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The detectability, discriminability, and perceived magnitude of painful electrical shock

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Thresholds for sensation, pain, and tolerance were obtained from 20 male and 20 female observers who received trains of electrical pulses applied to the volar forearm. Also determined were estimates of sensory magnitude for a series of stimuli that spanned the pain sensitivity range (PSR) between pain threshold and tolerance, as well as Weber fractions for the discrimination of stimuli at the midpoint of the PSR. There were great individual differences in all dependent variables. Females had significantly lower values for all thresholds but did not differ from males in the growth of sensory magnitude or in discriminatory capacity. Power functions, with a median exponent of 1.74 and a mean of 2.39, fit the scaling data well. The results are analyzed for a suggested negative correlation between exponent and stimulus range. The presence of such an effect indicates that electrocutaneous stimulation provides a powerful technique for the analysis of individual differences and the evaluation of psychophysical theories.

Electrical stimulation of the skin provides a useful induction method for laboratory studies of pain (Procacci, Della Corte, et al., 1974; Rollman, 1983a; Smith & Andrew, 1970): it is readily graded in intensity, can be turned on and off instantaneously, and produces no lasting physical damage.

Past research has typically demonstrated that the subjective magnitudes of the sensations produced by electrical pulses can be related to their current or voltage by a power function with an exponent greater than unity, indicating that the perceived intensity grows at a rate faster than the physical one. The reported value of the exponent of the power function has varied considerably, from near 1.0 to beyond 3.0 (e.g., Algom, Raphaeli, & Cohen-Raz, 1986; Babkoff, 1976, 1978; Beck & Rosner, 1968; Bevan, 1966; Bromm & Treede, 1980; Bujas, Szabo, Kovacic, & Rohacek, 1975; Ekman, Frankenhaeuser, Levander, & Mellis, 1964, 1966; Hawkes, 1960; McCallum & Goldberg, 1975; Sachs, Miller, & Grant, 1980; Sternbach & Tursky, 1964; Stevens, Carton, & Shickman, 1958; Tashiro & Higashiyama, 1981). These differences can be ascribed, in part, to the effects of stimulus parameters and correction of the power function for threshold (Rollman, 1974), to the nature and scaling of the physical stimulus (Myers, 1982), to the painfulness of the presentations (Jones, 1980), and to regression and range effects (Cross, Tursky, & Lodge, 1975).

Although electrical shocks can be painful, most of the studies cited above determined power functions at levels that were weak enough for the sensation to be described as being tactile rather than nociceptive. Although there have been attempts to obtain psychophysical functions for intense stimuli in several modalities (e.g., Adair, Stevens, & Marks, 1968; Cooper, Vierck, & Yeomans, 1986; Craig, Best, & Ward, 1975; Ekman et al., 1964; Gracely, McGrath, & Dubner, 1978; Grossberg & Grant, 1978; Hilgard et al., 1974; Hill, Flanary, Kernetsky, & Wikler, 1952; Stam, Petrusic, & Spanos, 1981; Sternbach & Tursky, 1964; Tursky, Jamner, & Friedman, 1982), at present considerably more is known about the psychophysics of thermal pain than about electrocutaneous discomfort.

Psychophysical investigation in general, and perhaps pain research in particular, is affected by the presence of individual differences. Most perceptual studies have treated such differences as error or noise and have pooled data across observers; only a few have examined the data from single subjects (e.g., Algom et al., 1986; Ekman, Hosman, Lindman, Ljungberg, & Åkesson, 1968; Luce, 1972; Luce & Mo, 1965; Marks & Stevens, 1966; Pradhan & Hoffman, 1963). M. Teghtsoonian and R. Teghtsoonian (1971) reported individual differences in exponents for judgments of line length and apparent area, but the intersession correlations were generally insignificant, leading them to suggest that the differences do not reflect enduring characteristics of sensory or judgmental processes. Engeland and Dawson (1974) found considerable reliability in area and loudness exponents obtained 1 week apart. Using data obtained from comparisons of sensory intervals, Schneider (1980) derived individual power functions for loudness of pure tones which spanned about a threefold range of slopes and showed considerable consistency across replications. Enduring individual differences in loudness scaling were also found by Barbenza, Bryan, and Tempest (1970), Hellman (1981), Logue (1976), J. C. Stevens and Guirao (1964), and Wanschura and Dawson (1974). Where reported, the range of exponents was about threefold to sixfold.

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More recently, M. Teghtsoonian and R. Teghtsoonian (1983) observed that correlations between exponents for magnitude estimates of line length dropped to nearly zero after 1 week, as did those for cross-modal matches between line length and brightness. The correlations between magnitude estimates of loudness, given a week's delay, were significant, but alterations in the modulus between sessions eliminated this relationship. They suggested that the apparent consistency of individual exponents depended on memory factors rather than persistent characteristics of transduction or response pattern.

Individual differences in judgments of line length, area, or loudness may well be considerably smaller than those for judgments of pain. The latter reflect a complex interaction of sensory, motivational, and cognitive factors (Melzack & Wall, 1965), and it is well established both in the laboratory and in the clinical literature that wide ranges exist for pain thresholds, tolerance levels, requests for analgesics, and other behavioral measures of response to discomfort.

Observers also differ markedly in their dynamic ranges, the ratio of the strongest to the weakest stimulus they can report, and their pain sensitivity ranges (PSRs) (Wolff, 1971), the interval between pain and tolerance thresholds. R. Teghtsoonian (1971) suggested that, across continua, "variation in power law exponents is primarily due to variation in dynamic ranges" (p. 71), and he showed a powerful negative relationship between dynamic ranges and exponents. Only one study, conducted by R. Teghtsoonian, M. Teghtsoonian, and Karlsson (1981), has explored the association between dynamic range and exponent for a single continuum (effort on a bicycle ergometer). Although their analysis failed to find the predicted negative correlation, demonstration of such a relationship within the pain modality might indicate stable individual differences in the factors underlying pain reports and psychophysical judgments.

METHOD

Subjects

Twenty male and 20 female undergraduate students read and signed a consent form prior to participation in the study.

Apparatus

A constant-current stimulator, incorporating a crystal clock timer, delivered trains of 40 1-msec monophasic square-wave pulses, with a stimulus onset asynchrony of 10 msec (total duration = 391 msec), to the prepared left volar forearm through a pair of Grass silver electrodes, 1 cm in diameter, filled with Grass electrode paste and taped to the skin with a center-to-center distance of 2 cm.

Procedure

Stimulation current was adjusted using an ascending method of limits, with discrete steps of .075 mA. After considerable familiarization with apparatus and procedure, the subjects reported, on a single ascending trial, when the electrocutaneous pulse trains first became detectable (sensation threshold), when they became painful (pain threshold), and when they reached a point at which no stronger stimuli were acceptable (pain tolerance).

The pain sensitivity range (PSR) was calculated as the difference between the two latter levels. The maximum current used in the direct scaling experiment was set at three-fourths of the value between pain threshold and tolerance, that is, at pain threshold plus 0.75(PSR). The range between this level and the pain threshold was then partitioned for each observer, providing six stimulus levels beginning somewhat above the pain threshold. Each of these stimuli was presented four times in randomized order. Following each of these presentations, observers assigned a number to the magnitude of the painfulness experienced, so that the ratio of numbers used reflected the ratio of perceived painfulness. No modulus or standard was employed.

A determination of the just noticeable difference (ΔI) was also obtained, using the method of limits (Underwood, 1966) for a standard (I) set at about the midpoint of the PSR. The step size was .04 mA and the data were averaged across two ascending and two descending runs.

RESULTS AND DISCUSSION

Principal Results

The sensation threshold, pain threshold, tolerance, power function exponent, PSR, dynamic range, and Weber fraction ($\Delta I/I$) were determined for each of the 40 observers, and are presented in Table 1. The PSR was obtained by subtracting the pain threshold from the tolerance current; the dynamic range is the ratio of tolerance to sensation threshold. The logarithm of the geometric mean of the magnitude estimations were plotted against the logarithm of the six stimulus levels for each observer, and the best-fitting line was determined by the method of least squares. The fit of the data to a power function was good; 36 of the 40 rs equaled or exceeded .90, and half of the correlation coefficients were .97 or higher. These values are presented in Table 1 as well. There were great individual differences in the exponents of the power functions: the range was from 0.29 to 9.93 (but the interquartile range was 1.24 to 2.58) and the median slope was 1.73.

Analyses of variance demonstrated sex differences in sensation threshold [$F(1,38) = 4.15$, $p < .05$], pain threshold [$F(1,38) = 7.8$, $p < .01$], and tolerance [$F(1,38) = 4.68$, $p < .05$], with females having significantly lower values (for absolute threshold, females had a mean value of .52 mA, whereas males had one of .71 mA; corresponding values for pain threshold were .95 and 1.37 mA and for pain tolerance, 3.01 and 4.07 mA, respectively). There were no significant differences between females and males in the size of the exponent (means of 2.36 and 2.42, respectively) or Weber fraction (means of 0.08 for both groups). The difference and ratio measures, PSR and dynamic range, also showed no differences across the genders.

Correlations were obtained between thresholds, exponents, range measures, and Weber fractions. Table 2, which presents these, indicates that the slope of the power function relating magnitude judgments to stimulus current showed significant negative correlations with pain tolerance, PSR, and dynamic range.

Table 1
Thresholds, Power Function Characteristics, Range Measures, and Weber Fraction for Each Observer

		Thresholds (mA)						Dynamic	Weber
Subject	Sex	Sensation	Pain	Tolerance	Exponent	*r*	PSR	Range	Fraction
1	M	0.79	1.65	4.50	2.24	.98	2.85	5.70	0.097
2	M	1.20	1.88	4.05	1.36	.98	2.17	3.38	0.093
3	M	0.15	0.45	1.65	2.16	.98	1.20	11.00	0.105
4	M	0.56	1.20	4.05	3.29	.997	2.85	7.23	0.106
5	F	0.49	0.75	2.55	3.14	.95	1.80	5.20	0.030
6	M	0.83	1.35	4.35	1.79	.93	3.00	5.24	0.091
7	M	0.53	1.50	3.15	1.01	.91	1.65	5.94	0.155
8	F	0.71	1.95	3.60	0.29	.59	1.65	5.07	0.086
9	F	0.20	0 45	2.55	1.72	.97	2.10	12.75	0.033
10	M	0.98	1.95	2.55	2.83	.95	0.60	2.60	0.057
11	F	0.68	0.90	7.35	1.32	.98	6.45	10.81	0.082
12	F	0.90	0.98	2.25	2.43	.93	1.27	2.50	0.108
13	M	0.41	0.90	5.40	0.80	.95	4.50	13.17	0.121
14	M	1.43	1.65	5.85	0.71	.99	4.20	4.09	0.061
15	M	0.79	2.40	6.00	1.24	.96	3.60	7.59	0.081
16	M	0.75	1.50	4.65	1.62	.97	3.15	6.20	0.075
17	M	0.71	1.50	4.05	1.77	.98	2.55	5.70	0.047
18	M	0.75	1.65	5.55	0.60	.99	3.90	7.40	0.053
19	F	0.41	0.90	2.10	1.11	.94	1.20	5.12	0.113
20	M	0.26	0.60	3.30	1.76	.93	2.70	12.69	0.108
21	F	0.56	1.65	3.75	2.57	.97	2.10	6.70	0.078
22	F	0.45	1.05	4.50	2.03	.97	3.45	10.00	0.083
23	M	0.53	1.05	2.25	7.70	.90	1.20	4.25	0.103
24	F	0.90	1.35	2.40	2.44	.95	1.05	2.67	0.112
25	F	0.75	1.65	4.95	1.07	.95	3.30	6.60	0.067
26	F	0.15	0.45	1.50	2.76	.99	1.05	10.00	0.112
27	M	0.45	1.05	1.50	9.93	.86	0.45	3.33	0.040
28	F	0.60	0.90	1.95	6.17	.99	1.05	3.25	0.035
29	F	0.45	0.60	1.35	7.86	.71	0.75	3.00	0.044
30	F	0.15	0.30	0.90	2.40	.99	0.60	6.00	0.067
31	F	0.45	0.90	1.65	4.04	.99	0.75	3.67	0.070
32	M	1.13	1.58	6.60	1.72	.93	5.02	5.84	0.046
33	M	1.13	1.65	2.25	2.60	.99	0.60	1.99	0.043
34	F	0.60	0.75	4.35	1.12	.93	3.60	7.25	0.051
35	F	0.60	0.75	4.35	1.23	.96	3.60	7.25	0.125
36	M	0.26	0.45	3.60	1.48	.99	3.15	13.85	0.067
37	M	0.53	1.35	6.00	1.69	.96	4.65	11.32	0.052
38	F	0.45	0.75	3.45	0.50	.88	2.70	7.67	0.090
39	F	0.30	0.60	2.40	1.69	.99	1.80	8.00	0.106
40	F	0.68	1.35	2.40	1.29	.99	1.05	3.53	0.108

The results provide evidence concerning a number of issues in the psychophysics of pain, and these will be reviewed in turn. These issues are: individual and sex differences in pain responsiveness, perceived magnitude of painful electrical pulses, the relationship between physical range and exponent, and the discriminability of painful shocks.

Individual Differences in Pain Responsiveness

The pain threshold and tolerance measures show enormous variation across subjects, with ranges of 2.10 mA, or 8-fold in ratio terms, for threshold and 6.45 mA, or greater than 8-fold, for tolerance. At the least, they demonstrate the need to determine stimulating parameters on an individual basis in any experiments or applications involving electrocutaneous stimulation. The current range is less, in absolute terms, for sensation threshold (1.28 mA) than for the pain measures, but the ratio is greater than 9-fold. Laitinen and Eriksson (1985), using saline-soaked felt electrodes, found a 5-fold range for pain threshold but a considerably smaller one for sensation threshold. Larkin and Reilly (1984) reported a 2-fold range for sensation threshold voltage when stimulating the skin by capacitative electrical discharges. R. L. Brown, Spern, Schmitt, and Solomon (1966) indicated wide variability in both electrocutaneous sensation and pain thresholds; the range of the latter was greater than 4-fold. The range for exponent of the best-fitting power function is greater than any of the above (more than 30-fold); the implication of this finding will be discussed in detail later, as will that for the Weber fraction, $\Delta I/I$, which spanned a 5-fold range.

Wide variability in threshold measures is not confined to the study of electrocutaneous stimulation. Although data

Table 2

Pearson Product-Moment Correlations Between Thresholds (mA), Exponent, Range Measures, and Weber Fraction

	Sensation Threshold	Pain Threshold	Tolerance Threshold	Exponent	PSR	Log PSR	Dynamic Range	Log Dynamic Range
Pain Threshold	0.7642‡							
Tolerance Threshold	0.4471†	0.4730†						
Exponent	−0.1757	−0.2164	−0.5165‡					
PSR	0.2279	0.1729	0.9496‡	−0.5004‡				
Log PSR	0.1812	0.1786	0.9045‡	−0 5969‡	0.9476‡			
Dynamic Range	−0.5819‡	−0.4229†	0.3366*	−0.3771*	0.5268‡	0.5568‡		
Log Dynamic Range	−0.5808‡	−0.3705*	0.4008†	−0.4199†	0.5798‡	0.6336‡	0.9662‡	
Weber Fraction	−0.1565	−0.0515	−0.0391	−0.3000	−0.0254	0.0781	0.1397	0 1694

*$p < .05$. †$p < .01$. ‡$p < .001$ (two-tailed tests).

on individual differences are rarely presented, examples can be found in the literature for other modalities. For instance, in audition, Steinberg, Montgomery, & Gardner (1940) tested 35,589 subjects, between 20 and 29 years of age and without known otological pathology, at the 1939 New York World's Fair. Thresholds for pure tones covered an enormous range; the interquartile range spanned more than 20 dB (a 10-fold range of sound pressure).

A similar range of thresholds was found by Dadson and King (1952), who determined pure-tone thresholds for 99 otologically normal subjects between the ages of 18 and 25 years and found standard deviations of 5.7 to 10.7 dB for a series of frequencies between 80 Hz and 15 kHz.

Hecht and Mandelbaum (1948) published the range incorporating 80% of a group of 110 normal observers tested during a 30-min dark-adaptation period. Their thresholds spanned about 0.6 log units (4-fold). Comparable values have been reported by others (Le Grand, 1957).

Rabin and Cain (1986), citing an estimate that human olfactory sensitivity varies within a 256-fold range, used a normalization procedure to correct for stimulus noise and measurement errors. Nonetheless, a 20-fold range of threshold remained. R. Teghtsoonian et al. (1981), studying individual differences in perceived effort on a bicycle ergometer, observed that both absolute threshold ("the workload perceived as just requiring any muscular force at all") and terminal threshold ("the greatest workload the subject could pedal at 60 rpm") showed a 5-fold range across subjects. Vibration sensitivity on the fingertip, as a function of frequency, was tested by Goff, Rosner, Detre, and Kennard (1965) for 417 normal subjects who ranged in age from 10 to 72. Standard deviations were on the order of 10 dB.

Ippolitov (1972) studied individual differences in three modalities for a large group of subjects. Among those 27 who were consistent in their performance, scotopic visual threshold varied over a 28-fold range, pure-tone threshold over 14.5 dB (5.3-fold in voltage), mechanical pressure, using von Frey hairs, over a 3.5-fold range, and electrocutaneous threshold, using a constant voltage stimulator, over a 6-fold range. Correlations between rank orders of sensitivity were considerable for the two forms of somatosensory stimulation ($r = .76, p < .01$); they were not significant for cross-modal comparisons.

Relationship Between Threshold and Tolerance

Within an individual, there is considerable consistency in pain responsiveness. The Pearson correlation between pain threshold and tolerance is +.47 ($p < .002$), and both pain threshold ($r = +.764, p < .001$) and pain tolerance ($r = +.447, p < .004$) correlate significantly with sensation threshold. In general, the pain threshold is about twice the sensation threshold; the tolerance threshold is about six times the detection level. Significant correlations between the two nociceptive indices have been found by Harris and Rollman (1983) for pain induced by cold and pressure; in that experiment, the correlation between shock pain threshold and pain tolerance was insignificant. Tursky and O'Connell (1972) made similar comparisons. Under their conditions, 7 out of 10 correlations between sensation threshold and pain threshold were significant. Likewise, 8 out of 10 correlations between sensation threshold and pain tolerance and 10 out of 10 correlations between pain threshold and tolerance were large enough to achieve significance.

Might correlations among sensory threshold, pain threshold, and pain tolerance simply reflect the fact that they were determined on a single trial? The results obtained by Harris and Rollman (1983), Tursky and O'Connell (1972), and others (e.g., R. A. Brown, Fader, & Barber, 1973; Clark & Bindra, 1956) demonstrate that significant correlations between sensation threshold, pain threshold, and pain tolerance are frequent but not inevitable outcomes. Correlations can be significant even when pain threshold and tolerance are measured on separate days. For example, Rollman and Clohosey (1984) found a correlation of .47 ($p < .01$) for pain threshold on Day 1 and pain tolerance on Day 2 for a group of 26 males receiving trains of electrical pulses.

Gelfand (1964) sought to redefine pain tolerance as the region between pain threshold and withdrawal from the session. Under this definition, the correlation between pain threshold and "tolerance" for ultrasonic heat was extremely low, whereas it was about .65 under the more usual definition. On the other hand, Wolff and Jarvik

(1963) found significant correlations using either operational definition. Wolff (1964) suggested that a more appropriate term for Gelfand's "tolerance" would be "pain sensitivity range."

Logically, each of these measures can involve different components of sensitivity and criterion. Merskey and Spear (1967), for example, concluded that "pain threshold is more dependent on physiological factors and pain tolerance upon psychological ones" (p. 142). Similar views were expressed by Beecher (1959). Harris and Rollman (1983) found that correlations for thresholds or tolerance levels were higher across stressors (shock, cold, and pressure) than within a stress condition, providing evidence of discriminant validity (Campbell & Fiske, 1959) for the two measures, and noted that pain threshold emphasizes the discrimination of nociceptive quality, whereas pain tolerance serves as an expression of unwillingness to receive more intense stimulation. Emotional and motivational factors may be more important in the second of these.

Gender Differences in Pain Responsiveness

The question of sex differences in pain responsiveness has long interested researchers. Clark and Mehl (1971) summarized much of the early data: some studies found that women have a lower pain threshold than men, whereas others reported no difference. Inconsistencies across pain studies may be ascribed to stimulus and response differences, among others (Rollman, 1983a).

For a single form of pain induction, radiant heat, Clark and Mehl (1971) found that pain thresholds did not differ across sexes, whereas Della Corte, Procacci, Bozza, and Buzzelli (1965) reported that they were significantly lower in women than in men. Goolkasian (1980) found that women who used oral contraceptives did not differ from men in the likelihood of reporting thermal stimuli as painful; however, women who experience ovulation demonstrated a heightened pain responsiveness. Later studies by Goolkasian (1983) and Goolkasian and Rimer (1984) indicated effects of dysmenorrhea and pregnancy on responses to thermal pain.

Responsiveness to another form of pain induction, mechanical pressure on the Achilles tendon, was determined for over 40,000 members of a prepaid health plan in northern California (Woodrow, Friedman, Siegelaub, & Collen, 1972). The mean pain tolerance of the 17,393 male subjects was nearly 81% greater than that of the 23,726 females.

Sex differences have been shown in the tolerance of electric shock, with males having a higher tolerance than females (Notermans & Tophoff, 1967; Tedford, Warren, & Flynn, 1977) and a higher "insensitivity" score on a nonparametric pain rating task (Buchsbaum, Davis, Coppola, & Naber, 1981). Jones and Gwynn (1984) reported that females typically rated the same shock intensities as being more painful than did males. Notermans (1966) and Notermans and Tophoff (1967) found no effect of gender on the threshold for pain produced by electrical stimuli. However, a conclusion that sex differences exist for tolerance but not for pain threshold is not supported by the present data (or by some of those presented by Mumford & Stanley, 1981, for stimulation of the dental pulp).

For all three measures—absolute threshold, pain threshold, and pain tolerance—women exhibit significantly lower values than men. It is unlikely that the effects can be related to menstrual periods in the female subjects; even if such effects are not balanced by the selection methods, they are generally quite small, about 5% to 10% of the mean (Procacci, Zoppi, Maresca, & Romano, 1974; Tedford et al., 1977).

In this study, the pain threshold for men was 44% greater than that for women; the pain tolerance threshold was elevated by 35%. It is important to recognize that gender differences were not limited to pain responsiveness. The absolute threshold for male observers was .71 mA, a value 37% greater than the .52-mA level at which women, on average, reported the presence of the stimulus. Consequently, there seems to be a general sex difference in response to electrocutaneous shock.

Demonstration of a sex difference in responsiveness does not explain its cause. It remains to be determined whether the contribution of sensory and non-sensory factors can be distinguished (Clark & Mehl, 1971; Clausen & King, 1950; Rollman, 1977). Larkin and Reilly (1985), for example, found that the lower detection thresholds shown by female subjects for electrical stimulation of the forearm and fingertip were no longer apparent when the data were corrected for body size. If further differences in reactions to electrical stimulation are due to motivational or attitudinal predispositions (Rollman, Harris, & Scudds, 1986), it is of interest to see whether cognitive interventions (Tan, 1982) can selectively remove them.

Sternbach and Tursky (1965) reported an example of tolerance differences across groups (ethnic origin) which were assumed to be attitudinal because the absolute or sensation thresholds were not different. In the present experiment, although differences occurred for both measures across sex, attitudinal inequality could still be a factor.

Gender differences in responsiveness are not unique to electrocutaneous stimulation or to pain—they are widely found in studies on sensory function. Archer (1976) concluded that "women show lower thresholds than men for touch, pain, hearing, taste, smell and rod vision, whereas men show lower thresholds for cone vision" (p. 242). The results in the literature are sometimes inconsistent, but when sex differences occur they are generally in the direction reported above. Reviews of the literature on sex differences in perceptual and cognitive tasks, examining the role of sociodevelopmental and biological factors, can be found in Butler (1984), McGuinness (1976b), McGuinness and Pribram (1979), Mosley and Stan (1984), and Wittig and Petersen (1979).

In audition, Corso (1959) tested 500 subjects and found that females had lower pure-tone thresholds in all age groups, starting with 18–24 years, and that the difference increased with age. Women's thresholds were generally about 2 dB lower than men's at lower frequencies and about 10 dB lower between 4 and 8 kHz. Sizable differences have also been found by McGuinness (1972).

McGuinness (1974) measured the auditory counterpart of pain tolerance, the level at which pure-tone sounds become "just too loud," and found that women selected levels 7 to 8 dB lower than those selected by men throughout the 125-Hz to 12-kHz range. Individual tolerance levels ranged from 40 to 100 dB for women and from 60 to 115 dB for men. Pishkin and Blanchard (1964) found that women were more accurate in judging changes in auditory intensity, but did not differ from men in frequency discrimination.

In vision, there are data suggesting that males have better static (Brabyn & McGuinness, 1979) and dynamic (Burg & Hulbert, 1961) acuity than females. McGuinness (1976a) tested 25 men and 25 women on four tasks: acuity, dark-adapted absolute threshold, visual persistence, and comfortable brightness (the maximum level one "could look at indefinitely"). Men had better acuity and were marginally less tolerant of light than women. Females with normal acuity had lower absolute thresholds than normal males. Also, women had longer visual persistence in the dark.

Le Magnen (1952) reported that women were more sensitive, by three orders of magnitude, in detecting the odor of Exaltolide, a synthetic musk-like odorant. Data supporting a marked female superiority in identifying common odors comes from Cain (1982). Sizable sex differences, with women having lower thresholds than men in detecting a series of odorants, were obtained by Koelega and Koster (1974), using a forced-choice task.

Maccoby and Jacklin (1974), in a detailed review of the literature on sex differences, described eight studies of neonatal tactile sensitivity. Three of them reported a sex difference, each finding lower thresholds in girls. A number of other neonatal studies, yielding similar results, were reviewed by Gerai and Scheinfeld (1968).

Goff et al. (1965), who tested vibration sensitivity for 213 men and 204 women, found highly significant sex differences ($p < .001$) at all frequencies between 50 and 600 Hz except for the very lowest one. Men had the lower thresholds, with a mean difference of 5.8 dB. However, Weinstein and Sersen (1961), who tested 68 men and 68 women for pressure threshold on the forearm, palm, and sole, observed that women were significantly more sensitive at the latter two sites.

No gender differences were found for the scaling or discrimination components of this study. The exponents of the power functions and the Weber fractions were nearly equivalent across groups, indicating that whatever factors account for the detectability effects influence neither the perceived growth of unpleasantness as a function of stimulus intensity nor the ability to discriminate changes in pain-inducing current. Swartz (1953) also failed to find sex differences in scaling pain produced by electrical tooth-pulp stimulation.

Perceived Magnitude of Painful Electrical Pulses

The results demonstrate that power functions well describe the data obtained from individual subjects for painful electrocutaneous shock trains. For at least half of the subjects, total variance in magnitude estimation accounted for by log current value is 94% or greater.

The version of the power law that directly relates subjective judgments to physical intensity has a median exponent, across subjects, of 1.74. This confirms the oft-reported finding of exponents greater than unity for electric shock. The median exponent is comparable to the value of 1.75 obtained by Cross et al. (1975) for magnitude estimations of nonpainful electrical stimuli. The distribution of exponents is markedly skewed (whereas those for the other variables are not). Consequently, the mean value of 2.39 is higher than that of the median and comes close to the mean value of 2.5 reported by R. Teghtsoonian (1971) for several studies of shock scaling. The parameters in each of these studies are quite different, but it is possible that the transfer functions for electric current are the same no matter whether the stimulus is judged to be tactile or nociceptive in quality.

An alternative power law formulation that describes physical input in terms of intensity above the pain threshold reduces the exponent markedly, whereas that which uses the sensation threshold causes a smaller decline. Bromm and Treede (1980) determined exponents, using a visual analogue scale, for both nonpainful and painful values of electrical shock applied to the fingertip. Their median exponent was 1.44 across the full range. When the data for the tactile range were corrected for sensation threshold (mean = 0.75 mA) and those for the painful range were corrected for pain threshold (mean = 5.54 mA), two separate power functions, each with a slope of unity, were obtained. Ekman et al. (1964, 1966) found a slight reduction in exponent (from 1.81 to 1.54) when a correction was applied for sensation threshold; Rollman (1974) showed a much larger effect and indicated that the uncorrected power law more adequately described the subjective effects of electrocutaneous pulses.

Algom et al. (1986) had 10 subjects make magnitude estimates for six levels of electrocutaneous stimulation paired with six levels of sound pressure. Although their major interest was in the integration of noxious stimuli, it is possible to obtain individual psychophysical functions for each modality. The data for electrocutaneous stimuli alone, derived on trials when tones were well below the threshold of audibility, yield power functions, corrected for threshold, with an exponent of 1.15.

The present study demonstrated wide individual differences in the slope of the best-fitting power function. Some of the most extreme values, at both the upper and lower end of the range, had functions with large amounts of variance unaccounted for by linear regression on log current. Cross et al. (1975) reported similar findings with more experienced subjects—a wide range of exponents with low correlations at the extremes. In their study, exponents showed a 3-fold range. Individual values of exponents determined by Algom et al. (1986) ranged from 0.70 to 2.48. In the present experiment, with a larger number of observers, the range was wider, since even if correlations of .97 or greater were required ($N = 20$), slopes extended from .60 to 6.17. Only two of these values, however, were less than 1.0, and only two were greater than 3.3.

The Relationship Between Physical Range and Exponent

The observers differed markedly in sensation threshold, pain threshold, and pain tolerance, and, consequently, in dynamic range and pain sensitivity range. The observers also differed markedly in the exponents of the functions relating sensory magnitudes to physical stimuli. Are these outcomes related?

Poulton (1968) described numerous instances in which the slopes of power functions were steeper for a narrow range of stimuli than for a wide one. Jones and Woskow (1966), in an analysis of some of S. S. Stevens's (1960) data, discovered a rho rank correlation of −.93 ($p < .01$) between the size of the exponent and the geometric stimulus range employed; Poulton (1967), using another set of data from S. S. Stevens, obtained a tau rank correlation of −.60 ($p < .001$). Poulton (1968) noted, "This strongly suggests that in designing the experiments to measure the exponents, the experimenters did not adequately compensate for the effects of the different physical ranges available along the different stimulus dimensions" (p. 5).

R. Teghtsoonian (1971) acknowledged the relationship between stimulus range and exponent (in fact, he reanalyzed the data Poulton examined and found a Pearson r of −.935), but he gave it another interpretation. Rather than depending upon the experimenter's choice of stimulus range, Teghtsoonian proposed, the correlation between these variables was due to the differences, across modalities, in the ratio of the greatest to the smallest stimulus intensity to which the subject was responsive (the dynamic range), coupled with a constant maximum range of subjective sensory magnitude. Teghtsoonian did not deny that range effects might influence the exponent, as in studies in which range is varied intramodally (R. Teghtsoonian, 1973; R. Teghtsoonian & M. Teghtsoonian, 1978), but he said they appeared to be insufficient to explain the large effects that occurred intermodally.

Although complete data on diversity in dynamic range for different modalities are lacking, it seems likely that nowhere else will one find the spread that exists for electric shock. As noted earlier, the question arises of how the range for each individual is influenced by sensory and attitudinal factors. Nonetheless, the data show a remarkable spread in the range of currents that individuals are willing to endure.

This range can be expressed in a number of ways. Wolff (1964, 1971) introduced the PSR, the interval between pain and tolerance thresholds. In the present study, this arithmetic index is largely determined by tolerance ($r = +.950$, $p < .001$) rather than the pain threshold ($r = +.173$) and has a mean value of 2.92 mA with a range of .75 to 6.67 mA). The dynamic range, which is important in R. Teghtsoonian's (1971) hypothesis about power law exponents, is estimated as the ratio of tolerance threshold to sensation threshold. Its mean is 6.64 and, again, there is a very wide range, 1.99 to 13.85. The Pearson correlation of these difference and ratio scores is +.53 ($p <$ 001); this is comparable to +.57 ($p < .001$) for the dynamic range (a ratio) and the difference between sensation threshold and tolerance and to +.70 ($p < .001$) for the PSR and the tolerance ratio (Mumford & Stanley, 1981), the pain tolerance level divided by the pain threshold. As noted earlier, individuals with a high tolerance will tend to have large PSRs ($r = +.95$); the correlation of tolerance with the dynamic range, expressed as a ratio, is smaller ($r = +.34$, $p < .03$).

In selecting the stimuli to be used in the direct judgment task, two approaches can be contrasted. The first is to present the same set of stimuli to all observers; the second is to tailor the stimulus set to each individual's range. In most scaling experiments, the first approach is utilized. For example, Cross et al. (1975) delivered currents of between 1.0 and 5.5 mA through a concentric electrode to all of their subjects, obtaining exponents that ranged from 1.65 to 4.08.

The present study used the second approach, to acknowledge individual differences explicitly. The stimuli spanned a roughly constant proportion of the dynamic range. Exponents were not constant across observers, nor should they be expected to be.

R. Teghtsoonian (1971) proposed his model relating exponent and dynamic range as an explanation of intermodal differences in sensory magnitude scales, but it is instructive to examine it for a situation in which wide intramodal differences are found. His hypothesis states that "the ratio of the greatest to the smallest possible sensory magnitude is approximately constant for all perceptual continua" (p. 72) and "variation in power law exponents reflects variation in the ratio of the greatest to the smallest stimulus intensity to which [the subject] is responsive" (p. 72). It follows that "the relative size of exponents reflects the relative size of dynamic ranges" (p. 74). On the basis of an analysis of 21 experiments by S. S. Stevens and his associates, R. Teghtsoonian found an excellent fit to an equation describing an inverse relationship between these variables—$n = K/(\log R_\phi)$, where n is the exponent, K is a value reflecting the constant ratio of sensory judgments, and R_ϕ is the dynamic range.

R. Teghtsoonian et al. (1981) examined the capacity of R. Teghtsoonian's (1971) theory to account for individual differences in exponent for a single task, the scaling of perceived effort on a bicycle ergometer. Based upon the notion that the maximum range of subjective magnitude is equivalent across perceptual continua (i.e., dynamic ranges are subjectively equal), the theory predicts that various dynamic ranges will be matched by the same response range on the judgmental continuum. Given that psychophysical power relations represent a linear association between the logarithm of the stimulus intensity and the logarithm of the matching response, it follows that the slope of the psychophysical function (the exponent) will be inversely related to dynamic range, even within a given modality. R. Teghtsoonian et al. (1981) pointed out an assumption that accompanies this argument, namely that the judgmental continuum is related, in a known way, to subjective magnitude, and noted that many have argued that the number scale used in magnitude estimation experiments bears the desirable linear relation.

In the bicycle ergometer study, magnitude estimates and dynamic ranges were obtained on four blocks of trials. Absolute and maximum thresholds showed a 5-fold range. The correlation between estimates of individual exponents and reciprocals of log dynamic range varied somewhat across blocks, ranging from 0 to 0.10. It was 0.29 for the combined data. None were statistically significant. In a preliminary analysis of these results, in which the 30 subjects were divided into five groups on the basis of size of dynamic range, the rank order correlation between mean dynamic range and mean exponent for each group was, however, statistically significant.

R. Teghtsoonian et al. (1981), in reviewing the failure of their study to find the predicted correlation, suggested that either individuals differ markedly in their ranges of subjective magnitude or the numerical judgment ranges differ widely. Their preference is for the second, based upon both anectodal evidence regarding maximum exertion and the lack of direct evidence for number's being linear with sensation. It is easier to test whether maximum subjective range is constant over perceptual continua (since these comparisons are made within a single central nervous system) than to test whether maximum subjective range is constant over individuals (Borg, 1962), since there is no single response system that can be known to be constant for different observers. It is possible that newer psychophysical methods, such as category-ratio judgments and magnitude matching (Marks, Borg, & Ljunggren, 1983), may help to clarify these matters.

Is there a negative correlation between exponent and dynamic range in the present study? The answer is yes, although the relationship, for an intramodal range that spans less than 1 log unit, is not as dramatic as that which R. Teghtsoonian (1971) found for S. S. Steven's intermodal physical ranges, which exceeded 6 log units.

The Spearman rank order correlation, rho, between exponent and dynamic range is −.40 ($p < .005$). For electric shock, small increases in sensation threshold current produce large decreases in the ratio value; difference scores may more adequately express the variability in pain responsiveness across individuals. The PSR has already been described (tolerance − pain threshold); the counterpart of the dynamic range, expressed as a difference score (tolerance − sensation threshold), might be called the full sensitivity range (FSR). The PSR and FSR correlate highly ($r = +.97, p < .001$), so there is little basis upon which to choose between them. Individual exponents correlate significantly with PSR (rho $= -.60, p < .001$) and FSR (rho $= -.61, p < .001$).

Given the variable use of number scales by psychophysical observers, the finding of correlations of this magnitude in an intramodal experiment is impressive. It demonstrates a clear relationship between exponent and range, as both Poulton (1968) and R. Teghtsoonian (1971) would expect.

R. Teghtsoonian (1971) explicitly provided for stimulus range as well as dynamic range effects, and suggested that the small variation in exponent generally obtained in intramodal experiments (R. Teghtsoonian & M. Teghtsoonian, 1978) was attributable to the first factor. The broad spectrum of exponents obtained for electrical pulses could be the exception to this proposal. The predicted linear relationship between $1/n$ and $\log R_\phi$ receives weak support on an individual basis (Pearson $r = +.18$), although the rank order correlation is more substantial (rho $= .40, p < .005$). The mean exponents and dynamic ranges suggest that the value of K (the range of subjective magnitude in log units), in R. Teghtsoonian's (1971) analysis, takes on a value of 1.96, although his obtained value was 1.53 for less intense maximum stimulus levels.

Whether the present findings are simply dependent upon stimulus range effects or reflect, rather, an inherent interindividual difference in dynamic or sensitivity range may best be answered by experiments that vary the former for a population of observers differing in the latter. Then it may be possible to determine whether a small range gives rise to a steep function because the responses are distributed across the stimulus set (Poulton, 1968) or because the responses are distributed across the dynamic range (R. Teghtsoonian, 1971). The collection of exponents found by Cross et al. (1975), for a constant stimulus set, coupled with the present findings favor the second explanation.

Corresponding Analysis of Evoked Potential Data

An analysis similar to the present one can be performed on the data presented by Fernandes de Lima et al. (1982), who obtained sensation thresholds, power functions, and cerebral evoked potentials for brief electrical pulses applied to the tooth pulp of 11 observers. The behavioral data alone were obtained from 3 other subjects as well. Thresholds spanned more than a 20-fold range, psychophysical exponents (corrected for sensation threshold) varied more than 4-fold, and the exponents of the power functions that relate the tooth-pulp evoked potentials (TPEPs) to stimulus current differed by more than 6-fold. The exponents of the TPEP functions were much smaller than those of the psychophysical ones, and the Pearson correlation of the two ($r = +.51, p < .055$) just failed to reach significance in a one-tailed test.

Wide intersubject variability in neural and psychophysical responses were also obtained by Knibestol and Vallbo (1976). Electrodes inserted into the median and ulnar nerves of human volunteers permitted the determination of stimulus-response functions for slowly adapting mechanoreceptors. Direct scaling procedures were used to obtain magnitude estimates for the same skin displacements. Power function exponents for the neural data spanned a 6.6-fold range (from .25 to 1.65). The range for psychophysical functions was comparable at 5.8-fold (0.35 to 2.04) and had a higher mean (1.2 compared to 0.72). Simultaneously determined neural and psychophysical functions frequently had vastly different exponents.

Fernandes de Lima et al. (1982) divided the range between absolute threshold (mean = 21.4 μA) plus 10 μA and a fixed upper limit (500 μA) into six equally spaced steps, eliciting reports that ranged from "innocuous" to "uncomfortable" to "painful." The resulting dynamic ranges (as ratios) varied from 6.25 to 65.5 (mean = 23.8), but even this span does not fully reflect the range that would have been obtained if the highest intensity, as well as the lowest one, had been dependent upon the observer's responses (since they report, in an accompanying publication [Chatrian et al., 1982], "in no instance did the maximal current of 500 μA evoke sensations approaching tolerance levels" [p. 241]). The exponents were also based upon the attenuated range. The correlation between exponent and dynamic range is in the expected direction ($r = -.236$) but fails to reach significance; the same is true for the correlation between the TPEP exponent and dynamic range ($r = -.242$). Both exponents are derived from power functions fitted to threshold-corrected data. To compare the results with those obtained in the present study, it would be desirable to know the slopes of the uncorrected functions. However, although the correlation between threshold and reported dynamic range is high ($r = -.75, p < .002$), the correlations between the sensation threshold and the behavioral exponent ($r = +.17$) or the electrophysiological one ($r = +.11$) are not.

The interpretation of evoked potentials, particularly in the study of pain, is controversial. Somatosensory evoked responses can be influenced by cognitive or affective variables as well as sensory ones (Barrett, A. M. Halliday, E. Halliday, & Rudolf, 1979). Furthermore, the qualitative effects of stimulating tooth-pulp afferents are complex (e.g., Chatrian et al., 1982; Sessle, 1979). However, the suggestion that TPEPs may grow more rapidly in observers with a small dynamic range deserves further investigation, particularly under conditions in which the stimulus set is predicated upon the tolerance as well as the sensation threshold.

Craig et al. (1975) showed that psychophysical exponents can be manipulated by social modeling influences (exposure of observers to tolerant models increases their pain tolerance and reduces the magnitude of their exponent). The dynamic range, the power function, and the cerebral evoked response may be tempered by an interaction of sensory, motivational, and cognitive processes, and not by sensory factors alone. It would be useful to determine whether other manipulations that alter detectability measures alter psychophysical and neural exponents as well.

The Discriminability of Painful Shocks

The relationship between I and ΔI is generally examined by adjusting I within individuals. The robustness of the Weber fraction is demonstrated by the significant correlation ($r = .68, p < .001$) of intensity and just noticeable differences across individuals as well. Nevertheless, there are wide individual differences in resolving power, since the fraction varies from 0.03 to 0.16. The mean of these values is 0.08, and the slope of the best-fitting linear relation between I and ΔI is 0.07.

These data can be compared with those obtained by Hawkes (1961), who used alternating current applied to the fingertip at 120% and 200% of the absolute threshold. Hawkes found mean Weber fractions of 0.053 at the lower intensity and 0.038 at the upper one, when he employed a method of successive stimuli comparable to the one used in this study. The values obtained, using a beat method, were 0.051 and 0.035, respectively.

Although Hawkes's (1961) study differed from the present one in many respects—using alternating current rather than trains of dc pulses, stimulating the densely innervated fingertip rather than the forearm, and using vibratory rather than painful sensation levels—the results are strikingly similar. The somewhat higher values of the Weber fraction reported here suggest that discrimination capacity is at least mildly impaired by the painful nature of the stimuli.

Two other recent studies, which examined the discriminability of intense electrical shocks, give credence to the concept of Weber fractions between 0.06 and 0.08 for noxious electrical stimuli. Jones, Planas, and Anuza (1982) presented 40 trials for each of three stimulus pairs (low, medium, and high) separated by 8%. Discriminability was attenuated slightly for painful shock pairs. The mean proportion of correct responses in a forced-choice task was 0.74, thus confirming, with a psychophysical technique of greater precision, the Weber fraction obtained in the present study. Rollman (1983b) had subjects use rating scales to describe the painfulness, intensity, unpleasantness, or discriminability of intense stimulus pairs separated by 6%. The mean value of d_e' depended upon the dimension, but was highest (about 1.6) for the discrimination task (confidence that the signal was the stronger or the weaker of the pair).

Is there a relationship between the Weber fraction and the exponent? R. Teghtsoonian (1971) proposed that "just noticeable changes occur when sensory magnitudes are altered by a constant fraction ... regardless of the form of input energy" (p. 79). It follows that, across perceptual continua, small Weber fractions should be associated with steep exponents. The results of the present study provide weak support ($r = -.30, p < .03$, one-tailed test) for such a relationship within a single modality, and suggest an interaction of sensory-cognitive variables and physical characteristics (Laming, 1985) in discrimination performance.

SUMMARY

As has been shown earlier (R. Teghtsoonian, 1973; R. Teghtsoonian & M. Teghtsoonian, 1978), exponents in direct scaling studies are influenced by both dynamic range (intermodally) and stimulus range (intramodally). In this study, explicit recognition of dynamic range has taken place (occasioned by the finding that electrical current provides a stimulus continuum for which sizable intramodal dynamic range differences will occur). In R. Teghtsoonian's (1973) experiment, involving the scaling of apparent length, apparent distance, and loudness with stimulus range variation over 1 log unit, exponents varied at most by 50% and, more generally, by 20% or less. In the present study, even when one deletes the results for the 5 subjects whose coefficients of determination (r^2) were .81 or less, the exponent varies more than 10-fold. Future research will establish whether these exponents are enduring characteristics of individual observers. Current evidence (Rollman & Clohosey, 1984) indicates that the dynamic range appears to be a consistent trait. Just as electrical shock provides a stimulus with unique transduction effects (Rollman, 1974, 1975, 1982), it may also provide unique opportunities for understanding the relationships between subjective magnitudes and physical stimulus dimensions.

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