 Encyclopedia of Cognitive Science.

Psychopathy

See **Antisocial Personality and Psychopathy**

Psychophysics

Introductory article

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Psychophysics is the scientific study of the relation between stimulus and sensation, and therefore its study concerns fundamental questions of psychology and cognitive science.

INTRODUCTION

Psychophysics is the scientific study of the relation between stimuli and sensations. According to the consensual view in psychophysics, the human perceptual system is a measuring instrument whose sensitivity to changes in the environment can be quantitatively analyzed. Of the many aspects of impinging stimuli and the corresponding sensations, three stand out and have received much attention. First, the system's response must exceed that triggered by a critical stimulus intensity – threshold – for any sensation at all to be experienced. Second, when a stimulus more intense than the threshold impinges on the sense organ, its intensity must be increased by a critical amount – the difference threshold – for the person to sense a just noticeable difference (JND) in sensation. Finally, of paramount importance is specifying the functional relation between stimulus magnitude as assessed by the instruments of physics and sensation magnitude as assessed by the *scaling* of people's perceptions.

Before describing each of these traditional problem areas, the fundamental finding of psychophysical research should be appreciated: a human being is not a perfect measuring instrument, infinitely sensitive to changes in the impinging stimuli. High levels of refinement are thus required of the methods and theories of psychophysics in their quest to unravel the operational characteristics of the human perceptual system.

ABSOLUTE THRESHOLD AND SENSITIVITY

The absolute threshold, the smallest amount of stimulus energy necessary to produce sensation, specifies the sensitivity in a given sensory modality. Despite the appealing simplicity of the concept of threshold, its measurement poses difficult problems. First, the absolute threshold is not a rigidly fixed value because both sensitivity and the intensity of a nominally invariant stimulus fluctuate irregularly over time (the latter variation refers to quantal fluctuations). Second, the threshold also varies with changes in the conditions of stimulation. For example, to produce threshold sensation in vision requires substantially more energy at one wavelength than at another. In general, the senses are not uniformly sensitive over their respective ranges of detectable energy.

There is no answer to the simple question 'how sensitive is the eye to light?' The sensitivity of the eye cannot be gauged by a single threshold because it depends on the conditions of stimulation such as prior exposure of the eye to light, and the wavelength, area, and duration of the stimulus. In contrast, the sensitivity of the eye under optimal conditions of stimulation can be determined. In order to see, it is necessary for only one quantum of light to be absorbed by a single molecule of photochemical pigment in each of five to 14 receptors in the retina. The maximum sensitivity of the eye is constrained only by the limit imposed by the nature of light. The ear nearly matches that remarkable sensitivity: under optimal conditions, the eardrum has to move a distance less than the diameter of a hydrogen molecule for a sound to be heard. Given its dependence on the conditions of stimulation, the absolute sensitivity of a perceptual system is best described by examining the relations between the threshold and the various stimulus dimensions that affect its value.

Given the variability, the threshold must be measured statistically. For instance, it can be calculated as that level of energy detected on half the stimulus presentations. This definition is adopted in the *method of constant stimuli* in which fixed stimulus levels are presented many times in an irregular order. In the *method of limits*, stimuli are presented in order of increasing or decreasing magnitude until the observer modifies her or his responses from 'not perceived' to 'perceived' in an ascending series, or from 'perceived' to 'not perceived' in a descending series. The average value of the reversals defines the threshold. Finally, in the *method of adjustment* the observer sets the level of the stimulus so that it is just perceptible. The threshold is the average of several settings. The three methods, known as the classical psychophysical methods, have been in widespread use ever since their inception by Gustav T. Fechner, the founder of psychophysics in the nineteenth century.

Novel methods include variations on the classical ones. In the *staircase method*, a variation on the method of limits, stimulus levels around the threshold are made weaker when the observer detects them and made stronger when they go undetected. Hence, the method is adaptive and saves time because stimuli much below or above threshold are never presented. In the *threshold tracking method*, the observer maintains just perceptible intensity of the stimulus as it continuously changes on another dimension such as frequency. Individuals differ greatly in how much they tend to report the presence of sensation when no stimulus is present, a tendency referred to as 'response bias'. Methods of *forced choice*, in which the observer *must* select on each trial that time interval or location that contains the stimulus, control for response bias, as do the methods based on the theory of signal detectability (TSD) that include presentations of *catch trials* containing no stimuli. Within the framework of TSD, separate and pure measures have been developed for sensitivity and for response bias.

DIFFERENCE THRESHOLD, SENSORY RESOLVING POWER, AND WEBER'S LAW

The difference threshold (DL for the German *Differenz Limen*), the smallest detectable change in energy, specifies the resolving power of a given sensory system. It is the stimulus increment, ΔI, required to produce a JND in sensation. Because the difference threshold is as variable as the absolute threshold, the same methods of measurement are adapted to specify its value. Using the *method of constant stimuli*, for instance, the observer reports on each trial whether a stimulus (selected from a set of predetermined levels) is stronger than the invariant standard stimulus. The difference threshold can be defined as half the distance between the levels reported stronger than the standard on a quarter and on three-quarters of the presentations. The stimulus level that is perceived to be stronger than the standard as often as not, is defined as the point of subjective equality (PSE), and the difference between the PSE and the standard stimulus is a psychophysical quantity called the 'constant error'.

Applying the method of constant stimuli (or any other method) recurrently, DLs can be specified for several stimuli taken as standards. Does the DL remain invariant at different intensities along a given continuum? Ernst H. Weber discovered that it does not. According to Weber's law, the DL depends on the starting intensity in a linear manner such that $\Delta I = cI$, where ΔI stands as before for the stimulus increment necessary to produce a JND when added to the starting stimulus level I; c is a constant known as Weber's fraction. Dividing both sides of the equation by I gives what is perhaps the better-known form of Weber's law, $\Delta I / I = c$, where $\Delta I/I$ is again Weber's fraction. Weber's law states that the minimum change in stimulus intensity that can be noticed is a constant fraction of the starting intensity of the stimulus. To be discriminable, the intensities of two stimuli must differ by an amount that is proportional to their absolute level.

Weber's fraction differs for different sensory reactions, which means that sensory systems differ in their resolving power. The constant is less than 1 percent for pain, about 4 percent for visual length and heaviness, approximately 8 percent for brightness and loudness, and can be as high as 20 percent for saltiness. Weber fractions thus vary over an order of magnitude across the full range of human sensory systems.

Because the Weber fraction is a dimensionless number, sensory systems can be directly compared on resolving power (it is impossible to perform a meaningful comparison of sensitivity because the absolute thresholds do carry various physical dimensions). Gauged by the Weber fraction, pain is more acute than the perception of length, which in turn is more acute than either brightness or loudness.

Figure 1 shows two characteristic renditions of Weber's law. From its inception in the nineteenth century, Weber's law has been repeatedly tested, and has been to shown to hold remarkably well over most of the dynamic ranges of the respective sensory continua. Deviations occur at very low intensities (in the vicinity of the absolute threshold) and at extremely high intensities. Weber's law remains the oldest, broadest, and most useful empirical generalization in the behavioral sciences.

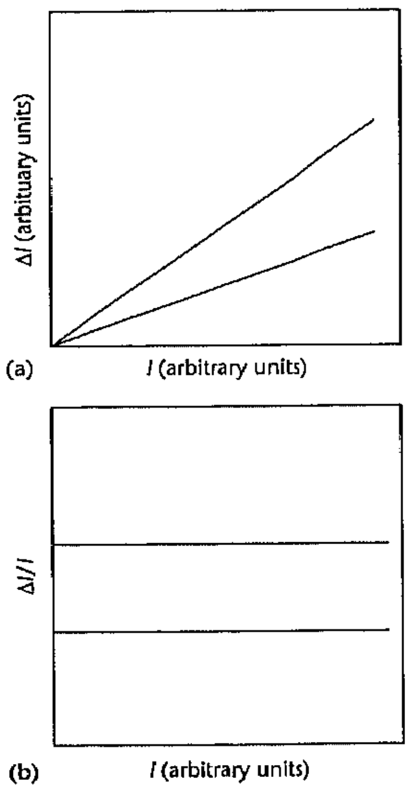

Figure 1. Two characterizations of Weber's law for two sensory continua: (a) the DL (or ΔI) as a function of stimulus intensity I, or (b) the Weber fraction, $\Delta I/I$, as a function of I. In both characterizations, the lower functions mark finer resolving power (i.e. smaller Weber fractions).

PSYCHOPHYSICAL SCALING: FECHNER'S LAW AND STEVENS' LAW

Fechner used Weber's relativity principle, namely that DLs are proportional to stimulus intensity, in deriving his psychophysical law, the first explicit, quantitative statement relating sensations to stimuli.

Fechner complemented Weber's law by assuming that all JNDs comprise equal increments in sensation magnitude regardless of the size of the DL in physical units. Therefore, the JND can serve as a unit of sensation. According to Weber's law, pairs of stimuli discriminable by single DLs are separated by different physical increments, although the ratios, I_2/I_1, I_3/I_2, ... I_n/I_{n-1}, are equal. According to Fechner, these stimulus ratios correspond to equal *increments* in sensation because the respective JNDs are equal in magnitude. As a result, a geometrically spaced series of values on the physical continuum gives rise to an arithmetically spaced series of values on the psychological continuum. This relation defines the logarithmic function, and Fechner's law accordingly is $R = M \log (I/I_0)$, where R is sensation magnitude, M is the constant of proportionality, and I_0 is the threshold. Fechner's law implies that equal *ratios* of stimulus magnitude produce equal *differences* in subjective magnitude; hence, as is apparent in Figure 2, sensation magnitude increases as a negatively accelerated function of stimulus intensity.

Following Fechner's law, actual scaling requires determining I_0 and ΔI in the laboratory through the classical psychophysical methods. For suprathreshold scaling, the observer has to arrange stimuli in equal-appearing intervals, or to rate or classify them in equally spaced categories. The hallmark of these methods is that the observer merely matches or orders stimuli on a continuum (by responses such as 'greater', 'smaller', or 'equal'). These responses avoid many of the pitfalls associated with 'direct' numerical responses. Their validity is guaranteed by their extreme familiarity and simplicity.

It is important to distinguish between the laws of Weber and Fechner (there exists no Weber–Fechner law). Weber did not refer to a concept of sensation magnitude or sensation difference in his law. The sole psychological component in Weber's law is the observer's indication of when two stimuli are

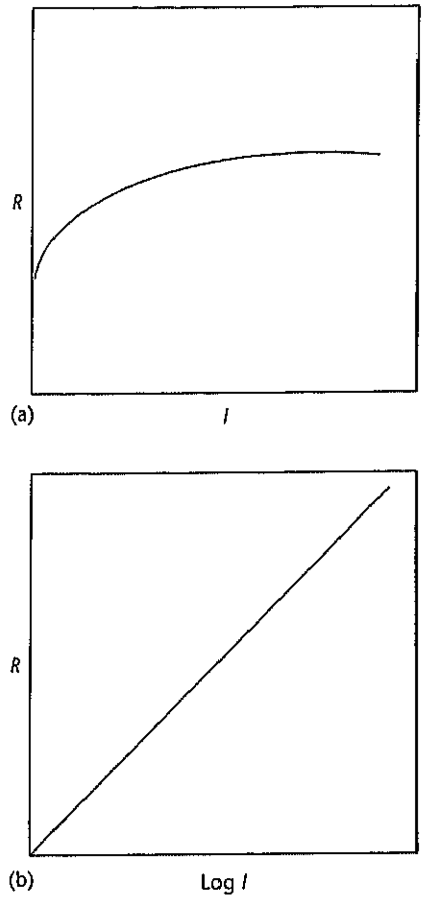

Figure 2. Two characterizations of Fechner's law. (a) Sensation magnitude R increases as a negatively accelerated function of stimulus intensity I. (b) When stimulus intensity is plotted logarithmically the function appears as a straight line.

discriminably different. Yet Weber's law is silent on the crucial question: 'What sensation is felt at a given JND?' It was Fechner who created the notion of sensation magnitude and assumed that all JNDs were subjectively equal, thereby conceiving a truly 'psycho-physical' relation.

Fechner's logarithmic law has had a profound influence in science, from promoting the decibel scale, which is a logarithmic scale of (sound) energy, to aiding in the development of measures of pain such as the dol scale, to quantifying the results of electrical recording from receptors. Nevertheless, the universal validity of Fechner's law has been challenged. For one objection, reports by expert observers – acoustical engineers – judging the relative loudness of sounds did not agree with the logarithmic function. For another, the adaptive value of a logarithmic function for pain is questionable, given the paramount importance of good discriminability at high levels (the logarithmic function, in contrast, implies good discriminability at low levels). Finally, applying direct numerical estimates of the magnitudes of sensations typically yields power functions of intensity rather than logarithmic functions of intensity. Capitalizing on these results, S. S. Stevens has proposed the power function as *the* psychophysical law, replacing Fechner's logarithmic formulation.

According to Stevens, $R = kI^b$, where b and k are constants. The size of the exponent b varies from one continuum to another, subject, of course, to the conditions of stimulation. Exponents can take on values that vary from much smaller than unity (0.33 for brightness) through near unity (1.0 for perceived length) to much greater than unity (3.5 for the perceived intensity of alternating electric current). The power functions for such continua are depicted in Figure 3; the same functions become straight lines when plotted in logarithmically spaced axes because the logarithmic form of the power law is $\log R = \log k + b \log I$. The slopes of these linear functions correspond to the values of the respective exponents.

Assuming that a rule like Weber's law also holds for sensation results in the psychophysical power law. According to Ekman's law, JND is not constant but rather a linear function of sensation magnitude such that $\Delta R = gR$, where g is a constant, Ekman's fraction (which may or may not equal Weber's fraction for a particular modality), and ΔR is the increment in sensation that is just noticeable when added to starting sensation R. Assuming the validity of Weber's law for values of the stimulus and the validity of Ekman's law for values of the sensations, a geometrically spaced series of values on the physical continuum gives rise to a geometrically spaced series of values on the psychological continuum. This relation defines the power function with the exponent b reflecting the ratio of the respective fractions of Ekman and Weber.

In contrast to the Fechnerian approach, the methods of scaling advocated by Stevens are direct. Chief among the latter is *magnitude estimation* in which the observer is required to make direct numerical judgments of the stimuli in proportion to their sensory magnitudes. If one stimulus feels twice as strong as does another, the observer should give them numbers standing in a 2 to 1 ratio. The experimenter may provide the starting stimulus (standard) and assign it a certain numerical value (modulus) such that numbers are assigned to subsequent stimuli relative to the value of the modulus. The most popular method, however, is free magnitude estimation in which stimuli are randomly presented and the observer

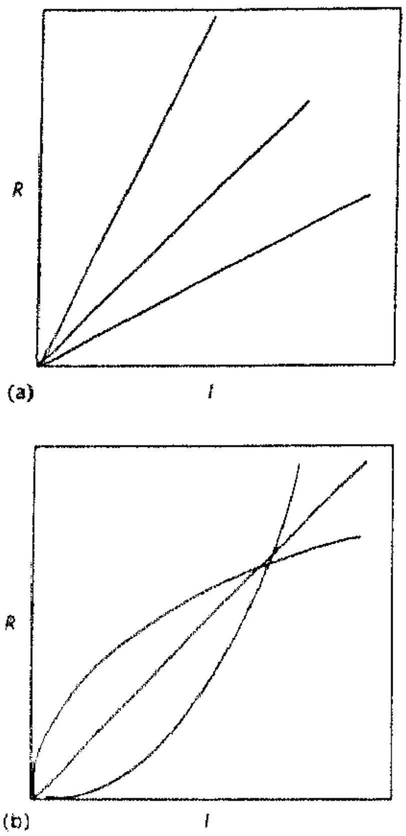

Figure 3. Two characterizations of Stevens' power law. (a) The power functions appear linear on double logarithmic coordinates, with the slopes corresponding to the respective exponents of the power functions. (b) Plotted on linear coordinates, the form of the functions is greatly influenced by the size of the exponent. An exponent of 1.0 corresponds to a linear function; an exponent smaller than 1 corresponds to a concave down function; an exponent greater than 1 corresponds to a concave upward function.

assigns numbers to them in proportion to the magnitudes of the respective sensations. No standard is provided and the observer is able to establish her or his own modulus. Other direct scaling procedures include *magnitude production*, in which the observer adjusts the level of the stimuli in proportion to numbers called out by the experimenter, and *absolute magnitude estimation*, in which the observer is asked to assign a number to each stimulus in a unique fashion, independent of the values of the other stimuli (hence, the resulting scale is an absolute one that cannot be transformed in any way).

In *cross-modality matching* (CMM) the observer is not required to make numerical judgments. The task is to set the magnitude of sensation in one modality equal to that presented in another modality. For instance, the observer might be asked to adjust the intensity of a vibration on the fingertip to that produced by a sound presented by the experimenter. If power functions are valid descriptions for vibration and for sound, then plotting the matching stimulus levels of the two modalities through CMM results in a power function with an exponent that is the ratio of those for vibration and sound. This result has often been confirmed in the laboratory. Stevens sought to use CMM to validate magnitude estimation and the associated power law. However, results of CMM predictable on the basis of the power law are better considered successful tests of transitivity or internal consistency. A good case can be made for magnitude estimation comprising a special case of CMM in which the observer matches number magnitude to that of the stimuli on the tested continuum. Consequently, any continuum could be substituted for numbers as the standard continuum to measure sensation magnitude on all of the other continua.

CONCLUSION

The implicit assumption that people are able to assign numbers to stimuli in a manner proportional to their inner sensations has been increasingly challenged in modern psychophysics. If it is not the case, then it is illegitimate to treat R as true numbers, let alone introduce them to quantitative, functional relations. Stevens' power law conflates the function relating stimulus intensity to sensation magnitude (the psychophysical function) and the function relating sensation magnitude to the observable verbal response R (the response function). Specifying the former as a power function strongly depends on the unjustified assumption that the latter is linear with zero intercept. The psychophysical function thus is indeterminable when a single stimulus factor is considered, as is usually the case in standard magnitude estimation scaling. Advanced multidimensional models have been developed in modern psychophysics to provide the necessary constraints for deriving and validating the 'true' psychophysical function.

Further Reading

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