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Psychophysical Measurement of Thresholds: Differential Sensitivity

Prior to a century ago the approach to psychological problems consisted primarily of philosophical speculation. The transition of psychology from a philosophical to a scientific discipline was greatly facilitated when the German physicist G. T. Fechner introduced techniques for measuring mental events (1860). The attempt to measure sensations through the use of Fechner's procedures was termed psychophysics and constituted the major research activity of early experimental psychologists. Since this time psychophysics has consisted primarily of investigating the relationships between sensations (ψ) in the psychological domain and stimuli (ϕ) in the physical domain.

Central to psychophysics is the concept of a *sensory threshold.* The philosopher Herbart (1824) had conceived of the idea of a threshold by assuming that mental events had to be stronger than some critical amount in order to be consciously experienced. Although measurement is not a part of this description of the threshold, scientists eventually were able to see the implication of such a concept for psychological measurement. In the early nineteenth century, for example, German scientists such as E. H. Weber and G. T. Fechner were interested in the measurement of the sensitivity limits of the human sense organs. Using measurement techniques of physics and well-trained human observers, they were able to specify the weakest detectable sensations in terms of the stimulus energy necessary to produce them. The *absolute threshold* or *stimulus threshold* (RL for the German *Reiz Limen*) was defined as the smallest amount of stimulus energy necessary to produce a sensation. Since an organism's sensitivity to external stimuli tends to fluctuate somewhat from moment to moment, several measurements of the threshold value of the stimulus are averaged to arrive at an accurate estimation of the absolute threshold. When a stimulus above absolute threshold is applied to the sense organ, the intensity of this stimulus must be increased or decreased by some critical amount before a person is able to report any change in sensation. The *difference threshold* (DL for the German *Differenz Limen*) was defined as the amount of change in a stimulus ($\Delta\phi$) required to produce a *just noticeable difference* (jnd) in the sensation. If the intensity of the stimulus is 10 units, and the stimulus must be increased to 12 units to produce a just noticeable increment in the sensation, then the difference threshold would be 2 units.

Sensation intensity is only one of several ways in which sensations can differ, and DL's have also been measured for other dimensions of sensation. It is generally agreed that sensations can differ on at least four basic dimensions—intensity, quality, extension, and duration. The dimension of quality refers to the fact that sensations may be different in kind. The different sensory modalities have unique kinds of sensations; for example, seeing is an entirely different kind of experience than hearing. Within sensory modalities, sensations also vary in quality. A sound becomes higher or lower in pitch as the vibration frequency of the stimulus is changed. Variations of the wavelength of light are accompanied by changes in hue. A cutaneous sensation may be felt as pain, warmth, cold, or simply a pressure. If the underlying stimulus dimensions for a sensation are known, the difference thresholds can be measured to find the changes in these dimensions necessary to produce just noticeable changes in the sensation. For example, in auditory pitch discrimination the DL for changes in frequency has been measured. In color discrimination the DL for the perception of changes in the wavelength of light has been measured. Since sensations can vary along the dimension of extension, the DL can be measured for variation in spatial aspects of physical stimuli, such as size, location, and separation. And, finally, since sensations last for varying periods of time, the DL for stimulus duration has been of interest to psychophysicists.

Much work in psychophysics has consisted of investigating how the absolute and difference thresholds change as some aspect of the stimulus (wavelength, frequency, adaptation time, intensity level, etc.) is systematically varied. The resulting relations are called *stimulus critical value functions*, since they describe how the threshold (critical stimulus value) changes as a function of other aspects of the stimulus.

DIFFERENTIAL SENSITIVITY

One of the first stimulus critical value functions to be investigated was the relation between the difference threshold for intensity and the intensity level of a stimulus. If, for example, the difference threshold is 2 units when the intensity level of the stimulus is 10 units, what would the difference threshold be for intensity when the stimulus is set at 20, 30, 40, or 50 units? Working mainly with the discrimination of lifted weights, the German physiologist E. H. Weber (1834) discovered that two relatively heavy weights must differ by a greater amount than two relatively light weights for one weight to be perceived as heavier than the other; that is, heavier weights are harder to discriminate and are associated with larger DL's. More precisely, the size of the difference threshold was a linear function of stimulus intensity. Thus, increases in the intensity of the stimulus that were just noticeably different to the observer were always a constant fraction of the stimulus intensity. For weights placed on the skin, this fraction is about 1/30.

The size of Weber's fraction is quite different, however, for other stimulus conditions and sense modalities. What is significant is that whether the stimulus is applied to the eye, ear, skin, nose, tongue, or other sense organs, there appears to be a lawful relationship between the size of the difference threshold and the stimulus intensity level. This relationship is known as *Weber's law*: the change in stimulus intensity that can just be discriminated ($\Delta\phi$) is a constant fraction (c) of the starting intensity of the stimulus (ϕ):

$$\Delta\phi = c\phi \quad \text{or} \quad \Delta\phi/\phi = c. \tag{1.1}$$

As seen graphically in our hypothetical situation, the size of the difference threshold is one-fifth of the starting stimulus intensity at all intensity levels (Fig. 1.1). If Weber's law is valid, we would expect, $\Delta\phi/\phi$ to be constant as intensity level is varied ($\Delta\phi/\phi = c$). This prediction is typically confirmed for a fairly wide range of stimulus intensities. However, the Weber fraction, $\Delta\phi/\phi$, tends to increase greatly at extremely low intensities. In Figure 1.2 the relationship between the Weber fraction and intensity is shown for an experiment on lifted weights (Engen, 1971). The observer was required to successively lift weights with one hand, and the value of $\Delta\phi$ was determined for six different values of ϕ. The results for each of two observers indicate that $\Delta\phi/\phi$ is nearly constant for all but the lightest weights.

Technically, the Weber fraction is an extremely useful calculation providing an index of sensory discrimination which can be compared across different conditions and different modalities. It is impossible, for example, to compare meaningfully the $\Delta\phi$ for vision in luminosity units with the $\Delta\phi$ for audition in sound pressure units, but the relative sensitivities for the two modalities can be gauged through a comparison of Weber fractions. Some of the results from two classic studies on intensity discrimination are presented in Figures 1.3 and 1.4. In the study

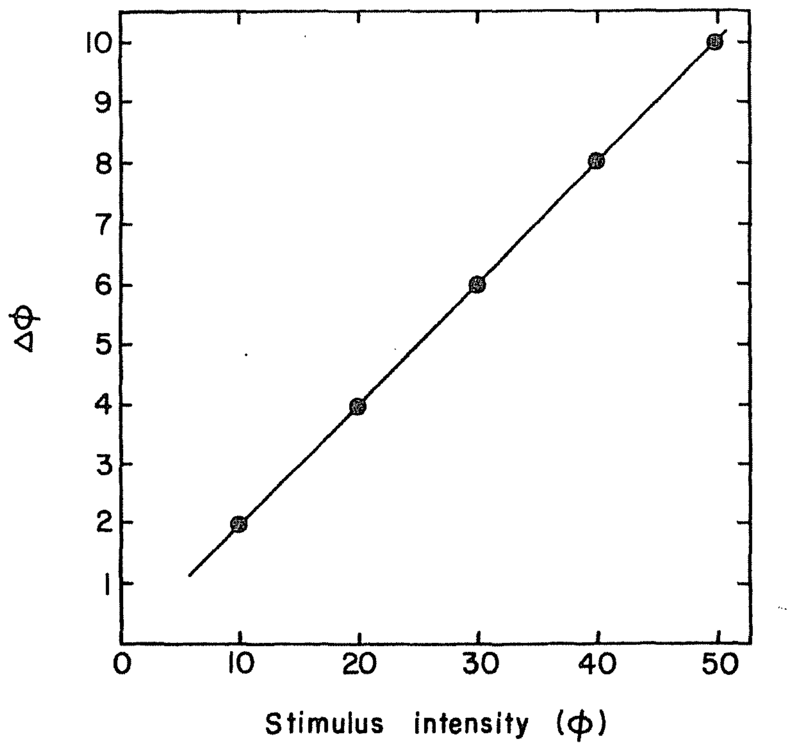

FIG. 1.1. The relationship between Δφ and φ according to Weber's law.

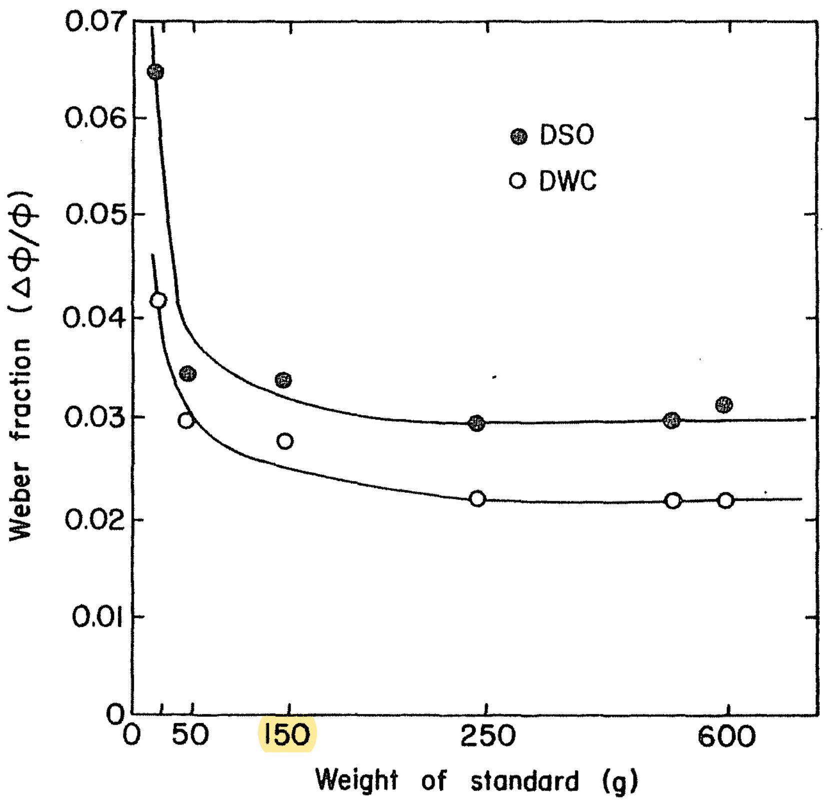

FIG. 1.2. The Weber fraction for lifted weights. The value of $\Delta\phi/\phi$ for each of two observers was nearly constant over the stimulus range, except for the lowest stimulus values. (From Engen, 1971.)

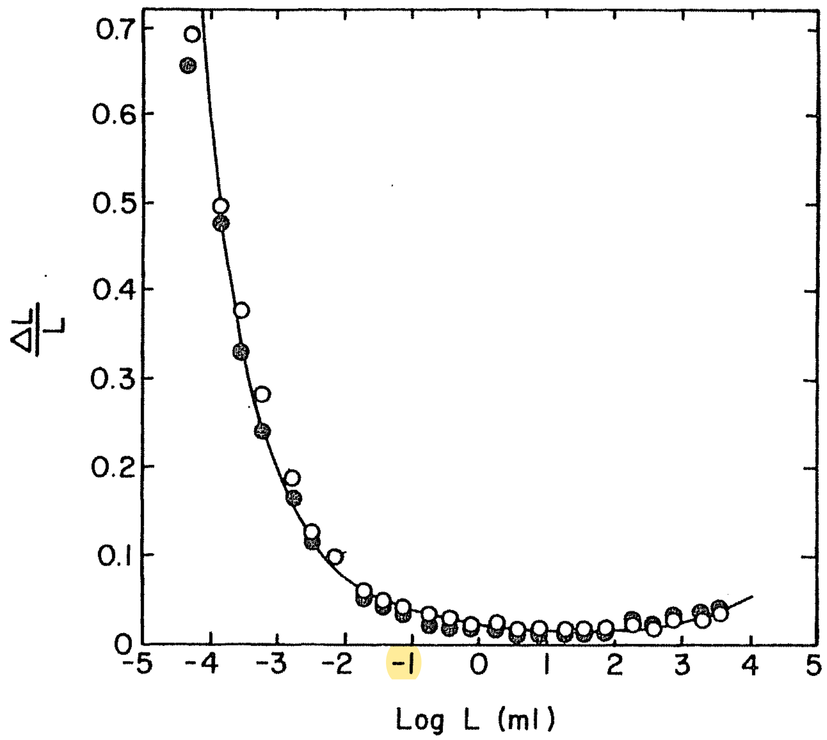

FIG. 1.3. Relation between $\Delta\phi/\phi$ and log luminance as shown by König (open circles) and Brodhun (solid circles). (From König & Brodhun, 1889; after Hecht, 1934, Fig. 27, p. 769.)

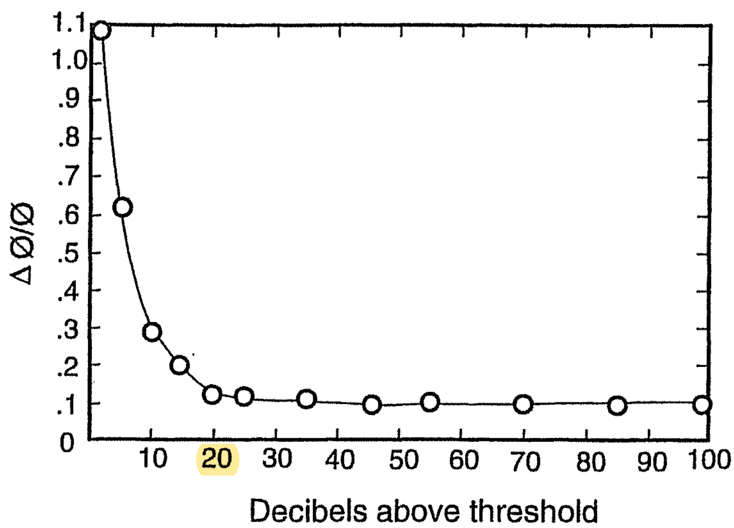

FIG. 1.4. Relation between $\Delta\phi/\phi$ and the intensity of auditory noise expressed as decibels above the absolute threshold. (From Miller, 1947.)

by König and Brodhun (1889), the observer viewed a split field in which the two sides could be made to differ in intensity by various amounts. The difference in intensity necessary for discrimination of a brightness difference between the two sides was determined for nearly the full range of visual intensities. Figure 1.3 contains data from separate experiments by König and Brodhun on the discrimination of intensity differences in white light. At low intensities, $\Delta\phi/\phi$ decreased as intensity increased, but then became approximately constant for the higher intensity values.

In a similar study, Miller (1947) determined the intensity difference in a burst of white noise necessary for discrimination at various intensity levels. We see again from the results presented in Figure 1.4 that $\Delta\phi/\phi$ first decreased as a function of ϕ, and then becomes approximately constant. A comparison of the lowest Weber fractions in Figure 1.3 and Figure 1.4 reveals that brightness discrimination is somewhat keener than loudness discrimination.

A modification of Weber's law more closely corresponding to empirical data states

$$\frac{\Delta\phi}{\phi + a} = c \quad \text{or} \quad \Delta\phi = c(\phi + a), \tag{1.2}$$

where a is a constant that usually has a fairly small value. The empirical values of $\Delta\phi/(\phi + a)$ obtained in a discrimination experiment are often approximately the same for all values of ϕ when the correct value of a has been chosen. Since the original version of Weber's law does not correspond to the data for intensity values near absolute threshold, it would seem that the constant a, which brings Weber's law into line with the data, must be related to the operation of sensory systems near threshold. The exact significance of a has not been determined, but it may represent the amount of sensory noise that exists when the value of ϕ is zero. The actual stimulus intensity which effectively determines $\Delta\phi$ may not be ϕ, but rather ϕ plus the continuously fluctuating background noise level of the nervous system. Since sensory noise as spontaneous activity in the nervous system exists as a background to stimulation, its level may greatly influence the value of $\Delta\phi$ for very low intensity values. When the level of sensory noise is taken into account, Weber's law may be essentially correct.

The hypothetical results shown in Figure 1.5 illustrate the effects of employing an additive constant a when describing how $\Delta\phi$ changes as ϕ increases. In the top graph $\Delta\phi/\phi$ is approximately constant over most of the range of ϕ values with the exception of the substantial deviation at low values of ϕ. When a constant a is added to all values of ϕ and $\Delta\phi/(\phi + a)$ is plotted as a function $\phi + a$, the results are described by Weber's law over the entire range of ϕ values.

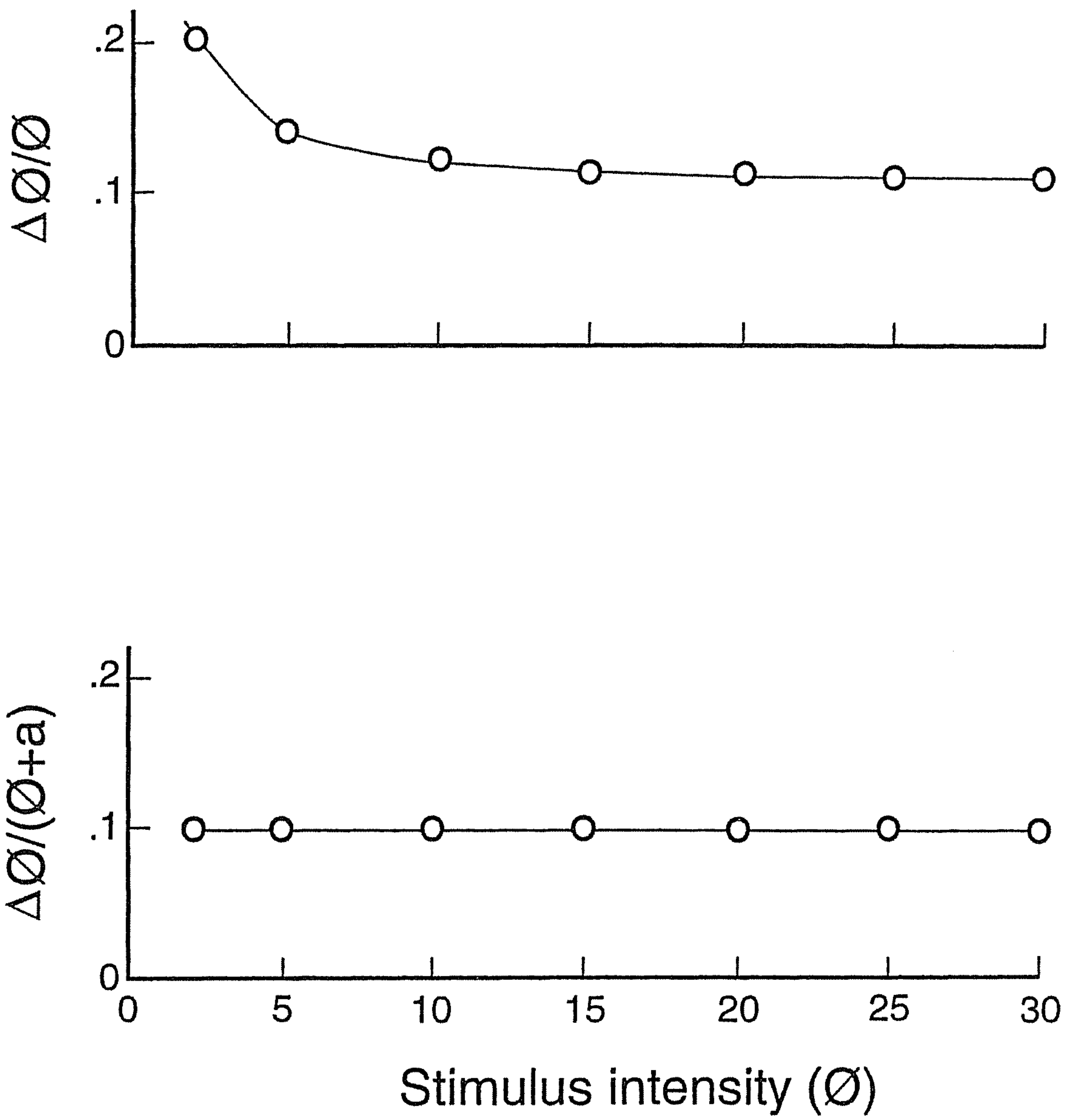

FIG. 1.5. Hypothetical results in which $\Delta\phi/\phi$ is plotted as a function of ϕ(top) and $\Delta\phi/(\phi + a)$ is plotted as a function of ϕ (bottom).

One advantage of the previous interpretation of the constant a is that the concept of sensory noise provides a unifying principle for understanding absolute and difference thresholds. The absolute threshold can be regarded as the value of ϕ needed to increase the neural activity level above the sensory noise level by some critical amount. The difference threshold can be thought of as the change in ϕ needed to produce a critical difference in neural activity level associated with two intensities of stimulation. Thus, both the absolute threshold and the difference threshold involve the discrimination of differences in levels of neural activity. The importance of the concept of sensory noise will become increasingly apparent in our subsequent discussions of psychophysical theory.

Noise in a psychophysical experiment may originate from outside as well as from inside the observer. One source of external noise is uncontrolled fluctuations in the stimulus. Attempts to determine the difference threshold for the sense of smell have illustrated the large effects that such external noise can have on psychophysical experiments. For many years the highest reported values of $\Delta\phi$ were for the sense of smell. The intensity of an odorant typically had to be changed by 25% to 35% for the perceived intensity of the smell to change (e.g., Gamble, 1898). A high Weber fraction for smell is surprising, since absolute thresholds for detecting odorants are among the lowest measured for any sensory modality. Cain (1977) has argued that the high difference thresholds for the sense of smell are an artifact of uncontrolled fluctuations in the concentrations of the olfactory stimulus. In olfactory psychophysics, substances are placed in an apparatus designed to deliver odorants to the observer's nose. The change in concentration of these substances required to produce a just noticeable difference in smell is the difference threshold. This procedure would be acceptable only if the changes in concentration of an odorant *at the nose* of the observer were entirely determined by changes in concentrations of the substance *in the apparatus*. Cain, however, demonstrated that, although the concentration of the substance in the apparatus may be constant, the concentration at the nose of the observer will vary greatly from one presentation to the next. When this "noise" at the nose was taken into account, Weber fractions for smell were found to be as low as 4%, which is about one-tenth the value commonly accepted. Cain's research illustrates the importance of precise stimulus control in psychophysics. Measurement of the stimulus should always be made as close to the sensory receptors as possible. Cain's analysis of the olfactory stimulus teaches us the important lesson that failure to control the stimulus at the receptors can lead investigators to make false conclusions about the nature of a sensory system.

Although Weber's law, at all but the lowest stimulus values, provides an excellent description of most intensity discrimination data, there are notable exceptions that have been repeatedly observed for the auditory discrimination of pure tones and tactile discrimination of vibration. For example, Riesz (1928) determined the intensity increment in an auditory tone necessary for discrimination at various intensity levels and at various frequencies. Because the frequency of 4000 Hz yielded the lowest values of $\Delta\phi$, only the data for this frequency are presented in Figure 1.6. We can see that the value of $\Delta\phi/\phi$ first decreases rapidly as a function of ϕ, but, instead of becoming constant as it did with white noise, $\Delta\phi/\phi$ continues to decrease gradually with further increases in ϕ. This gradual decrease in $\Delta\phi/\phi$ that can be observed even at the highest intenstiy levels, because it is so slight, has become known as the "near miss" to Weber's

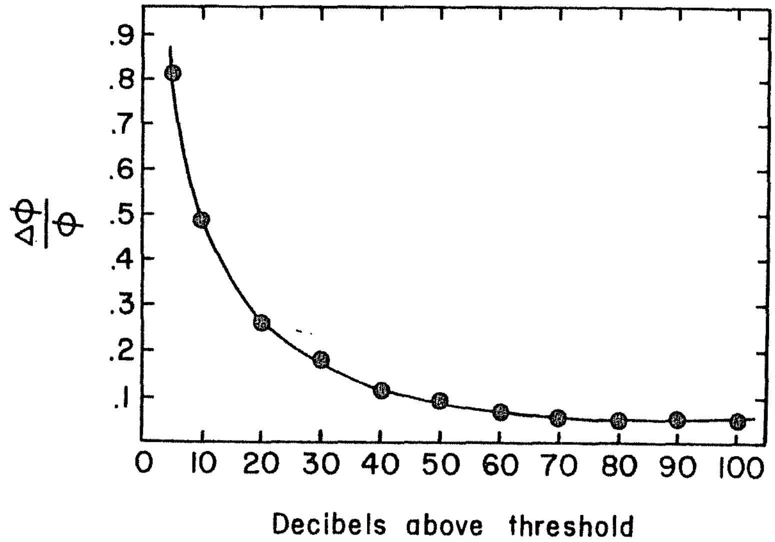

FIG. 1.6. Relation between $\Delta\phi/\phi$ and the intensity of a 4000-Hz tone. The intensity of the tone is expressed in decibels above absolute threshold. (From Riesz, 1928.)

law (McGill & Goldberg, 1968a, b). As yet, there are no widely agreed on explanations for this phenomenon. The near miss to Weber's law has also been observed for vibratory stimulation of the palm near the base of the thumb, and the results for 250 Hz sinusoidal stimulation and vibratory noise are seen in Figure 1.7. It is curious that the near miss has been found when random noise stimulation is presented to the skin as well as when sinusoidal stimuli are applied (Gescheider, Bolanowski, Verrillo, Arpajian, & Ryan, 1990). Recall that, in hearing, Weber's law describes intensity discrimination of white noise and the near miss is observed only for sinusoidal stimulation of pure tones. Perhaps the explanation for the near

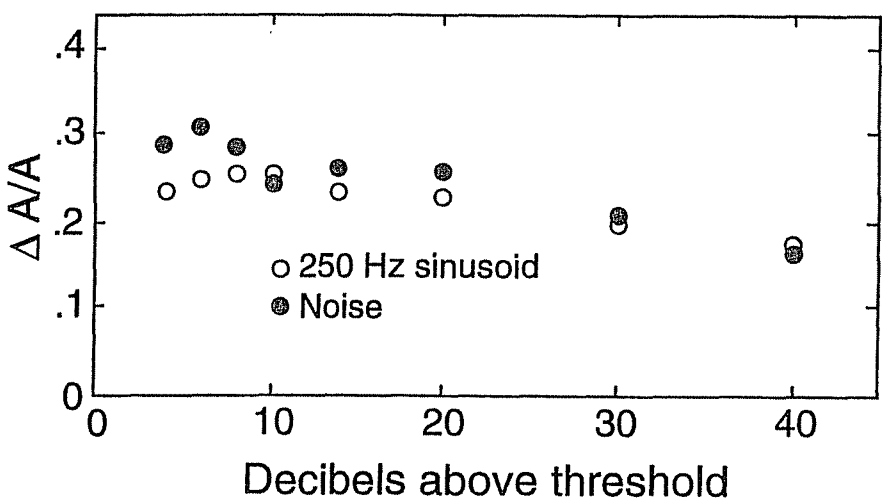

FIG. 1.7. Relation between $\Delta\phi/\phi$ and the intensity of a vibrotactile stimulus expressed as decibels above the absolute threshold. (From Gescheider, Bolanowski, Verrillo, Arpajian, & Ryan, 1990.)

miss to Weber's law will eventually come from a careful comparison of the conditions under which the phenomenon is observed in the auditory and tactile modalities.

FECHNER'S PSYCHOPHYSICS

It was from Weber's work on the DL that Fechner extracted the theoretical implication which led to his formulation of the discipline called psychophysics. Fechner's investigations, originating from an attempt to establish a precise relationship between the physical and mental, were published in 1860 as *Elements of Psychophysics*. In this work, Fechner was concerned with the problem of measuring private experience. For example, if a room appeared to become brighter, a sound louder, or an injury more painful, Fechner wanted to find a way to give the brightness, loudness, or painfulness a number that represented the experience. As a result of his background in physics and mathematics, he approaches these problems in a quite different manner than those who preceded him. In the last 35 years of his life, Fechner's work focused on the idea that mind and matter are equal and are merely two alternative ways of regarding the universe. His psychophysics was a small, but highly significant, part of this concept.

Seeking proof for his ideas about the equivalence of mind and matter, Fechner tried through measurement and quantification to derive a mathematical equation to describe the relationship between physical events and conscious experience. Fechner's first insights into the problem came when he proposed that an arithmetic series of mental intensities might correspond to a geometric series of physical energies. He later realized this principle was exactly what Weber's results seemed to imply: that as the stimulus intensity increases, it takes greater and greater changes in intensity to change the sensation magnitude by some constant amount. Fechner proposed that sensation magnitude could be quantified indirectly by relating the values of $\Delta\phi$ on the physical scale to the corresponding values of the just noticeable difference (jnd) in sensation on the psychological scale. His central assumption was that all jnd's were equal psychological increments in sensation magnitude, regardless of the size of $\Delta\phi$. Fechner's proposed relationship between the size of $\Delta\phi$ in physical units (from Weber's law) and the size of the jnd in psychological units is illustrated in Figure 1.8. It is very important to understand that two independent dimensions exist in this relationship—the stimulus dimension, ϕ, and the sensation dimension, ψ. Fechner was saying that, regardless of its size in physical units, the jnd is a standard unit of sensation magnitude because it is the smallest detectable increment in a sensation and is therefore always psychologically the same size. As is the case with any scale of

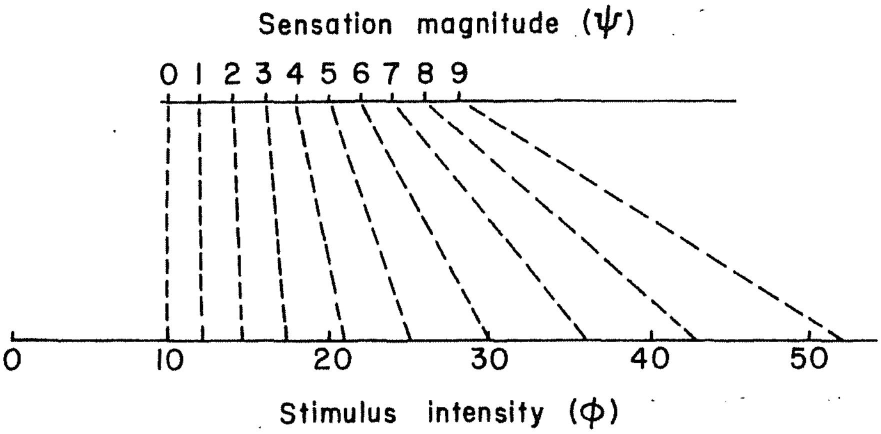

FIG. 1.8. Relation between Weber's law and Fechner's law. Stimulus values that are marked off according to Weber's law were assumed by Fechner to result in equal steps in sensation magnitude.

measurement, once a basic unit is established, one has only to count up units in order to specify the amount of a measured property. Thus, Fechner developed a scale of sensation magnitude by counting jnd's, starting at absolute threshold. The intensity in physical units of a stimulus at absolute threshold, which represents the transition between sensation and no sensation, was assumed to correspond to the zero point on the psychological scale of sensation magnitude. A sensation produced by a stimulus 20 jnd's above absolute threshold should therefore have a psychological magnitude twice as great as a sensation produced by a stimulus that is only 10 jnd's above absolute threshold.

In order to determine empirically the number of jnd's above absolute threshold corresponding to values of the physical stimulus, one would have to undertake the arduous task of starting at absolute threshold and measuring successive values of $\Delta\phi$ along the physical continuum. The first $\Delta\phi$ above the absolute threshold would be measured, and the stimulus intensity value for one jnd above absolute threshold would be recorded and used as the starting stimulus for the measurement of the next $\Delta\phi$. The measurement of the second $\Delta\phi$ would provide a stimulus value two jnd's above the absolute threshold; this value would then be recorded and used as the starting stimulus for the measurement of the third $\Delta\phi$, and so on. Once the physical intensity values had been determined for successive jnd's over the range of energies to which the sensory system responds, the relationship between stimuli in physical units (ϕ) and sensation magnitude in psychological units (number of jnd's above absolute threshold) could be specified in terms of a graph or an equation.

Rather than employing the laborious procedure of experimentally determining successive $\Delta\phi$ values along the entire physical dimension, Fechner, by assuming the validity of Weber's law, was able to calculate the number of jnd's above absolute threshold for specific values of the stimulus. For example, if $\Delta\phi/\phi$ is ⅕, and the absolute threshold is 10, then the stimulus value corresponding to the first jnd would be $10 \times ⅕ + 10 = 12$. The stimulus value corresponding to the second jnd is obtained by the same procedure ($12 \times ⅕ + 12 = 14.4$). This method of successive calculation provides the basis for Table 1.1. This table contains stimulus intensity values and the corresponding number of psychological units (number of jnd's). The results of this procedure are presented graphically in Figure 1.9. If the number of jnd's above absolute threshold is a valid measure of sensation magnitude, then it is apparent from Figure 1.9 that equal increments in sensation correspond to larger and larger increases in stimulus intensity as stimulus intensity increases. In fact, if sensation magnitude is plotted against the logarithm of stimulus intensity, the relationship is linear (Fig. 1.10). A considerable amount of labor would be saved if the equation were known for this logarithmic relationship. The sensation magnitude produced by some specific stimulus intensity could then be quickly calculated. Fechner derived a general formula from Weber's law by integration over a series of ϕ values; it has become known as Fechner's law:

$$\psi = k \log \phi. \tag{1.3}$$

In the formula, ψ is the sensation magnitude, ϕ is the intensity of the stimulus in units above absolute threshold, and k is a constant multiplier, the value of which depends upon the particular sensory dimension and modality.

In evaluating Fechner's law, we must consider the two main assumptions which he had to make to derive the equation. First, Fechner's law

TABLE 1.1
Number of jnd's Above Threshold
Corresponding to Stimulus Intensity Values

Number of jnd's	*Stimulus intensity*	*Log stimulus intensity*
0	10.00	1.000
1	12.00	1.079
2	14.40	1.158
3	17.28	1.238
4	20.79	1.316
5	24.89	1.396
6	29.86	1.476
7	35.83	1.554
8	43.00	1.633
9	51.60	1.713

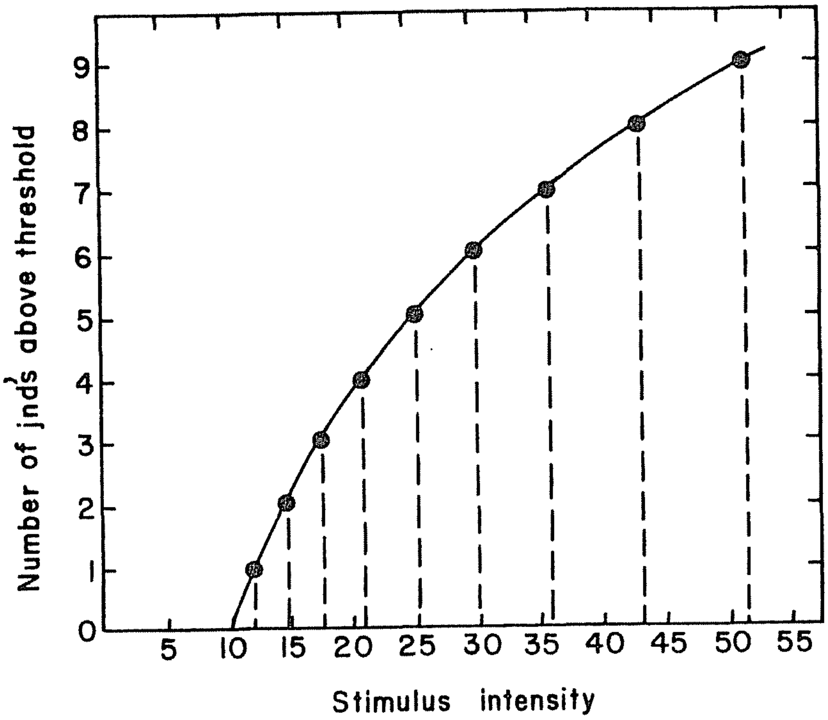

FIG. 1.9. Number of jnd's above threshold plotted against stimulus intensity. The points are from Table 1.1, which contains the calculated values based on the assumption that the Weber fraction is ⅕ and the absolute threshold is 10 units.

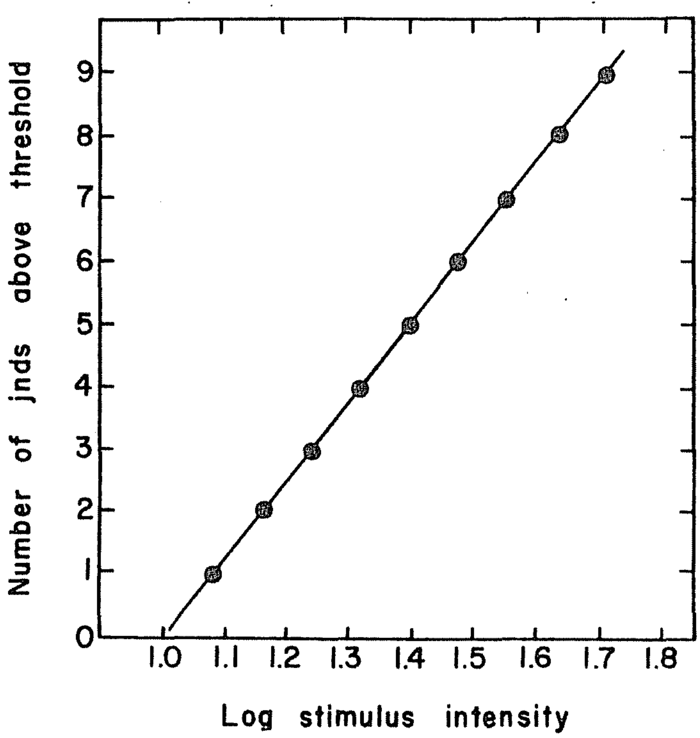

FIG. 1.10. Number of jnd's above threshold plotted against the logarithm of stimulus intensity. The calculated values are in Table 1.1.

is valid only to the extent that Weber's law is correct, and we have already seen that the Weber fraction is not a constant at the low end of the stimulus range. Thus, the generality of the law is necessarily restricted to ranges of stimulus intensity over which $\Delta\phi/\phi = c$. In the second place, Fechner's law rests upon the assumption that the jnd is an equal increment in sensation at all levels of stimulus intensity. This assumption is basic to the entire concept of scaling sensations by using the jnd as the unit measurement. However, experimental tests have shown that jnd's along the intensive dimension are psychologically unequal (S. S. Stevens, 1936). A sound 20 jnd's above absolute threshold is judged to be much more than twice as loud as a sound 10 jnd's above absolute threshold.

In another experiment, Durup and Piéron (1933) had observers adjust the intensities of blue and red lights so that they appeared equal in brightness. Contrary to Fechner's notion that all jnd's are subjectively equal, the two stimuli no longer appeared to have the same brightness when their intensities were increased by the same number of jnd's. If jnd's are subjectively equal, then two stimuli that appear equal in subjective magnitude should continue to appear so when their intensities are both increased by the same number of DL steps. For example, increasing the intensity of both stimuli by 10 DL steps should increase the sensation magnitude of both stimuli by 10 subjectively equal jnd's. According to Fechnerian thinking, the sensation magnitudes of both stimuli, in this situation, have been raised by the same amount and therefore the two stimuli should still appear subjectively equal. Because this prediction was not confirmed, it follows that jnd's are not subjectively equal and therefore cannot be used as the basic unit for measurement of sensation magnitude.

For more than 100 years, Fechner's equation was widely accepted in psychology and, to some extent, in other fields, such as physiology and engineering. Today, it is not considered an accurate statement of the relationship between stimulus intensity and sensation magnitude. However, the fact that experimental results have not led to the verification of Fechner's law does not detract from the overall significance of his work. The importance of his accomplishments lies in the direction he took while trying to deal with problems of mental events. The concept of measurement, a primary goal of science, became a part of psychological investigation through Fechner's work.

PROBLEMS

1.1. Using Weber's formula $\Delta\phi = c\phi$ calculate $\Delta\phi$ for ϕ values of 10, 15, 20, 25, and 30, when c is .1 and when it is .2. On the same graph plot $\Delta\phi$ as a function of ϕ for the two values of c. On another graph plot $\Delta\phi/\phi$ as a function of ϕ for the two values of c.