginal means—approximate power functions (with the proviso that the function includes a subtractive constant as a "threshold" correction). The functions in both cases are mildly expansive, with exponents of 1.145 and 1.117 for the magnitude estimates and marginal means, respectively. The fits to the power functions (straight lines in the double logarithmic coordinates) are good ($r^2$ equals .979 for the single row function and .951 for the marginal function). Linear fits to the same data were less satisfactory, yielding $r^2$s of .972 and .903, respectively.

Other assessments of the respective functions alter the absolute values, but none of the slopes (exponents of the power functions), described above, change appreciably. Thus, the rescaled estimates yielded exponents of 1.13 and 1.102, but with improved fits ($r^2$ equals .981 and .960, respectively). When intersubject differences in number magnitude are eliminated, the slopes have values of 1.102 ($r^2 = .990$) and 1.157 ($r^2 = .986$), respectively, for magnitude estimates and for marginal means. The evidence for a rather moderately expansive electrocutaneous psychophysical power function characterized by an exponent in the vicinity of 1.1 seems quite strong.

The fact that felt unpleasantness is an expansive power function of the physical intensity of the electrocutaneous pulse (current) agrees with the conclusion of most previous investigations (see introduction). Yet large portions of previous data are suspect because they rest on the assumption that the overt response was (at least) an interval scale of perceived aversiveness in each case. However, as Anderson has repeatedly pointed out (e.g., 1981, 1982), this assumption may or may not be correct in special cases, and, in general, it lacks needed empirical justification.

Nevertheless, the estimates of exponent obtained herein are relatively small. Although they agree with some of the previous results from this laboratory (Babkoff, 1976, 1977, 1978), they are lower than those reported in the literature, with the exception of the exponents calculated by Beck and Rosner (1968) after correction for threshold. Note that the present estimates are also threshold corrected, and yet they yield greater than unity exponents. Interestingly enough, a threshold correction applied in conjunction with the stimulation technique originally used by S. S. Stevens and his co-workers (Stevens et al., 1958)—resulting usually in the highest estimates of exponent in the order of 3.5 (e.g., Bujas et al., 1975)—brought about a considerable reduction in exponent magnitude (to 1.81, Ekman et al., 1964). The relatively small exponent obtained in the present study may reflect also the use of a shock duration (3.2 ms) that was considerably shorter than that used in most other studies (but see Babkoff, 1978).

Jones (1980) and Jones and Gwynn (1984) have also employed functional measurement methodology and derived validated psychophysical scales. However, the various marginal means' functions obtained by Jones are unique only up to a multiplication by a constant and addition of a constant (i.e., they are equal-interval scales) due to lack of threshold correction.

Figure 3 plots the psychophysical functions characterizing tone-induced painful sensations. Again, the upper plot is based on tone-burst judgments only, that is, on data that derive from the first column of the response matrix. The lower part of Figure 3 depicts the function based on the SPL marginal means (i.e., on data averaged across the different current levels).

The exponent values found here for the unpleasantness of massive tone bursts remain stable across different determinations of the underlying scale. Thus, the rescaled magnitude estimates yield exponents in the order of 0.67 ($r^2 = .987$) and 0.83 ($r^2 = .998$) for the magnitude estimates and marginal means, respectively. Removal of individual differences in modulus—what probably results in the best unbiased estimate of scale values—yielded exponents of 0.74 and 0.86 ($r^2 = .989$ and .997, respectively). The results are, therefore, consistent with the notion of a unique scale for painfulness of massive auditory stimuli. This scale must be distinguished from the various loudness scales (e.g., Algom & Marks, 1984; Garner, 1954; Marks, 1974a, 1978a, 1978b, 1983; Stevens, 1956, 1975; see also Schneider, 1980, and...
Schneider, Parker, & Stein, 1974, for much lower loudness ex-
ponents derived by nonmetric scaling techniques) on the one
hand, and from other stimulus-specific representations of ex-
perimental pain on the other (e.g., Rollman, 1974, 1983a, 1983b).

High-level auditory stimulation has for a long time been known
for its aversive properties (poor little Albert may be mentioned
here, Watson & Rayner, 1920; see Licklider, 1951) and has re-
cently become a popular pain-inducing device in both learning
and social psychology experiments (e.g., Hiroto, 1974). However,
this is the first time, to the best of our knowledge, that subjective
representations of auditory pain are functionally related to the
physical parameters of the stimulating tone signals.

Three main conclusions can be drawn from the group results:
First, rescaled or unrescaled magnitude estimates of pain evidence
additive structures. Taken as a whole, the results can, therefore,
be characterized by a simple rule: Overall pain equals the linear
sum of the component electrotaneous and auditory pain when
pain is counted in stimulus-specific subjective units. Second, pain
as a function of electric shock and as a function of sound pressure
level can both be characterized by a simple two-parameter psy-
chophysical power function. Third, the parameters of the func-
tions differ. The electrotaneous function is moderately expan-
sive, whereas the auditory function is moderately compressive
(though clearly differing from the rather extensively scrutinized
various loudness functions).

**Individual Data**

The type of analyses and kind of interpretation used with the
pooled results were applied to the data of each individual subject.
Thus, the group data serve as a common frame of reference to
evaluate individual cases.

Three aspects of each subject’s results are of special interest:
(a) the rule of pain summation, (b) the psychophysical function
for pain induced by electric shocks, and (c) the psychophysical
function for pain induced by high-level tone bursts.

The question of integration rule may yield to an analysis of
the additivity evident within each subject’s entire response matrix.
As Figure 1 shows, the pooled data conform well to a simple
additive mode. So, too, do most (but not all) of the individual
data. Graphic displays of each subject’s pain contours show that
despite considerably greater noisiness, in most cases the curves
are about equally displaced in the vertical plane (see Figure 4
for two examples).

Analyses of variance confirmed that the data for 9 of the 10
subjects had nonsignificant ($\alpha = .01$) interaction terms, implying
additivity of their numerical estimates: For the 9 subjects, $F(25,
125) < 1.85, p > .01$; for the remaining 1, the interaction term
was significant, $F(25, 125) = 2.13, p < .01$. Employing the 5%
significance level showed, however, that the data for only 6 of
the last 9 subjects had nonsignificant interactions: For the 6 sub-
jects, $F(25, 125) < 1.55, p > .05$; for the other 3 the interaction
terms were $F(25, 125) = 1.77, 1.84, 1.85, 0.01 < p < .05$.

As Anderson (1981, 1982) has pointed out, deviations from
a prescribed theoretical pattern must not automatically lead to
the rejection of that pattern as a valid representation. Possible
nonlinear response biases should always be considered. The
method of orthogonal polynomials can be diagnostic in this re-
spect, and so we applied it to the analysis of the interaction vari-
ances of the 4 subjects having significant terms at the 5% level
(using coefficients relative to the psychological values rather than
the standard ones). Results showed that interaction variance for
2 of the 4 subjects had sizable Linear X Linear components in
each case (60.3% and 40%). For these 2 subjects the bilinear
component was highly significant, $F(1, 25) = 27.78$ and 17.68,
$p < .01$, whereas the residual was not, $F < 1$, and $F(24, 100) =
11.11, p > .10$, respectively. The data of these subjects were sub-
jected to the same type of rescaling (to additivity) used with the
pooled data. The procedure involved a strong negatively accel-
erated transformation ($m = 0.45$) in the first case, a mild posi-
tively accelerated transformation ($m = 1.05$) in the other.

Noteworthy is the fact that the above analyses failed with the
2 remaining subjects. Although both of them had some of the
interaction variance concentrated in the bilinear component
(15.8% and 19.7%), sizable (and significant) nonlinear compo-
nents appeared, too. For instance, the data for the second subject
(characterized originally by the most significant, $p < .01$, in-
teraction term) showed negligible Linear X Quadratic (Shock X
Tone; 0.3%) and Quadratic X Linear (0.8%) trends, but an im-
pressive 30.3% Quadratic X Quadratic component, $F(1, 25) =
16.2, p < .01$. We could find no monotonic (power-class) trans-
fom to bring the two sets of data to parallelism. Most likely,
these 2 subjects used inherently nonadditive cognitive strategies
in coping with and integrating the sensations of pain coming
from the different bodily sources.

Besides their intrinsic interest, the present individual analyses
entail an important caveat with regard to the interpretation of
functionally derived factorial plots based on group data. Although
the possibility of artificial interpretation of pooled patterns is
at times acknowledged (e.g., Anderson & Cuneo, 1978), careful
individual analyses are needed to explore the exact nature of
individual differences. These should apply to both the integration
rule and the psychophysical function, and in special cases even
to possible trade-off relations between the two. The present out-
come suggests an additive integration rule for pain for 8 subjects,
but a more complex, distinctly nonadditive rule for 2 subjects.

On the assumption that additivity of pain exists at least as a
first-order approximation, we can derive scale values from each
subject’s data matrix by calculating marginal means down col-
umns (i.e., across SPLs) and across rows (i.e., across current
levels), adjusting to zero the scale values for zero-intensity stimuli.
Single row (current only) and column (sound pressure only) scales can also be calculated. Columns 2 and 4 in Table 1 show, respectively, for magnitude estimates and for marginal means, the exponents of power functions fitted to the electrocutaneous data.

The fits to the power functions are reasonably good. The spread of exponent—somewhat more than 2:1—is typical (e.g., Ramsey, 1979; Stevens & Guirao, 1964; see also Marks, 1974a). However, the variability is inflated by the extreme values of one of the (anomalous?) subjects (E), whose data agree with a complex biquadratic model rather than with a simple additive model. The average exponents over subjects are much like the averages obtained from the pooled estimation. It is, perhaps, notable that for 9 of the 10 subjects at least one determination of exponent yielded a value greater than unity. The finding from the pooled data of a moderately expansive electrocutaneous pain function with an exponent in the vicinity of 1.1 is, therefore, substantiated by the individual results.

Table 2 gives the respective psychophysical functions and power fits for the auditorily induced painful sensations.

Again, the fits to the power functions are excellent, especially for the marginal means' functions. Variability of exponents is smaller though, inflated this time by an extreme value of the second deviant subject (B). Still, the most striking feature of these individual functions is the replication of the relatively high value for the auditory pain exponent (in the order of .90). Notable, too, is the fact that half of the individual exponents are equal to or greater than unity. Subjective representations of pain induced by tone-bursts rest on different scale values than do values of loudness aroused by the same sort of stimuli.

In sum, the results of the individual data suggest that the rules underlying the integration of separate painful somatosensory information vary somewhat from person to person, but that the typical underlying structure is an additive one. Sensory representations of pain are stimulus specific; the scales varying systematically across different sources of induction. For electrical shock, pain is an expansive power function of the physical stimulus; for loud tones, it is a compressive power function of the

Table 1
Parameters of the Psychophysical Power Function for Electrocutaneous Stimulation
Individually for 10 Subjects

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<th>Subject</th>
<th>b</th>
<th>r²</th>
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<td>.838</td>
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<td>2.563</td>
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<td>J</td>
<td>1.279</td>
<td>.917</td>
<td>1.505</td>
<td>.984</td>
</tr>
<tr>
<td>M</td>
<td>1.164</td>
<td>1.277</td>
<td>1.103</td>
<td>1.141</td>
</tr>
<tr>
<td>M'</td>
<td>1.013</td>
<td>1.084</td>
<td>1.064</td>
<td>1.023</td>
</tr>
</tbody>
</table>

Note. b = magnitude estimation exponent. b_m = exponent derived from marginal means. M' = mean based on 8 subjects; the two nonadditive data sets (Subjects B and E) excluded.

Table 2
Parameters of the Psychophysical Power Function for Massive Auditory Stimulation
Individually for 10 Subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>b</th>
<th>r²</th>
<th>b_m</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.52</td>
<td>.877</td>
<td>0.52</td>
<td>.865</td>
</tr>
<tr>
<td>B</td>
<td>0.40</td>
<td>.767</td>
<td>0.60</td>
<td>.996</td>
</tr>
<tr>
<td>C</td>
<td>0.62</td>
<td>.979</td>
<td>0.82</td>
<td>.974</td>
</tr>
<tr>
<td>D</td>
<td>0.72</td>
<td>.963</td>
<td>1.08</td>
<td>.996</td>
</tr>
<tr>
<td>E</td>
<td>0.82</td>
<td>.964</td>
<td>0.88</td>
<td>.996</td>
</tr>
<tr>
<td>F</td>
<td>0.60</td>
<td>.989</td>
<td>1.06</td>
<td>.991</td>
</tr>
<tr>
<td>G</td>
<td>0.74</td>
<td>.931</td>
<td>1.04</td>
<td>.995</td>
</tr>
<tr>
<td>H</td>
<td>0.86</td>
<td>.989</td>
<td>1.00</td>
<td>.990</td>
</tr>
<tr>
<td>I</td>
<td>0.76</td>
<td>.900</td>
<td>0.82</td>
<td>.998</td>
</tr>
<tr>
<td>J</td>
<td>0.92</td>
<td>.989</td>
<td>1.08</td>
<td>.994</td>
</tr>
<tr>
<td>M</td>
<td>0.70</td>
<td>0.89</td>
<td>0.72</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Note. b = magnitude estimation exponent. b_m = exponent derived from marginal means. M' = mean based on 8 subjects; the two nonadditive data sets (Subjects B and E) excluded.

Respective dimension. Here, too, there is some individual variation; it is small enough, however, to warrant the above conclusions.

General Discussion
A Functional Theory of Experimental Pain

Perhaps the simplest way to interpret the present set of results is to treat pain as a multicomponent, multistage process involving an amalgamation of sensory and cognitive transformations. At the initial sensory stage we assume that each noxious stimulus, $S$, undergoes a purely psychophysical transformation, $F$, into an internal painful sensation, $P$. These sensory transformations are, as a rule, discriminably different from one type of noxious stimulation to another. Thus, assuming a valid linear response scale, we have

$$ P = F(S). \tag{1} $$

When task or natural requirements cause the painful components to be integrated, the cognitive operations act on values of sensation $P$ rather than on the original stimuli $S$. Assuming the painful context comprises two stimuli, integration presumably takes the form

$$ T = P_o P_j, \tag{2} $$

where $T$ is the instantaneous level of pain and $o$ is an arithmetic operator such as addition. Again, we assume a valid linear response scale for $T$. The relation depicted in Equation 2 readily generalizes to any greater number of components.

The specific features characterizing each of the component noxious stimuli express themselves via their stimulus-specific sensory transformations. In the present study, for example, one such scale operates when subjects are called upon to make judgments of pain following powerful auditory stimulation. The subjective representations are best characterized by a mildly compressive power function governed by an exponent in the order of 0.90. This auditory pain function does not approximate the prototypical scales for loudness (with exponents in the order of
0.6) that come from magnitude estimation and magnitude production studies (Marks, 1974a; Stevens, 1975). Sound-induced painful sensations are rather transformed into values on what may be termed the $P_a$ (auditory induced pain) scale. These scale values express themselves whenever auditory stimulation is presented at sufficiently massive levels so as to cause discomfort of one degree or another. Given a loud tone, there are simultaneously two sets of scale values. One set operates when judgments of loudness are called for, but another nonlinearly related set of values operates when subjects are instructed to report the degree of pain or discomfort they feel. (Because loudness and pain are both presumed to be power functions of sound pressure, with different exponents for the different sensations, one scale must be a power function of the other). Another more expansive psychophysical transfer function $P_e$ (electrically induced pain) characterizes the transduction of electrocutaneous stimulation.4

As mentioned earlier, these initial sensory transformations, $E$, take place automatically like early transduction processes in other sensory systems. Therefore, once a powerful enough noxious stimulus is applied, it results in a painful central representation, $P$. These transformed values are projected as equivalent points—save for retaining their sensory identity—on a central cognitive space (Aristotle’s “common sense”?) to be integrated according to simple algebraic rules. The simple fact that subjects can trace their different painful sensations to discriminally different sources of irritation argues against a (probably simpler) assumption of a single common pain scale.5 In this sense, then, pain seems to behave analytically: Although there exist an overall feeling of pain or discomfort, the different nocuous components are, nevertheless, available to perception (see Marks, 1979a, 1980, for analogous phenomena in loudness, especially in the perception of complex tones whose frequency components are widely separated).6

Implications for Pain Theory and Research

The present theory spells out explicitly the assumptions of functional measurement theory for pain domain. The recurrent appearance of the additive structure both within a somatosensory communications system (Jones, 1980; Jones & Gwynn, 1984) and across separate systems (Gracely & Wolskee, 1983; the present investigation) fits well with a functional theory of pain. Because what is summed in central integration processes is pain rather than incoming electrocutaneous or acoustical energy, neither a priori dominance of one type of stimulus over the other nor any masking effects are expected. The simple additive model comes out, therefore, as a natural derivative of the information integration strategies acting on transformed $P$ values of pain.

Although the present study was not planned to test existing theories of pain, its results pose difficult problems for the now popular gate control theory (Melzack, 1973, Melzack & Wall, 1965, 1982).

Given (a) the ascending and descending projections assumed to influence the gate control system and (b) the completely unrelated nature of shocks and tones as noxious stimuli to be modulated at the gate, the appearance of the present additive model (as well as the ones demonstrated by Gracely & Wolskee, 1983; and by Jones, 1980, and Jones & Gwynn, 1984), though possible, is highly unlikely under the gate control theory. Some sort of a nonlinear model is the natural prediction of the gate control theory, given the complex and presumably different modulations at the gate of electrical shocks originated at the surface of the skin and auditory pulses coming from the ears. Indeed the notion

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4 It may be argued that the electrical stimuli used here might have activated primarily low-threshold mechanoreceptive afferents unrelated to nociception, so that the present study addresses mainly integration of perceived discomfort. Several lines of reasoning argue against such an interpretation. First, the same type of stimuli at much lower levels and shorter durations (see Rollman's and Babkoff's studies) have been shown or convincingly interpreted as directly stimulating nerve endings (recall, especially, the extremely steep psychometric functions obtained with such stimuli). Second, tremors and/or thumb twitches characteristic of aversive electrical intensity (Rosner & Goff, 1967) were occasionally observed with all of the present subjects. Third, there is some evidence (e.g., Wolbarth, 1960) that mechanoreceptors respond overall in a negatively accelerated fashion as a function of receptor potential. By contrast, positively accelerated electrocutaneous functions were obtained throughout in the present investigation. Fourth, and probably most important, our subjects were instructed to report the degree of pain or discomfort they felt upon the presentation of each compound stimulus. They completed this task in the most natural and straightforward manner without virtually a single "zero" judgment to nonzero stimulus intensities. Excessive pilot sessions demonstrated that the stimulus values used (including tone-free presentations) elicited aversive feelings that were reliably described as painful or uncomfortable. With pain, being a psychological experience, the subjective component should carry the most weight (Weisenberg, 1977). Taken as a whole, the present results are compatible with Rollman's (1969a) hypothesis that electrocutaneous stimuli bypass cutaneous receptors to excite afferent nerves directly.

6 If horizontal cuts are made at several values of the ordinate in Figure 1, the results are sets of stimuli that produce equivalent pain judgments. This analysis yields values of sound (dB) that are as noxious as appropriate values of electric current (mA). We do not present these data—though they are implicit—in order to avoid the impression of equivalent or interchangeable painful sensations. For even for identical ordinate values there are salient and ineluctable differences between sound-induced and electrically induced painful sensations. Of course, such an analysis can be useful for practical purposes, and the interested reader may well want to derive the respective values.

An alternative model might be proposed to account for the present data. The implicit combination rule may be of the form $R_{AE} = W_A S_A + W_E S_E$ where $R_{AE}$ is a response to combinations of tone and shock, the $S$s are scale values, and the $W$s are weights. According to such a model, the steeper rate of judgment for shock reflects the greater weighting of shocks over tones. The hypothesis advanced in this article seems, however, a more plausible explanation of our results. Given the peripheral and purely sensory nature of the psychophysical transduction process (Stevens, 1975), the notion of weight (to be distinguished from purely mathematical coefficients) does not, in our opinion, have much merit as an explanatory device in present context. Different sensory input—output systems, the operations of which are governed by different power function exponents, are a more natural description. Most successful applications of weight models in psychology have indeed been made in complex cognitive tasks such as judgments of seriousness of offences (Leon, Oden, & Anderson, 1973). Besides substantive considerations, there are great difficulties in separating weight and scale parameters, particularly when (a) an averaging response is not required nor assumed, and (b) row and column stimuli are composed of different types of information (both conditions apply to the present study). Because each weight parameter is conflated with
that resulting pain depends on the relative level of the respective noxious stimuli (i.e., there is an interaction) is at the very heart of the gate concept (see Melzack & Wall, 1982, chapter 10). Accordingly, one of the basic propositions of the theory states that "The spinal gating mechanism is influenced by the relative amount of activity in large-diameter (L) and small-diameter (S) fibers. . . ." (Melzack & Wall, 1982, p. 226, emphasis supplied). At other places it is argued that only when a stimulus is increased to levels sufficient to trigger a specific class of fibers would a "gate closing" effect exert (mostly inhibitory) influence on other stimuli (Higgins, Tursky, & Schwartz, 1971; see also Weisenberg, 1977). The functional theory, by contrast, argues that a given stimulus enters into the functional equation in the same way, no matter what it is added to. The present results bear out this prediction.

The gate control theory has been used to derive the interaction (i.e., nonadditive) prediction in a couple of laboratory studies that bear some resemblance to the present one. Thus Higgins, Tursky, and Schwartz (1971) conclude that "the present results are consistent with the postulated existence of a spinal gating mechanism capable of selectively reducing the affective reaction to a compound tactile–nociceptive stimulus" (p. 867, emphasis supplied). Melzack, Wall, and Weisz (1963) found vibration to reduce noxiousness of electric shock at low shock intensities but to enhance the aversive properties of the shock at higher intensities (see also, Halliday & Mingay, 1961; Melzack & Schecter, 1965; Wall & Cronly-Dillon, 1960). However, as some of the cited authors readily acknowledge, concurrency of nociception could not always be assured with enough rigor, given the stimuli used. More important, perhaps, is the fact that subjects in those studies were instructed to assess pain resulting from only one of the noxious dimensions. Considerations of adequate experimental control have dictated the present choice of electric shocks and loud auditory pulses from an enormous available range of pain-inducing stimuli (Rollman, 1983a, 1983b). Of course, the selection of separate somatosensory communication systems was imperative from a theoretical viewpoint.

The functional theory shares, therefore, the concern of the gate control theory (Melzack, 1973; Melzack & Wall, 1965, 1982) and of other approaches (Weisenberg, 1977, 1980, 1983, 1984) with motivational–affective and cognitive–evaluative components of pain. Yet it displaces the unnecessarily narrow, relatively peripherally located on–off concept of a gate by a multidimensional cognitive space where the different components interact (or fail to interact) according to simple algebraic models. The proposed integration processes, to be thought of as different organizations somewhere in the higher centers of the nervous system, fit well with the rich and multifaceted behavioral complexes characterizing pain phenomena.

Thus central representation of pain may interact with other related representations so as to potentiate, attenuate, or even eliminate a final painful reaction (such as in the following subtractive structure: Perceived Pain = Sensory Pain – Shamefulness of Overt Expression). Note that the associated integration model may act consciously (as may well be the case in the above hypothetical example) or wholly automatically as is sometimes found in the visual and the auditory systems (Algom & Cohen-Raz, 1984; Algom & Marks, 1984; Marks, 1979a).

References


INTEGRATION OF NOXIOUS STIMULATION


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