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Range of acceptable stimulus intensities: An estimator of dynamic range for intensive perceptual continua

ROBERT TEGHTSOONIAN and MARTHA TEGHTSOONIAN
Smith College, Northampton, Massachusetts

The dynamic range (DR) of a sensory system is the span (usually given in log units) from the lowest to highest intensities over which a continuously graded response is evoked, and may be a distinctive feature of each such system. Teghtsoonian (1971) proposed that, although DR varies widely over sensory systems, its *subjective* size (SDR) is invariant. Assuming the psychophysical power law, the exponent for any continuum is given by the ratio of subjective span to DR, both quantities expressed logarithmically. Thus, exponents are inversely related to DR and may be interpreted as indexes of it. Because DR can be difficult or even dangerous to measure directly, we sought to define a smaller range representing some fixed proportion of DR that could be used in its place to test the hypothesis of an invariant subjective range. Observers manipulated the intensities of five target continua to produce the broadest range they found acceptable and reasonably comfortable, a range of acceptable stimulus intensities (RASIN). Combined with an assumed constant SDR (derived from previous research), RASINs accurately predicted exponents obtained by magnitude production from the same observers on the five continua, as well as exponents reported in the literature.

The psychophysical power law states that judgments of perceived magnitude for unidimensional intensive continua grow as a power function of stimulus intensity, and there is now a large body of evidence establishing its empirical validity, whether the judgments are numerical (as in the method of magnitude estimation, or ME) or require the adjustment of intensities on a matching continuum (the method of cross-modal matching, CMM). But in discussions of the interpretation of these data, and the meaning of the exponent in particular, little or no consensus exists. Some (e.g., S. S. Stevens, 1975) have argued that the exponent is a defining parameter for the particular sensory system involved, reflecting perhaps the properties of the pertinent transduction process. Others (e.g., Link, 1992) have suggested that it encodes information about the differential sensitivity for any given continuum. And, it should be noted that some (e.g., Lockhead, 1992) have argued that its value is so context sensitive as to be of little or no theoretical importance.

Yet another approach (Teghtsoonian, 1971, 1973, 1974) has offered an interpretation of exponents in terms of another attribute of sensory systems, the dynamic range (DR)—the span of intensities to which a given sensory system can respond. This value is usually expressed as a ratio of maximum to minimum values and is often specified on a logarithmic scale, as in the case of bels or decibels. It is of course a basic property of any physical measurement device and is widely accepted and understood as such among engineers and scientists: A light meter, for example, is characterized by a given dynamic range, and another light meter might be distinguished from the first by having a larger or smaller DR. However, among students of sensory systems, the concept of DR has received (despite some honorable exceptions, such as Borg, 1990; Kaczmarek, Webster, & Radwin, 1992) remarkably little attention. Whereas standard texts routinely offer information about detection and differential thresholds for various sensory systems, none (that we have found) offer comparative data for DR, and few even mention the concept.

It is plausible that the human senses, like their mechanical or electronic counterparts, can be characterized by the range of intensities to which they are capable of differential response. Indeed, there is plentiful evidence showing that both the eye and the ear can distinguish intensities over a ratio of at least millions to one. In contrast, length experienced by grasping an object between thumb and finger cannot exceed a ratio much greater than 100 to 1, and the experience of electric shock delivered to the fingertips is limited to, roughly, a threefold span of current. It has been proposed (Teghtsoonian, 1971) that when experimenters pick the range of intensities to use in a psychophysical scaling experiment, they are heavily constrained by the relevant DR, and that, in consequence of the desire to explore as large a range as is practical, choose a span of values that is closely correlated with DR. It has been suggested further that any given experimenter is likely to reveal a consistent set of biases in picking what

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seems to be the largest practical span, and will therefore end up choosing, over a set of different perceptual continua, an approximately constant proportion of the DR.

In that same report, a second conjecture was offered about DR: Despite the wide variation in DRs over the several sensory systems, their *subjective* counterparts (SDRs) may be invariant. Thus, the subjective magnitude of the loudest sound we can tolerate may stand in the same ratio to that of the faintest sound we can hear as does the subjective magnitude of the most intense tolerable electric shock to that of the weakest shock we can detect. This invariance in maximum *subjective* spans over highly variable DRs (maximum *physical* spans) may be called exhaustive mappability, because it implies that there cannot be an unmatchable intensity in a cross-modal matching experiment: For any loudness, there must be a matching brightness, odor strength, or heaviness. Given these two assumptions about (1) the variability of the DR and (2) the invariance of its subjective equivalent, and a third assumption, (3) that a cross-modal matching procedure yields a power function (i.e., a matching function that is linear in logarithmic coordinates), it is clear that exponents will be inversely related to dynamic range. More precisely, if we begin with the power law in the form

$$\Psi = \alpha\phi^{\beta}, \qquad (1)$$

where Ψ is perceived magnitude and ϕ is stimulus intensity with α and β as parameters, and we define DR as $R_{\phi}\text{max}$ and its subjective equivalent SDR as $R_{\psi}\text{max}$, assuming the latter to be a constant C, then the exponent is given by

$$\beta = \frac{\log C}{\log R_{\phi}\text{max}}. \qquad (2)$$

The notion that there is but one scale of subjective magnitude with a range that remains constant regardless of the input modality (and its empirical counterpart, the exhaustive mappability hypothesis) received at least indirect support from a meta-analysis that included 21 studies reported by S. S. Stevens and his associates and showed a correlation (Pearson *r*) of .935 between exponent and the reciprocal of log R_{ϕ}, where the latter refers simply to the range of intensities selected by the experimenter. If these ranges define an approximately constant proportion of the relevant DRs, then the close association with the obtained exponents implies a constant subjective range whose size will be a correspondingly reduced proportion of its maximum possible value. For these data, the average value of the estimated subjective span was 1.53 common log units, and if the ranges tested by Stevens averaged, for example, 75% of the full DRs on a log scale, this would imply a maximum subjective range of about 2 log units, a ratio of 100 to 1.

Although it may be reasonable to suggest that the power law exponent constitutes an index of DR, a direct test of this interpretation remains difficult. As noted, direct measurement of DR in human observers presents a more daunting prospect than does the equivalent operation for a piece of laboratory equipment, especially as regards the determination of upper bounds. For continua such as loudness and electric shock, the occurrence of discomfort and then pain at high intensities imposes practical limits. In other cases, such as the strength of taste, the upper limit is determined by limits of solubility; once a solution of sugar, for example, is saturated, no higher level of the stimulus for sweetness can be achieved. Further, there are conceptual problems associated with the determination of any limiting value, whether it occurs at the high or the low end of the intensity continuum. There is a large body of evidence demonstrating the dependence of measures of absolute sensitivity on biases influencing the choice of a decision-making criterion, and no doubt similar conditions apply at the other end of the intensity continuum as well.

Yet, even if such sources of uncertainty remain unresolved, it may be possible to obtain estimates of a usable range of intensities that could serve as an approximation of the "true" DR. The basic idea explored in this report is that such estimates might be obtained by asking observers to adjust stimulus intensities to indicate what they regard as an acceptable and reasonably comfortable range. Thus, observers who are familiar with the procedures used in scaling experiments—ME, for example—could be asked to adjust the intensity of a tone to produce both the weakest and the strongest signal levels that they would be willing to judge in an experiment that scaled loudness. Presumably, the observers, like the experimenter, would be constrained by the size of the relevant DR. Where the DR is large, one might expect observers to define a correspondingly large range of acceptability, in the same way that the experimenter is able to select a broad range of intensities when testing with such a continuum. If a group of observers were to designate ranges that, on average, defined a constant proportion of the corresponding average DRs, these observer-defined ranges could serve as estimators of the relative size of DRs and would have the considerable advantage of being obtainable quickly and safely.

The purpose of the present study was to measure ranges of acceptable stimulus intensities (RASINs) for the same group of observers on five different perceptual continua and then to determine whether these values, treated as estimators of DR, could predict power law exponents. If observers are constrained by their DRs in selecting values for a RASIN in approximately the same way that S. S. Stevens was in picking stimulus ranges, then we ought to be able to recover Stevens's exponents from our observers' RASINs and the subjective range estimated from his data. A more direct comparison can be made between the RASIN-based estimate of an exponent with values obtained for these observers on the same five continua by using a standard scaling procedure, magnitude production (MP); reasons for this choice are discussed in the next section.

Finally, although to our knowledge there has been no explicit statement of an alternative, one is clearly implied by objections to the exhaustive mappability model, and must be assumed as implicit in views that reject it. That alternative could be called the "variable subjective range model," and it would hold that the evidence for the exhaustive mappability model is not compelling and that the subjective range varies substantially across perceptual continua, being very large in some cases (like loudness, perhaps), and very small in others (like odor strength, perhaps). For the variable subjective range model, there are no necessary associations among DR, subjective range, exponent, and differential sensitivity, and each of these terms must be treated as an independent parameter. It is the view that seems implicit in much of Stevens's work (e.g., S. S. Stevens, 1975), and, failing a more explicitly defined alternative, the view implied by those who reject the exhaustive mappability model.

METHOD

Two independent studies of 10 observers each were conducted by different experimenters in successive years. One was based on a sample of students at Smith College; the other was drawn from a broader pool, including students from Smith and a local high school. Procedures were identical, and since no reliable differences were noted in the results, they will be described and the results reported as if for a single study. Some general comments on the selection of continua, observers, and procedures may be helpful, and these are given before details of the method.

The five continua chosen for study by both RASIN and magnitude production procedures were force of handgrip, heaviness, loudness, electric shock, and sniff vigor. Among the continua we were equipped to study, these were selected to maximize the range of obtained exponents. Each continuum is described in detail below. All subjects were drawn from a pool of those who had served previously in a study in which they had matched force of handgrip to loudness of a target tone. The rationale for this selection was twofold: First, because of the heavy investment of time required for each subject in the present study, we wished to choose only those who were familiar with matching procedures and had demonstrated their ability to rank-order stimuli varying in intensity. All subjects were tested individually in two separate sessions. In the first, RASINs were determined for all five continua; the session never exceeded 1 h. The second session took place at least 48 h after the RASIN session, and usually about 1 week later. The five continua were tested using magnitude production, and the total test time was under 90 min. Subjects were paid for their services.

Apparatus

Force of handgrip. The handgrip dynamometer employed was a copy of one first described by J. C. Stevens and Cain (1970). It consisted of a single piece of aluminum stock machined to a hairpin shape, with the two arms having an exterior separation of about 58 mm in the region to be grasped by the observer. The cross section of the arms in that section was about 19 mm square, and the outer edges were rounded for the observer's comfort. The entire assembly was suspended from the apex of the hairpin and hung in front of an armrest on which the observer's forearm rested comfortably.

Sets of capacitor plates were mounted opposite each other on the inside surface of the two arms just above the gripping area and formed part of an LC network. Any movement of the two arms produced by the observer changed the area of overlap between the two sets of plates, and thereby the capacitance. As one leg of an ac bridge, this capacitance determined the magnitude of a rectified voltage output fed to a meter and to a chart recorder. The whole system was calibrated using known forces and exhibited linearity between exerted force and output voltage over a range from less than 1 ounce to well beyond 100 pounds and the maximum value that any of our subjects could produce. The actual excursion covered by the movement of the arms of the aluminum pin was quite small—on the order of 5 mm for 100 pounds—and certainly not discernible as a cue to the observer.

Heaviness. The apparatus was designed to permit the adjustment of effective mass over a very wide range (from about 10 to 2,500 g), locating the apparent source of the mass in a plywood cube the size of which could also be selected from a wide range. (The original purpose of this equipment was to permit an exploration of the size–weight illusion without the restriction imposed on the available range of weights for a given volume by the rather limited range of densities provided by easily obtainable materials.) In this study, the cube was 14 cm on a side and rested on a tabletop 75 cm above the floor in front of the standing observer. It could be lifted by grasping a wooden knob 3.0 cm in diameter located at the center of the upper surface of the cube and extending 2.0 cm above that surface.

The cube was attached to a threaded metal rod that extended vertically from below through a hole in the tabletop; neither the hole nor the rod was visible to the observer in the course of a standard lift. The rod, in turn, was attached by a freely turning axle to a double-beam assembly that extended 132 cm from end to end and was balanced on a fulcrum located 88.5 cm from the vertical rod. By appropriate placement of weights on both the upper and lower elements of the horizontal-beam assembly, the effective mass at the cube could be adjusted over the range of values noted above. A metal plate was hung from the far end of the beam and was immersed in a viscous oil bath to dampen the bounce that could otherwise occur following a too-rapid lift. The entire system was calibrated to permit the easy conversion of weights and locations into effective mass at the cube. In operation, the short lift required of the observer (about 1 in. off the tabletop) felt quite natural, and the resistance experienced was perceived as that of the cube even though the observer was well aware of the fact that it was governed through adjustments made by the experimenter before each trial.

Loudness. A 3000-Hz tone was fed through an amplifier, electronic switch, and sone potentiometer to a pair of PDR-8 earphones. The tone was presented as a train of 2.5-sec pulses separated by 2.5-sec silent intervals. Observers were free to listen to as many pulses as necessary in arriving at a final judgment. The sone potentiometer, controlled by the observer, was designed to change signal strength in a way that made change in loudness roughly proportional to the linear excursion of the control knob. That knob, approximately 62 mm in diameter, bore no scale markings of any kind, and could be turned through approximately 350° from stop to stop, spanning a range from well below audibility to values higher than any observer was prepared to explore.

Shock intensity. The shock source was a Lafayette Instrument Company Model 82426 aversive shock apparatus, providing a constant ac current over a range from 0 to 5 mA. The shock was delivered by a concentric electrode, provided by Lafayette with the shock source, attached to the dorsal surface of the nonpreferred forearm following suitable preparation. The observer was instructed in the use of the gain control (a knob with no scale markings) allowing manipulation of the current through the available range and of a timer-regulated activating button that, when pressed, delivered a shock of 1.0-sec duration. The observer was thus able to alternate adjustments of the shock level with self-administration of the shock.

Sniff vigor. Tubing from one nostril was connected to a differential pressure transducer that provided a voltage output proportional to the difference between the pressure in the nostril and the air on the exterior. This voltage was displayed as a waveform on the face of a storage oscilloscope. Observers were trained (while watching the oscilloscope) to generate sniffs of approximately 1.5-sec duration and of varying amplitudes until they were able to produce on request and without visual feedback a sniff of constant amplitude throughout a 1.5-sec period. Calibration of the system showed a linear relation between sniff pressure and voltage output from the transducer, and the results of the experimental procedures are reported as voltages.

Procedure

A brief account of the rationales for the two major parts of the procedure may be helpful. In the case of the RASIN procedure, we recognized that observers might differ markedly in the biases exhibited in specifying a range of acceptability, but we assumed that on average, they would apply essentially the same set of biases to all five continua. We further assumed (correctly, as it turned out) that although observers may never before have had occasion to explore the limits of their sensitivity to changes in intensity, they could do so when asked.

The rationale for choosing a scaling procedure was somewhat more complex. The most commonly used technique for generating judgments of perceived magnitude fittable by a power function is ME. But for present purposes, ME poses insoluble problems concerning the choice of stimulus range. If the same range, R_ϕ, were used for all continua, that value would be determined by the continuum with the shortest practical range—probably electric shock—and would introduce range biases of varying degrees of severity in the scaling of the other continua (Teghtsoonian & Teghtsoonian, 1978). If, on the other hand, we tried to estimate a practical range separately for each continuum, we would be in the position of guessing at a value that the RASIN procedure was designed to measure. Another peril of ME derived from our desire to complete the scaling procedure for all five continua in a single test session. With short intervals between successive scalings, it seemed unlikely that the judgments would be truly independent; observers might simply use again for the next continuum the same (or a similar) range of numbers. A solution to all of these problems was provided through the use of magnitude production (MP). A fixed range of stimuli (specified as numbers) could not introduce any biasing range effects, and judgmental stereotypy could not be a problem since every continuum would involve a different variety of stimuli to be adjusted.

As noted, the RASIN procedure always preceded MP, and some explanation for this decision is in order. First, the RASIN procedure was the novel feature in this study, and we felt it essential to ensure that there be no risk of biasing the data by preceding it with another procedure. Further, given the heavy investment of time in the testing of each observer, we were reluctant to employ the balanced design that a complete control of possible order effects would require. Second, with several prior studies reporting the results for MP under conditions similar to those we used, it was possible to determine whether the MP data obtained from our observers was seriously distorted by its collection following the RASIN procedure. In short, we decided that the collection of bias-free RASIN data was our primary concern; the MP data were viewed from the outset as an extra that could be employed in our analysis if there were independent grounds for judging them to be valid.

The RASIN procedure. The ordering of the five continua was randomly determined for each observer. A lower limit of acceptability was always determined first, and the upper limit second. At the outset, the experimenter read aloud a set of instructions intended to define what was meant by RASIN, and these are reproduced verbatim in the Appendix. The principal points can be summarized briefly: (1) Observers were asked to specify a range that was as wide as possible while being "acceptable and reasonably comfortable" in a scaling experiment of the sort previously experienced—an allusion to the loudness–handgrip matching study in which all observers had participated previously. (2) Observers were told the identity of all five continua to be tested. (3) Observers were told that they should follow a bracketing procedure in arriving at a final judgment for both upper and lower limits, and that there was no limit to the time to be taken. There followed instructions specific to each continuum. In each case, stimulus durations were arranged to be the same as would be subsequently available in the MP procedure, but the stimulus could be repeated as often as needed in arriving at a final setting. Observers were encouraged to discuss the procedure with the experimenter to ensure clarity of understanding and to practice use of the equipment to ensure familiarity and ease of use.

Force of handgrip. Observers were instructed to produce triads of squeezes and practiced at intermediate levels until they could produce squeezes of the required 2.5-sec duration. The median force of each triad was determined for both the upper and lower limits.

Heaviness. Adjustments were made by the experimenter on request from the observer. These requests were to indicate the direction of the change to be made ("lighter," "heavier"), but also its approximate magnitude, using phrases such as, "just a touch," "a little bit," and "quite a lot." Observers were instructed to lift the cube from the table about 1 in. and to hold it for about "one or two seconds." Observers were free to repeat lifts at any given weight as often as needed and to use a bracketing procedure. Two determinations were made for both limits, one beginning well above the estimated limit and the other beginning well below it.

Loudness. The procedure in this case followed quite directly from the general instructions.

Shock intensity. As in the case of loudness, the procedure followed directly from the general instructions.

Sniff vigor. Observers made their judgments by producing three successive sniffs at the criterial level, and did so without visual feedback. Median scores for each such triad were determined.

Magnitude production. Continua were tested in random order. Nine numbers were selected as target values, ranging from 1.0 to 35 in approximately even logarithmic steps: 1.0, 1.5, 2.5, 4.0, 6.0, 9.0, 14, 22, and 35. (This range, about 1.53 log units, was the average value for the range of MEs in the analysis of S. S. Stevens's studies noted above.) Numbers were presented in two successive random orders. Observers were told to follow a bracketing procedure in arriving at an intensity with a subjective magnitude that matched that of the target number. They were told that they would not need to exceed a reasonably comfortable range in order to make their matches, and in the few cases in which such a problem arose, the trial was terminated without recording a response, and a third trial was introduced. Following the general instructions, more details were provided relevant to the particular apparatus being used.

Force of handgrip. The observers were instructed to seek a match for each number by producing 2.5-sec squeezes separated by 2.5-sec rest intervals, adjusting the force for each successive squeeze until a match was achieved, to report that to the experimenter, and then to produce three successive matches. The median of that triad was recorded as the matching value.

Heaviness. As in the RASIN procedure, adjustments were made by the experimenter at the direction of the observer. Observers were urged to continue the process of adjustment until a high level of confidence was achieved in the selected match.

Loudness. Observers adjusted the tone level by adjusting the knob of the sone potentiometer, following the bracketing instructions already described.

Shock intensity. Observers alternated manipulating the gain control and pressing the delivery button until a match to a given number was achieved.

Sniff vigor. Observers were asked, following each number presented, to produce three consecutive matching sniffs without feedback. The median score for that triad was taken as the matching response.

RESULTS AND DISCUSSION

For each observer, and for each of the five continua, two measures were calculated. First, the two values obtained by the RASIN procedure were expressed as a ratio,

R_ϕ. Second, the geometric mean of the two matches was calculated for each target number in the MP procedure, and the exponent of the best-fitting power function (least squares criterion) was determined for each observer for each of the five continua. Logs of R_ϕ were determined, and the median and interquartile range of these values for each continuum are shown in Table 1.[1] The exponents of the power functions obtained for the MP procedure were subjected to a reciprocal transformation to obtain a value comparable to the outcome in ME, where number is the dependent variable. The medians and interquartile ranges of these values for each continuum are also shown in Table 1. Finally, Table 1 shows an estimate of the exponent derived for each continuum by dividing log R_ϕ into 1.53, the estimate obtained earlier of the size of the subjective range in log units. The fairly good agreement between exponents derived from magnitude production (column 4) and the values derived from log R_ϕ (column 6) can be seen also in Figure 1, where the MP exponents are plotted against log R_ϕ along with the function $y = 1.53/x$. It is important to note that the smooth function is not an empirical fit to the data, but is a prediction based on the exhaustive mappability hypothesis and a determination of the relevant constant in an earlier report. This finding merits further discussion, but a question concerning the independence of the two primary measures in this study needs to be addressed first.

The agreement between β and estimates derived from R_ϕ would be rather uninteresting if the value obtained for β were artifactually determined by the observer's participation in the RASIN procedure before the MP judgments were obtained. Imagine that, having set the two limiting values required in the RASIN procedure, the observer then produced the one in response to the largest number in the MP task and the other for the smallest number, and distributed appropriately intermediate response values for the intermediate assigned numbers. Since the range of assigned numbers in this MP task is exactly 1.53 (in log units), the agreement noted above between columns 4 and 6 would not just be good, it would be perfect. One way to evaluate the possibility of such an artificial association is to compare MP exponents for the first continuum judged with those exponents derived from subsequent judgments. When the first continuum to be judged is presented, there is no way for the observer to know what range of numbers will occur, and therefore no way to identify the extremes of that range and to match them with stimulus values remembered as the extremes in the RASIN procedure. Since first-judgment exponents for a continuum cannot be biased by the RASIN procedure, a comparison of those values with the results for that continuum when it appears in the four later positions will show whether there is any systematic difference indicative of an order effect.

Table 1
Results of RASIN and MP Procedures: Medians and Interquartile Ranges

Continuum	Log R_ϕ	IQR	β	IQR	1.53/Log R_ϕ
Loudness	2.22	0.75	0.69	0.21	0.69
Heaviness	1.12	0.48	1.42	0.46	1.37
Sniff vigor	0.89	0.34	2.13	0.76	1.72
Handgrip	0.85	0.41	1.74	0.77	1.81
Shock	0.50	0.34	2.62	1.68	3.06

Note—RASIN, range of acceptable stimulus intensities; MP, magnitude production; IQR, interquartile range.

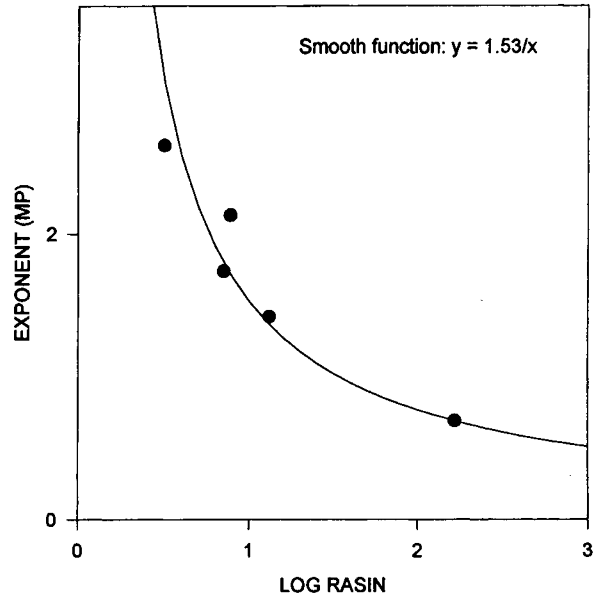

Figure 1. Exponents and log ranges of acceptable stimulus intensities (RASINs; medians) for five continua compared with the prediction based on the assumption that subjective range is constant and equal to 1.53 common log units. MP, magnitude production.

Table 2 shows this comparison for the three continua where the number of observers was sufficient ($n = 4$ or 5) to obtain a reasonably reliable estimate. There is no systematic relation: For two of the three continua, first judgments yielded higher exponents, but for the third they are lower. Wilcoxon–Mann–Whitney U tests show that, in each case, the median exponent for a continuum when it occurred first in order of judgment does not differ from the median exponent for that continuum when it occurred in later positions ($\alpha = .05$).

Another means for evaluating the influence of the prior RASIN procedure on MP exponents is to compare the latter with values reported in the literature. If our MP exponents are in reasonably good agreement with previous findings, that would be evidence to support the conclusion that our exponents were not seriously biased by the RASIN procedure. For three of the five continua, MP exponents have been reported in earlier studies. First, for a number range very close to what was used in this study, S. S. Stevens and Greenbaum (1966) reported an MP exponent of 0.67 for the loudness of a 1000-Hz tone, and Teghtsoonian and Teghtsoonian (1978) provided data indicating an MP exponent of 0.79 for a 3000-Hz tone and a comparable number range. These values are quite sim-

Table 2
Median MP Exponents for Continua When Judged First or in Later Positions

Continuum	Position	n	Median β
Loudness	1st	4	0.79
	2nd–5th	16	0.67
Handgrip	1st	5	1.69
	2nd–5th	15	1.73
Shock	1st	5	2.21
	2nd–5th	15	2.76

Note—MP, magnitude production.

ilar to the value of 0.69 shown in Table 1. Second, S. S. Stevens (1975) reported (in his Figure 38) MP data for force of handgrip (adapted from J. C. Stevens & Mack, 1959) with an exponent of 1.91, a value that is reasonably close to our 1.74, shown in Table 2. Finally, although S. S. Stevens, Carton, and Shickman (1958) reported an ME exponent of 3.50 for electric shock, later studies reported lower values, such as the 2.26 obtained by Cross, Tursky, and Lodge (1975) using a variety of methods to eliminate regression effects. Sternbach and Tursky (1964) reported an MP exponent of 2.68. Both of these studies lend credibility to our MP exponent of 2.62 for the apparent intensity of electric shock.

We have found no cases of an MP procedure for lifted weights or for sniff effort, so no direct comparison with our results can be made for those continua. It should be noted, however, that J. C. Stevens and Rubin (1970) reported an ME exponent of about 1.3 for lifted weights for a volume similar to that used in the present study. Given the common finding that MP exponents are larger than those obtained by ME, our finding of 1.42 is not unreasonable. The case of sniff effort is more difficult because there is only one prior report (Teghtsoonian & Teghtsoonian, 1982) of a directly comparable procedure, and that employed ME only, with a reported exponent of 0.8. The large difference between that value and the MP exponent of 2.13 noted in Table 1 is worrisome, but cannot be evaluated until both procedures have been replicated.

Thus, there is reason to believe that the MP exponents shown in Table 1 are unbiased estimates. Estimates derived from first judgments do not differ from those based on later judgments, when observers might use their knowledge of the range of assigned numbers and their recall of values employed in the RASIN procedure. Perhaps more important is the fact that, where comparison is possible, our MP exponents are consistent with prior evidence. It is therefore of some interest that these data should be in such good agreement with the RASIN measurements, and so lend support to the view that RASIN taps a feature of the observer's sensitivity that is also revealed by the more traditional methods of psychophysical scaling. It is suggested that the feature in question is DR. We can say that our RASIN measures, taken together with an estimate of the size of the subjective range of 1.53 log units, yield estimates of exponents that are in four of the five tested continua in good agreement with previously reported findings, and in fairly good agreement with the exponents reported here in all five cases. This successful combination of the subjective range derived from S. S. Stevens's experiments with the RASIN measures reported here implies that our observers produced stimulus ranges in good agreement with those selected by Stevens for use in ME studies. His intuitions about the largest ranges that would be acceptable to his subjects prove to have been remarkably accurate.[2]

Finally, it is of some interest to consider whether RASIN is unique in providing a simple two-valued measure that bears a clear relation to the power law exponent. L. E. Marks (personal communication, February 22, 1995) raised the possibility that a measure derived from any pair of verbally defined categories would show the same relation. For example, observers could have been asked to produce stimulus intensities corresponding to the categories *very strong* and *very weak*, and the ratios of the produced intensities computed as was done for RASIN. Ultimately, of course, this is an empirical question, but if the verbal categories are spaced in a roughly logarithmic manner, as in Borg's (1982) category–ratio scale, or as in Green, Shaffer, and Gilmore's (1993) labeled magnitude scale, and if the exhaustive mappability hypothesis is correct, then it seems likely that a similar finding would indeed occur, but only if the categories selected correspond to the same range of intensities as was obtained in the RASIN procedure. It seems that the latter match well with a subjective range of 1.53 log units, and no doubt it would be possible to find other verbal labels that achieve the same result. It remains an empirical question whether other subjective ranges, say 1.0 or 1.5 log units, can be consistently obtained for a set of continua using other pairings of verbally defined categories.

CONCLUSIONS

The main purpose of this paper is to draw attention to DR as an important and perhaps neglected parameter of sensory systems. Despite the difficulties, both conceptual and practical, that stand in the way of defining and measuring DR, it may provide an important clue to the meaning and form of psychophysical matching functions. There seems to be ample evidence supporting the view that sensory systems and even more complex perceptual continua may be distinguished by their effective range of sensitivity, and that an important empirical question exists about the subjective counterpart to this range. It is possible that these subjective ranges covary in some as yet unknown way with the size of the corresponding DR, or that they are variable but wholly independent of the size of the corresponding DR. Electric shock might have a short DR but a very large subjective range in comparison with, say, loudness, despite the much larger DR associated with the latter. But the proposal that there is but a single maximum subjective span for all perceptual continua, and its empirical counterpart that all DRs can be mapped exhaustively into any other through a matching operation (what we have called the exhaustive mapping hypothesis), has attractive theoretical properties. Earlier reports have shown that experimenter-selected stimulus ranges might serve as estimates of DR, and when combined with an assumed constant subjective range, could provide good approximations to exponents determined through number matching. What has been shown in this report is that RASIN, an observer-generated estimate of DR, can function in the same way, with the obvious advantage of being independent of the research habits of any particular investigator. RASIN also provides a means for obtaining an estimate of the power law exponent without the more extended procedures needed to determine the form of a matching function. But, in view of the large body of evidence establishing that cross-modal matching functions for intensive continua are linear in logarithmic coordinates, many research problems can be addressed more expeditiously with the RASIN procedure when only an exponent is needed.

It should be noted that the concept of DR has been employed to pursue the somewhat different problem of interindividual comparison (e.g., Borg, 1990; Teghtsoonian, Teghtsoonian, & Karlsson, 1981). Whereas we have argued that maximum subjective range is constant over many different perceptual continua despite large variations in DR, it can also be imagined that a similar invariance applies across individuals for any given continuum despite large individual differences in DR for that continuum. Thus, for example, the maximum range of perceived effort might be the same for two individuals who differ substantially in strength—that is, in their DR for, say, lifted weight. Borg and his associates have pursued this idea and its practical applications with considerable success. Here is yet more evidence that DR merits more attention than it has received, both as a theoretical construct and as a measurement problem.

Finally, we note the possible relation of the concepts treated in this paper to the question of differential sensitivity. In earlier statements of the exhuastive mappability hypothesis (Teghtsoonian, 1971, 1974), it was suggested that if there is but one range of subjective magnitude that fits all DRs, there may be but one minimum ratio of subjective magnitudes that defines just noticeably different ratios on all intensive continua. Thus it may be that what has been called the Ekman fraction, the subjective counterpart of the Weber fraction, may be a constant; evidence was reported (Teghtsoonian, 1971, 1974) showing this value to be in the vicinity of 3%. On logarithmic coordinates, it seems that just discriminable stimulus intervals covary with the size of the DR, but are all mapped by power functions of varying exponent into a constant interval on the scale of subjective magnitude. Though this proposal has been attacked by some (e.g., Laming, 1989), it is an attractively simple model for integrating the major facts about differential sensitivity with those of cross-modal matching. Given any two values among exponent, Weber fraction, and DR, the model permits the calculation of the third. It will be interesting to see whether DR can predict values for a Weber fraction as neatly as it seems to predict power law exponents.

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NOTES

1. In a previous version of this manuscript, we reported means and standard deviations for both measures. However, as pointed out by Rule (1969), if an average value of log R_φ is to be used to obtain an estimate

of an exponent comparable to the arithmetic mean of the individually calculated MP exponents, that average should be a harmonic mean. In our view, the harmonic mean carries the disadvantage of underestimating the location of a sample of scores; especially in the case of a new measurement, it seemed important to select an average that is more representative than the harmonic mean. Medians serve that function as well as the requirement that the averages for RASINs and MP exponents be comparable.

2. One of the reviewers raised the interesting possibility that the MP instructions so bias the observer in the direction of producing a range of responses smaller than that already provided in the RASIN procedure that the MP exponents can only be smaller than those estimated from RASIN and that, therefore, MP exponents can differ from RASIN-based estimates only by being smaller. This, he argued, meant that "only a 1-tail test of the hypothesis" is possible. We have two replies to this proposal. First, our hypothesis does not predict that the RASIN-based estimate of the exponent must be identical to that derived through MP. There may indeed be biases associated with either procedure, differing from individual to individual, that could create disparities between the two measures. What is compelling about the data reported in Figure 1 is not that the MP exponents fall on or near the function relating an assumed subjective range of 1.53 log units to the measured log RASIN, but that there is a systematic relation between these values over the five continua. It is the pattern of the results that supports the view that (1) RASIN may be regarded as an index of DR and (2) a constant divided by log RASIN is a good estimator of the relative value of the exponent for each continuum.

Second, we think that the argument that our observers were deterred from producing responses in MP with a range exceeding that obtained in the RASIN procedure is empirically testable. Once an MP exponent has been calculated for each observer, it can be used to calculate the stimulus intensity range spanned by the fitted power function, and that range can be compared to the RASIN obtained for that observer. A scatter plot of those values for all 20 observers was determined for the continuum of electric shock and showed that for 13 observers, the range was greater for the MP procedure than for the RASIN procedure. Similar plots for the other four continua show that number to vary around 10, sometimes a bit larger, sometimes a bit smaller. It is quite clear that observers were at least as likely to create a bigger range in the MP procedure as a smaller one.

Why in the MP procedure would observers exceed the span already produced as the largest with which they felt comfortable? First, they are responding to number targets provided in random order, and are more likely to be judging intermediate values at the outset. If they had been overly conservative in producing a RASIN, they might easily work with those intermediate values in a way that implies a broader total range and, when the extreme values are presented, produce intensities exceeding the two limiting values in the RASIN procedure. Second, the imperative of making a good subjective match might lead the observer to produce intensities that exceed the limits produced under the more general instruction of producing two intensities that span the range of acceptability and comfort.

Regardless of the reason for their behavior, it is clear that observers are just as likely to create an intensity range in the MP procedure that exceeds the previously produced RASIN as they are to produce a smaller one. The means of the two values (and the exponents derived from them) could just as easily differ in one direction as the other.

APPENDIX
Instructions to Observers in the RASIN Procedure

In this experiment I want you to identify the smallest and largest sensations that you would find acceptable and reasonably comfortable in a scaling experiment like the loudness–handgrip matching you did a while back. This means you will be identifying softest and loudest tones, weakest and strongest sniffs and handgrips, lightest and heaviest weights, and lowest and highest levels of electric stimulation. The low measure should be clearly discriminable from the point where you can first perceive a sensation. The upper limit of acceptability should not be your absolute tolerance level, but the level you would find acceptable and reasonably comfortable in a scaling experiment.

In all cases, whether you are identifying a low or a high limit, try to bracket the value which you think is most appropriate. In other words, find an area that contains the appropriate value. By moving higher and lower, zero in on that value. You should continue until you feel confident that you have found it. Don't worry how long it takes; I just want you to be as confident as you possibly can about the value you identify.

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