PSYCHOPHYSICS
Method, Theory, and Application

Second Edition

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ing sensory magnitude. These two advances have greatly broadened the applicability of psychophysics to areas far beyond the original problems of measuring sensory thresholds. Modern psychophysics can be credited with contributions to the solution of problems in such diverse realms as sensory processes, memory, learning, social behavior, and esthetics.

This book describes the methods, theories and applications of classical and modern psychophysics. It was written for advanced undergraduate students with some background in statistics; graduate students may also find it useful for obtaining an overview of the field. I hope *Psychophysics: Method, Theory, and Application* will be useful for courses in perception, general experimental psychology, and quantitative methods.

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In the interest of readability I use the masculine pronouns—he, his, him, himself. Please read this as what would be expressed as he/she, his/hers, him/her, and himself/herself.

1 Psychophysical Measurement of Thresholds

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 simulus 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 (Figure 1.1). If Weber's law is valid, we would expect, $\Delta\phi/\phi$ to be

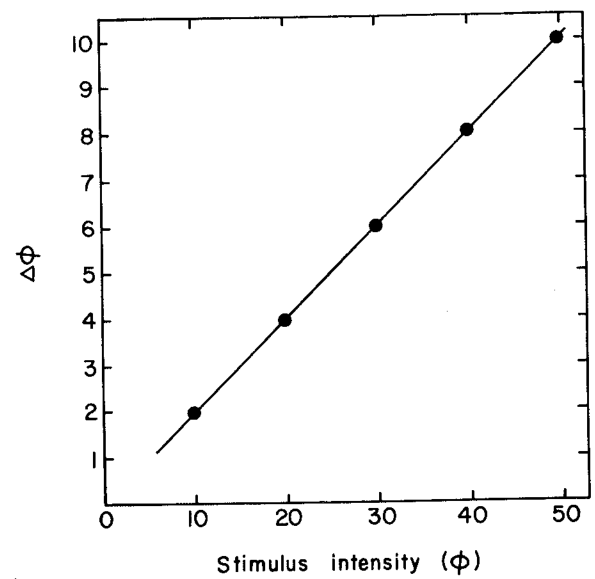

FIG. 1.1. The relationship between $\Delta\phi$ and ϕ according to Weber's law.

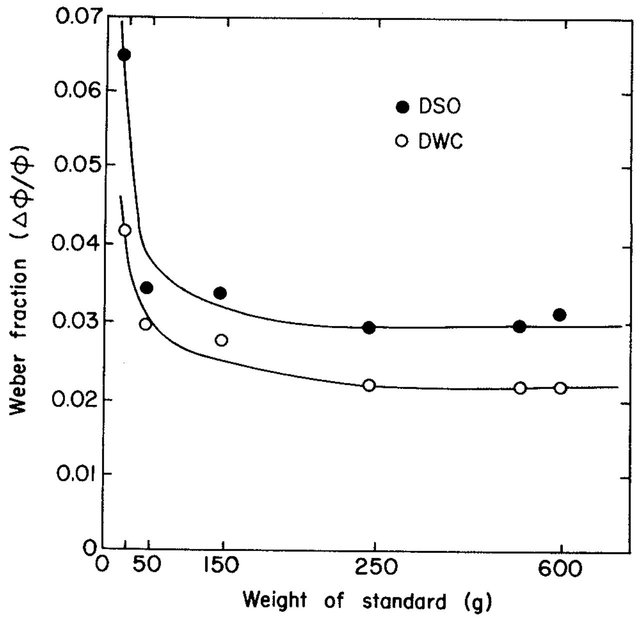

FIG. 1.2. The Weber fraction for lifted weights. The value of $\Delta\phi/\phi$ for each of two observers was nearly constant over the stimulus range, except for the lowest stimulus values. (From Engen, 1971.)

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 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, Riesz (1928) determined the intensity increment in an auditory tone necessary for discrimination for various intensity levels and various tone frequencies. Since the frequency of 4000 Hz yielded the lowest values of $\Delta\phi$, only the data for this frequency are presented in Figure 1.4. We see again that the value of $\Delta\phi/\phi$ first decreases as a function of ϕ, and then becomes approximately constant. A comparison of the lowest Weber fractions in Figures 1.3 and 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

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

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 corre-

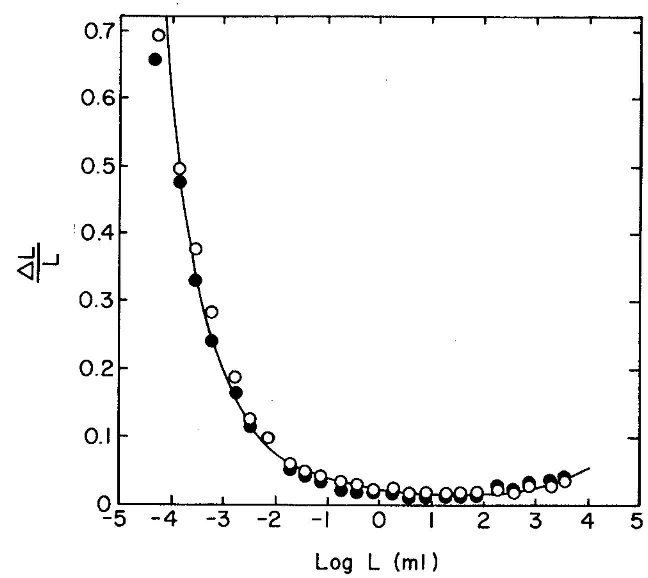

FIG. 1.3. Relation between $\Delta\phi/\phi$ and log luminance as shown by König (open circles) and Brodhun (solid circles). (From König & Brodhun, 1889; after Hecht, 1934, Fig. 27, p. 769.)

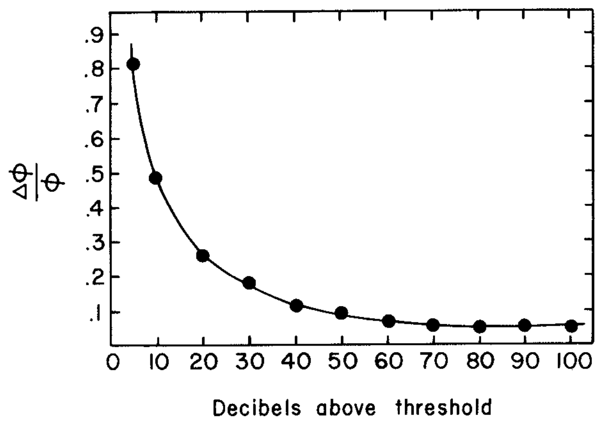

FIG. 1.4. Relation between $\Delta\phi/\phi$ and the intensity of a 4000-Hz tone. The intensity of the tone is expressed in decibels above absolute threshold. (From Riesz, 1928.)

spond 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.

One advantage of the above 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.

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*. Although Fechner was a physicist, in his later years he turned to the problems of philosophy. As a result of his background in physics and mathematics, he approached 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. 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 1.5. 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 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.

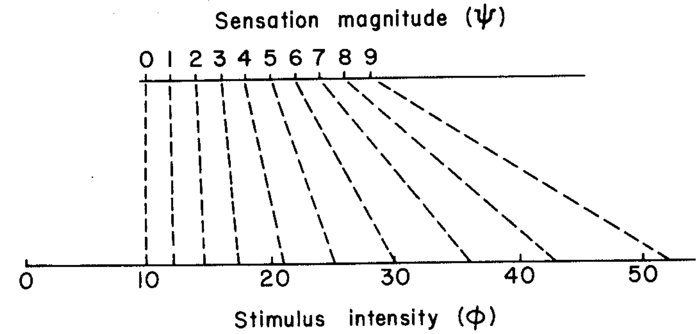

FIG. 1.5. Relation between Weber's law and Fechner's law. Stimulus values that are marked off according to Weber's law were assumed by Fechner to result in equal steps in sensation magnitude.

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 $\frac{1}{5}$, and the absolute threshold is 10, then the stimulus value corresponding to the first jnd would be $10 \times \frac{1}{5} + 10 = 12$. The stimulus value corresponding to the second jnd is obtained by the same procedure ($12 \times \frac{1}{5} + 12 = 14.4$). This method of successive calculation provides the basis for Table 1.1. This table contains stimulus intensity values and the corresponding number of psycho-

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

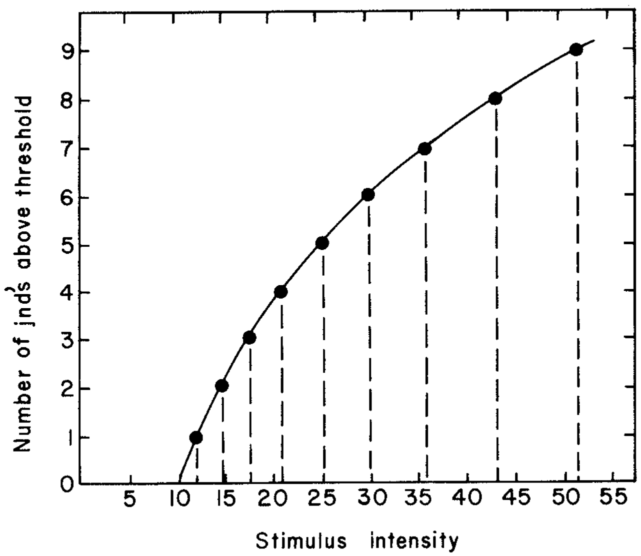

FIG. 1.6. Number of jnd's above threshold plotted against stimulus intensity. The points are from Table 1.1, which contains the calculated values based on the assumptions that the Weber fraction is ⅕ and the absolute threshold is 10 units.

logical units (number of jnd's). The results of this procedure are presented graphically in Figure 1.6. If the number of jnd's above absolute threshold is a valid measure of sensation magnitude, then it is apparent from Figure 1.6 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 (Figure 1.7). 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 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 of 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.

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.

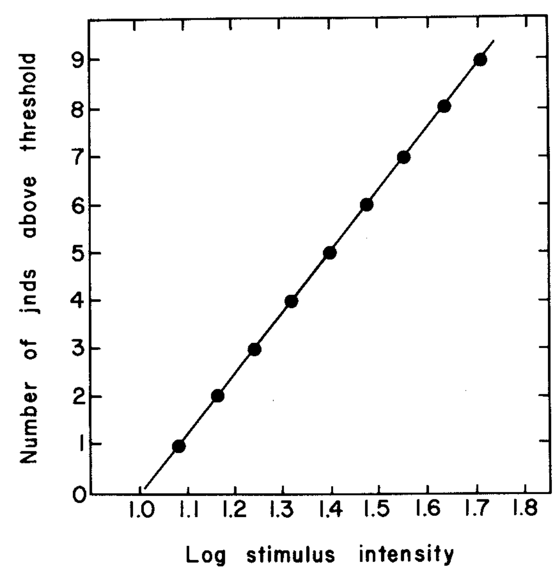

FIG 1.7. Number of jnd's above threshold plotted against the logarithm of stimulus intensity. The calculated values are in Table 1.1.

ABSOLUTE SENSITIVITY OF SENSORY SYSTEMS

The measurement of the absolute threshold, though perhaps not as important for the development of psychology as Fechner's insights into difference thresholds, has led to many significant advances in understanding sensory systems. Before considering in detail the various psychophysical methods for measuring DL's and RL's, let us consider examples of how measuring absolute thresholds has facilitated our understanding of vision, audition, touch, and olfaction.

The Absolute Sensitivity of the Eye

The eye is an extremely light-sensitive instrument capable of responding to almost unbelievably small amounts of light energy. However, a simple answer cannot be given to the question: How sensitive is the eye to light? The absolute sensitivity of the eye cannot be gauged by a single threshold value, since the minimum amount of light necessary for vision has been found to depend on the conditions of stimulation. Therefore, the absolute sensitivity of the visual system is best understood by examining the functional relationships between the absolute threshold and the conditions that determine its value.

The value of the absolute threshold depends upon previous stimulation. Exposing the eye to intense light greatly decreases the absolute sensitivity of the eye. Sensitivity is recovered gradually if the eye is subsequently kept in darkness. Nearly complete recovery of sensitivity occurs after about one hour in the dark. The dark adaptation curve is traced out by measuring an observer's absolute threshold periodically during the recovery period and plotting its value as a function of time in the dark. The threshold at the beginning of dark adaptation may be as much as 100,000 times as high (5 log units) as the threshold after complete dark adaptation.

In an experiment by Hecht, Haig, and Chase (1937), the test stimulus was presented to a region of the retina containing both rods and cones, and the dark adaptation curve was found to be biphasic (Figure 1.8). The first phase shows a relatively rapid reduction in the absolute threshold as a function of time in the dark and shows the threshold stabilizing after 5—8 min. The second phase, starting after about 10 min in the dark, was a relatively gradual decrease in the threshold which was complete after about 40 min. The point on the curve where the second phase begins is called the rod—cone break. The biphasic curve is caused by the intersecting of the cone and rod recovery curves, which start at different intensity levels, change at different rates, and approach different asymptotes. Before the rod—cone break, the absolute threshold of the rods is so high that the adaptation curve is determined completely by the changing sensitivity of the cones. The rod—cone break represents the point where rod sen-

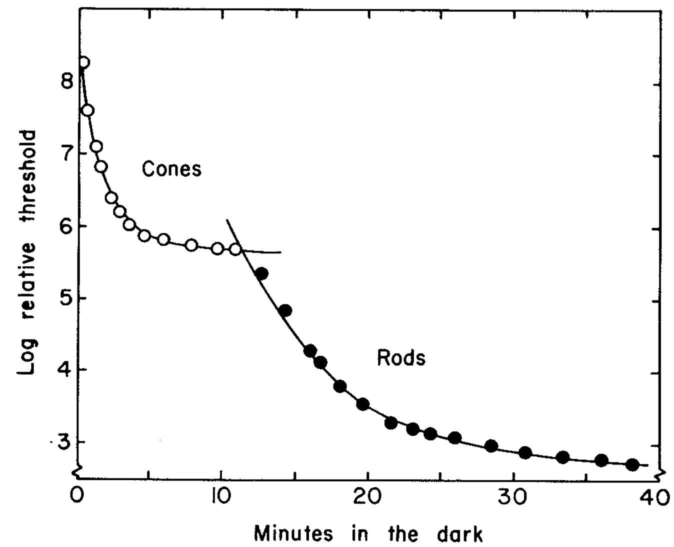

FIG. 1.8. Biphasic curve for dark adaptation. The logarithm of the threshold intensity is plotted against time in the dark. (From Hecht, Haig, & Chase, 1937.)

sitivity finally begins to exceed cone sensitivity, and thereafter the remainder of the dark adaptation curve is determined by the continuing recovery of the rods.

Under most conditions, the electromagnetic radiation is visible when its wavelength is between 400 and 750 nanometers (nm). However, the eye is not equally sensitive to light of all wavelengths. Spectral sensitivity curves showing the absolute threshold as a function of stimulus wavelength have been obtained for cone (photopic) and rod (scotopic) vision. In one such experiment, Wald (1945) measured the absolute thresholds of 22 observers for detecting a 1.0°, 40-msec test stimulus of variable wavelength presented either within the fovea or 8° above the fovea. Figure 1.9 illustrates that light in the extreme blue or red regions on the visual spectrum is relatively ineffective in producing visual responses. The periphery of the retina is most sensitive to light with a wavelength of approximately 500 nm, and the fovea is most sensitive when the stimulus wavelength is about 560 nm. For all wavelengths, the stimulus flash at threshold appeared to be colored for foveal stimulation, indicating the operation of cones, but all threshold stimuli appeared achromatic for peripheral stimulation, indicating the operation of rods. That rods are considerably more sensitive than cones at all but the longest wavelengths is illustrated by the fact that much less energy is required at threshold for peripheral stimulation than for foveal stimulation. The difference between rod and cone thresholds is clearly illustrated by gradually increasing the

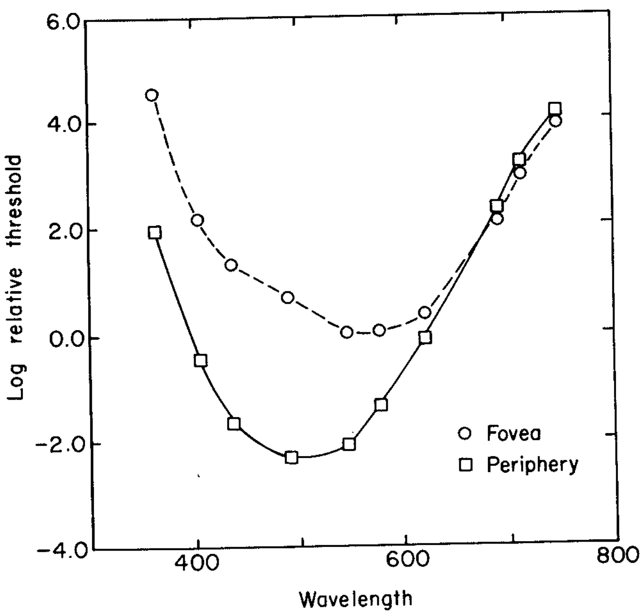

FIG. 1.9. Relative thresholds for detection of light as a function of wavelength and location of the stimulus on the retina. (From Wald, 1945. Copyright 1945 by the American Association for the Advancement of Science.)

intensity of a colored light presented to an extrafoveal region of the retina containing both rods and cones. When the rod threshold is reached, the light appears colorless; however, with continued increases in intensity, a point is reached where the light is above the cone threshold, and color is finally perceived. The difference between the rod and cone thresholds measured in this way is called the photochromatic interval. It is an interval on the stimulus intensity scale in which a colored light is perceived, but as colorless. As Figure 1.9 shows us, the size of the photochromatic interval varies with wavelength, being smallest for the long wavelengths and becoming larger for shorter wavelengths.

In physics, it has been shown that light can be described as both a wave and a particle, or quantum. Prior to this development it was thought that energy varied on a continuum. We now know that—due to its quantal nature—energy, including light, changes in discrete steps. The light quantum, also known as a photon, is the smallest possible unit of light energy. It has been determined that vision occurs when the number of quanta absorbed by retinal receptors exceeds some small critical number.

The receptors are able to summate energy over space, as indicated by the fact that within certain spatial limits the total number of quanta is constant at threshold, whether they are distributed sparsely over a large area (up to about 10 min of arc in the fovea and 1° in the periphery of the eye) or are concentrated in a small area. Likewise, the visual receptors are able to summate energy over time up to about .1 sec, since it has been found that the total number of quanta at threshold is the same when exposing the eye to a weak stimulus for a long time as when exposing it to a strong stimulus for a short time. Because the eye is unable to summate energy completely over time intervals exceeding .1 sec or areas exceeding about 10 min in diameter, beyond these limits a greater number of quanta are required at absolute threshold.

In what has become a classic experiment in visual science, Hecht, Shlaer, and Pirenne (1942) determined the amount of light at the retina necessary for vision under conditions yielding optimal sensitivity. The following steps were taken to provide optimal conditions for visual sensitivity: (*a*) the retina was dark-adapted for at least 30 min prior to the making of threshold measurements; (*b*) stimuli were presented on the temporal retina 20° from the fovea, since this area contains a maximum concentration of rods; (*c*) a very small test field (10 min in diameter) was employed to insure that within the visual system there would be complete spatial summation of the stimulus[1]; (*d*) similarly, the exposure time was very short (.001 sec) so temporal summation would operate; (*e*) a light of 510 nm was used because of the optimal scotopic sensitivity to light of this wavelength; and (*f*) so that he would be maximally set for each stimulus, the observer operated the shutter through which the stimulus was presented.

Stimulus intensity was measured by a thermopile which was substituted for the observer's pupil. A thermopile is a thin strip of metal which exhibits an increase in temperature when struck by light. The increment in temperature was then converted into units of light intensity. Thresholds were defined as the stimulus energy resulting in a sensation 60% of the time. They were measured over a period of months for seven observers and ranged between 2.1×10^{-10} and 5.7×10^{-10} ergs at the cornea. These minute amounts of energy represent between 54 and 148 quanta of blue-green light.

To specify the number of quanta absorbed at threshold by the photochemical pigment of the visual receptors (rhodopsin), the threshold values measured at the cornea were corrected for losses of light within the eye. Approximately 4% of the light reaching the cornea is reflected back in-

1. For stimuli smaller than 1° presented to the periphery of the dark-adapted eye there exists a perfect reciprocal relation between stimulus size and stimulus intensity at the threshold of detectability (Graham, Brown, & Mote, 1939); that is, the total effective energy for the eye is determined by the product of stimulus intensity and stimulus area for areas up to 1° in diameter.

stead of entering the eye. Ludvigh and McCarthy (1938) found that 50% of the light of 510 nm entering the eye is absorbed by the ocular media before reaching the retina. Finally, it has been estimated that at most only 20% of the light reaching the retina is absorbed by the rhodopsin of the receptors, the remainder being absorbed by other tissues such as blood vessels. The threshold value of 54 to 148 quanta measured at the cornea, when corrected for the above factors, is only 5 to 14 quanta absorbed by rhodopsin. In the 10-min retinal area stimulated, there are approximately 500 rods, thus making it highly unlikely that more than one quantum will strike a single rod at threshold levels of intensity. On this basis, Hecht et al. (1942) concluded that, 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 5 to 14 rods. The maximum sensitivity of the eye approaches a limit imposed by the nature of light.

The Absolute Sensitivity of the Ear

The remarkable sensitivity of the eye under optimal conditions of stimulation has been found to be nearly matched by that of the ear. Under normal conditions, a young person can hear sound when its frequency of vibration is between 20 and 20,000 Hz. However, the auditory system is most sensitive to vibrations between 2000 and 4000 Hz and is least sensitive to vibrations at the extremes of the audible range of frequencies. In Figure 1.10, the absolute threshold in decibels (dB) sound pressure level[2] is plotted for the frequencies that are employed in standard hearing tests. This graph, prepared by the International Organization for Standardization, is based on the combining of results from a number of studies in which an attempt was made to determine normal hearing for young people (Davis & Krantz, 1964). The extremely low thresholds for the middle frequencies can be better appreciated when the physical effects of such low sound pressure on the eardrum are determined. Wilska (1935) attached one end of a light wooden rod to the eardrum and the other end to a loudspeaker coil. The rod was vibrated, and voltage across the speaker coil was adjusted, so that a tone could hardly be heard. The vibration amplitude of the rod, and thus the amplitude of the in–out movement of the eardrum, was then measured under stroboscopic illumination with a microscope. Direct measurements of the movement of the rods could be made only for the low

2. Sound pressure is often expressed on a logarithmic scale as the number of decibels above a reference sound pressure. The most frequently used reference is .0002 dyne per square centimeter. The number of decibels can be computed by the formula

$$N_{dB} = 20 \log p_1/p_0,$$

where p_0 is a sound pressure of .0002 dyne/cm^2 and p_1 is the measured sound pressure.

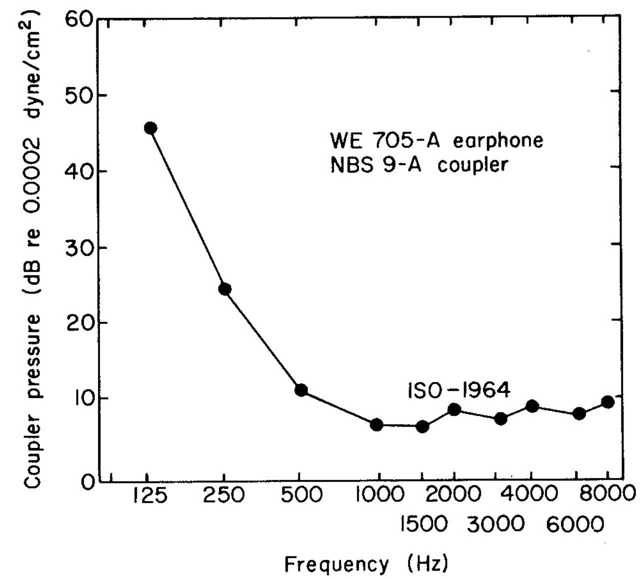

FIG. 1.10. Absolute threshold in decibels sound pressure level for the detection of pure tones as a function of stimulus frequency. (From Davis & Krantz, 1964.)

frequencies of vibration. At high frequencies, the movement was so slight at threshold that it had to be calculated from larger movements of the rod at low frequencies. The results of the study indicate that, for frequencies of between 2000 and 4000 Hz, the eardrum has to move only 10^{-9} cm in order for a sound to be heard. This amount of movement is less than the diameter of a hydrogen molecule. By using a highly precise laser interferometer to measure vibration amplitude of the cat's eardrum at threshold, Tonndorf and Khanna (1968) were able to confirm Wilska's findings. Peak displacement amplitude at threshold was 10^{-10} cm at 1000 Hz and close to 10^{-11} cm at 5000 Hz.

Is the sensitivity of the ear limited by its construction and physiological efficiency, or is it limited by the nature of air as a transmitting medium for sound? Sivian and White (1933) calculated the sound pressure generated by the constant random movement of individual air molecules within the frequency range of 1000–6000 Hz. These calculations indicate that a constant sound pressure exists which is only 10 dB lower than the average auditory threshold of approximately .0002 dyne/cm^2 for sounds within this frequency range. Furthermore, people with excellent hearing have thresholds which are approximately the same as the constant sound pressure from the random movement of air molecules. Therefore, for people with excellent hearing, having more sensitive ears would be useless because of the thermal noise continuously present in the air.

The Absolute Sensitivity for Touch

One way of measuring tactile sensitivity is to determine the smallest amplitude of vibration of the skin that can be detected by an observer. Vibrotactile thresholds depend on stimulus factors such as the locus of stimulation, the size of the stimulated skin area, the duration of the stimulus, and the frequency of vibration. An experiment by Verrillo (1963) will serve to illustrate the relationship which is found for the absolute threshold for vibration and the frequency of the vibratory stimulus. In Verrillo's experiment, a stimulator attached to a vibrator was placed in contact with the skin of the prominence on the palm at the base of the thumb. The stimulator protruded up into a hole in a rigid surface upon which the observer's hand rested. There was a 1-mm gap between the circularly shaped stimulator and the rigid surrounding surface. The small gap between the stimulator and the rigid surface upon which the hand rested served to control the area of stimulation by confining the vibration to the area of the stimulator. The data presented in Figure 1.11 were obtained when the size of the stimulator was varied over a range of .005 cm^2 to 5.1 cm^2.

It can be seen in Figure 1.11 that when the stimulator was larger than .02 cm^2, vibrotactile sensitivity was a U-shaped function of frequency and that sensitivity was greatest in the frequency region around 250 Hz where the amplitude of vibration needed to exceed threshold was approximately .1 micron (μm) for the largest contactor. Thus, under the best conditions

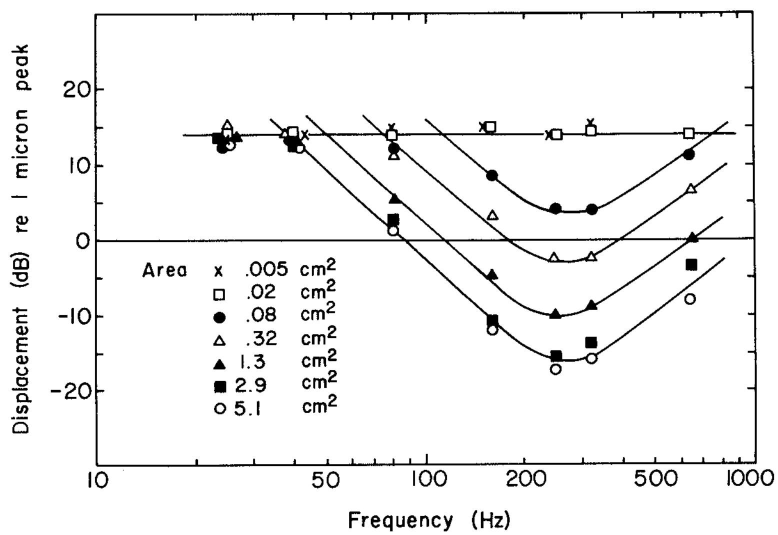

FIG. 1.11. Vibrotactile thresholds for seven contactor sizes as a function of vibration frequency. (From Verrillo, 1963.)

in which large areas of skin on a relatively sensitive part of the body are stimulated, vibration amplitude had to be 10^{-5} cm for the mechanical disturbance to be detected. This vibration threshold, although impressive, does not compare favorably with a vibration threshold of 10^{-11} cm for movement of the eardrum necessary for hearing a 5000-Hz tone. The superiority of auditory sensitivity may be due to the greater efficiency of the auditory system in conducting mechanical disturbances to the receptors and/or the greater sensitivity of the auditory receptors.

Variation of the size of the stimulator had an interesting effect in Verrillo's study. Increasing the size of stimulators larger than .02 cm^2 resulted in a proportional decrease in the threshold. This finding indicated that the tactile system is capable of summating stimulation over a relatively large area. For stimuli that were .02 cm^2 or smaller, no spatial summation was observed. Furthermore, it can be seen that the frequency curve for these small stimulators is not U shaped, but rather that the threshold is uniformly high at all frequencies. Verrillo concluded from these findings that the skin contains at least two receptor systems which are involved in the detection of mechanical disturbances. One system summates energy over space and accounts for the U-shaped frequency function obtained when all but the smallest stimulators are used. The other system, which is not capable of spatial summation, accounts for the flat frequency function when thresholds are measured for very small contactors. By comparing psychophysical data with data on the electrophysiological response of individual tactile receptors, Verrillo (1966) was able to identify the Pacinian corpuscle as the receptor responsible for spatial summation and the U-shaped frequency response curve. There is remarkable correspondence between the U-shaped psychophysical function and the neural response of a Pacinian corpuscle (Figure 1.12). More recently, the flat portion of the psychophysical curve has been associated with other mechanoreceptors, such as Meissner corpuscles and Merkel discs.

The Absolute Sensitivity for Smell

An experiment reminiscent of the work of Hecht et al. (1942) on vision was performed by Stuiver (1958), a Dutch investigator. After determining the smallest number of molecules of a substance that must enter the nose to be detected, Stuiver calculated the number of molecules that had to be absorbed by the olfactory receptors within the nose. Calculations were based on experiments with a physical model of the nasal cavity, which revealed that only 2% of the molecules entering the nose make contact with the olfactory receptors, while the remaining 98% are absorbed in mucus, are carried in air streams that never make contact with the receptor area, or are carried in air streams over the receptor area without affecting it. From his psychophysical data, Stuiver estimated that each of 40 receptor cells had to absorb only a single molecule for a substance to

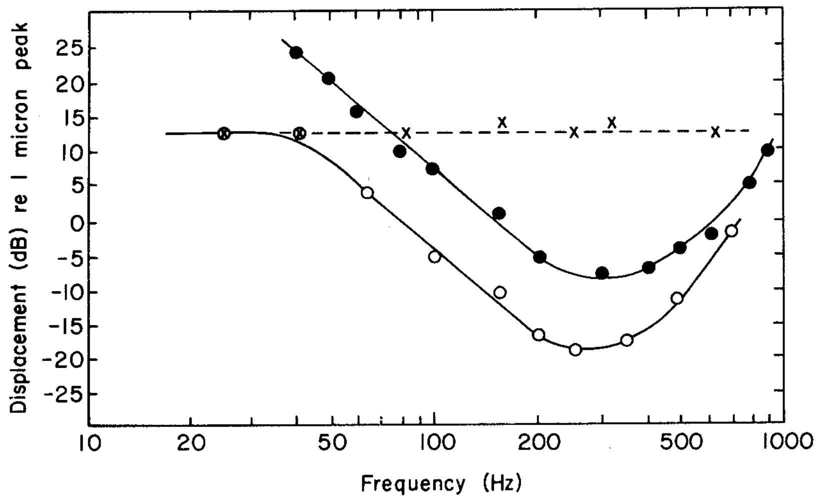

FIG. 1.12. Human psychophysical thresholds for the detection of vibrotactile stimuli (unfilled points) compared with the electrophysiological response of the Pacinian corpuscle in the cat (filled points). The flat curve is obtained when skin containing no Pacinian corpuscles is stimulated or when very small contactors are used. (From Verrillo, 1975. From *Experimental Sensory Psychology* by Bertram Scharf. Copyright © by Scott, Foresman and Company. Reprinted by permission of the publisher.)

be detected. The sensitivity of the nose, like that of the eye and the ear, approaches a limit imposed by the nature of the stimulus. In other words, under the very best conditions these systems are as sensitive as any sensing device could possibly be for detecting certain specific forms of energy.

TWO FUNCTIONS OF PSYCHOPHYSICS

From the discussions of threshold measurement, it should be apparent that psychophysics serves two basic functions. One function is descriptive and involves the specification of sensory capacities; the other is analytical and involves the testing of hypotheses about the underlying biological mechanisms that determine sensory capacity.

Descriptive Psychophysics

The descriptive function of psychophysics is illustrated by the experiment of Wald (1945), the results of which were seen in Figure 1.9. Through this experiment, we know how the visual threshold changes as the wavelength of light changes for stimuli presented to the fovea or to the periphery of the retina. It is evident from the results of this experiment that vision

occurs only within a narrow band of wavelengths within the electromagnetic spectrum which ranges from approximately 350 to 750 nm. It can also be seen that, within this narrow range of visible energy, sensitivity of the visual system changes greatly as the wavelength of light changes; that we are more sensitive to lights presented peripherally than to those presented centrally; and that the most effective wavelength for vision is about 560 nm (yellow) for the fovea and 500 nm (green) for the periphery. In the discussion of visual sensitivity, we also saw that other properties of the visual system, such as adaptation, spatial summation, and temporal summation, could be studied by measuring the threshold as a function of time in the dark after light exposure, size of the stimulus, and duration of the stimulus, respectively. In addition to increasing our understanding of human sensory capacity, knowing this kind of information has had significant practical benefits. For example, an architect must have knowledge of visual sensitivity in order to design a lighting system that will properly illuminate the rooms in a building as inexpensively as possible. In fact, the design of any environment or instrument in which vision is used must take into account the psychophysical capacities of the visual system. In the production of television sets, microscopes, and even in the publication of this book, the characteristics of the human visual system have been a central consideration.

Psychophysics has also been successful in providing quantitative descriptions of the capacities of the other sensory modalities, and such information has been helpful in designing environments and equipment for people's use. For example, the function relating the auditory threshold to the frequency of sound seen in Figure 1.10 has been indispensable in designing rooms for listeners, such as concert halls and classrooms. This function is also essential in designing any system that converts sound into some other form of energy and then back to sound again, such as a radio, phonograph, or telephone. The function tells us that the ear, in acting as a filter, can process information only within a limited range of frequencies. Thus, it is the frequencies of sound within this range that must be faithfully transmitted to the ear in a good sound system. Anything short of fulfilling this requirement will mean that some information in the form of audible sound in the original message will be missing in the transmitted message received by the listener. The consequences of this loss of information will depend on how much information is lost, where in the frequency spectrum the loss occurs, and the objectives of the listener. For example, if the listener is trying to comprehend a verbal message coming over a telephone, the essential information can be transmitted through a telephone, which fails to transmit very low and very high audible frequencies in the voice. On the other hand, if the objective is to listen to recorded music that sounds much like it did in the concert hall in which it was recorded, records or tapes should be played through a hi-fidelity system capable of transmitting all audible frequencies in the original sound.

Threshold functions for the detection of vibration on the skin, such as the one seen in Figure 1.12, have been useful in designing vibrotactile communication systems for deaf and blind people. For example, much of the early research on vibrotactile communication systems focused on the problem of developing devices capable of transducing speech and music into mechanical vibrations capable of being felt by the skin. In such a system, speech sounds might be converted through a microphone to electrical signals which, after amplification, are converted back to mechanical energy through a vibrator placed in contact with the skin. The design was based on the evolutionary fact that the eardrum, which does so well at responding to the wide range of frequencies present in speech, is a descendant of the skin. Thus, it was thought that we should be able to train the skin to do what the eardrum does (Gault, 1926). The results were disappointing. Although observers could learn to recognize certain speech sounds through their skin, performance was generally poor and unreliable.

A comparison of the psychophysical thresholds for detecting move-

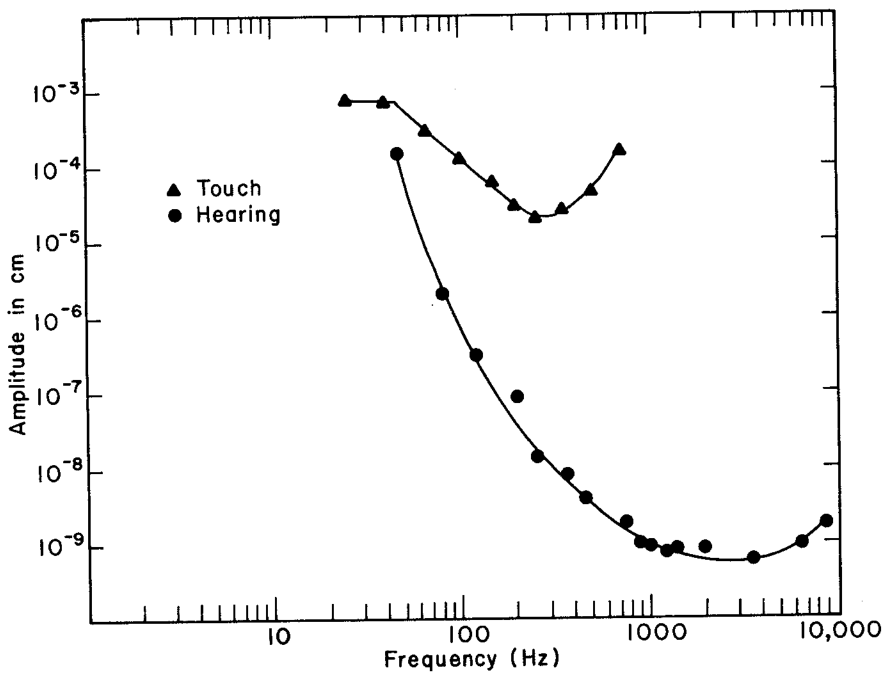

FIG. 1.13. Amplitude of vibration of the skin on the hand needed to feel the stimulus and amplitude of vibration of the eardrum needed to hear.

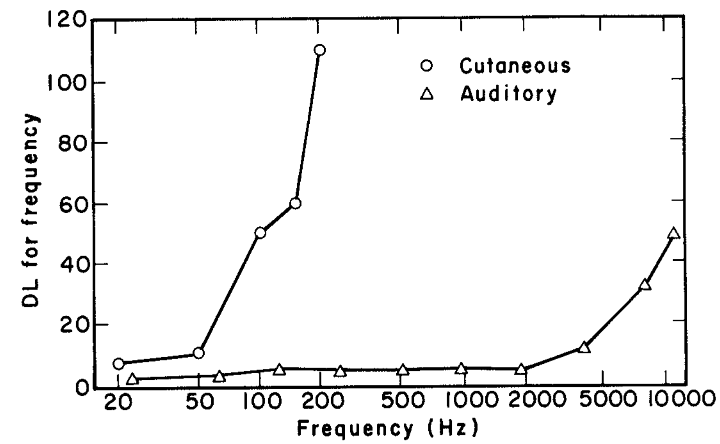

FIG. 1.14. Auditory and tactile difference thresholds for discriminating changes in frequency of vibration. (From Goff, 1967.)

ment of the skin and movement of the eardrum reveals one reason for the skin's relatively poor ability in speech perception (Figure 1.13). The amplitudes of vibration of the skin needed to feel the stimulus are much higher than the amplitudes of vibrations of the eardrum needed to hear. This difference in sensitivity, however, could be compensated for through amplification. A more serious deficiency of the skin is seen in the inability of observers to detect vibrotactile stimuli of frequencies above about 1000 Hz. Since frequencies of vibration contained in speech extend well above 1000 Hz, an accurate representation of speech cannot possibly be transmitted through the skin to the brain. On the other hand, as shown in Figure 1.13, the auditory system can detect very small movements of the eardrum for frequencies up to 10,000 Hz or higher. In addition to having a restricted frequency range, the skin is very poor in discriminating changes in frequency (Goff, 1967). The difference threshold for detecting changes in vibration frequency (ΔF) is plotted as a function of frequency for the skin and for the ear (Figure 1.14). Compared to the ear, the skin, although reasonably good at detecting changes in low frequencies, is poor in discriminating high frequencies. In the range of frequencies important for speech perception, the performance of the skin is very poor compared to that of the ear. For example, when the frequency of vibration is 200 Hz, an increase in frequency of only 2 or 3 Hz is detectable by the ear, while the required increase in frequency for the skin is over 100 Hz. Because of the relatively narrow frequency range and poor frequency discrimination of the skin, it will probably never be possible to "hear" speech through the skin by directly converting the sound to tactile vibration. Attempts are currently being made, however, to design tactile communication systems that operate within the frequency range and frequency discriminative capacities of the tactile sense. If successful, these systems will be a great help to deaf people.

Our brief treatment of descriptive psychophysics illustrates, through a few examples, the use of psychophysical measurements to define the sensitivity of a sensory system. It should be evident that this information can often be used for practical purposes.

Analytical Psychophysics

The second function of psychophysics has been the testing of hypotheses about the nature of biological mechanisms underlying sensory experience. The work of those investigators who use psychophysics in this way is based on the assumption that there is a basic correspondence between neural activity and perception. The *Principle of Nomination,* as Marks (1978a) has called it, declares that identical neural events give rise to identical psychological events. Thus, according to the principle, when stimulus A and stimulus B produce the same neural response, they will yield the same sensory experience. The reflexive form of the Principle of Nomination states that, when stimulus A and stimulus B produce the same sensory experience, they produce the same neural response. This principle, used in conjunction with those psychophysical procedures in which different stimuli are adjusted to yield identical sensations, constitutes a powerful tool for discovering the neural events that determine sensory experience.

The results of Wald (1945) plotted in Figure 1.9 provide an example of the use of the reflexive Principle of Nomination. In Wald's experiment, identical sensations of colorless light were experienced when the observer detected lights of different wavelengths presented to the peripheral retina. In other words, the rod (scotopic) spectral sensitivity curve gives the physical intensities of stimuli of different wavelengths needed to produce identical sensations. According to the reflexive Principle of Nomination, these combinations of wavelengths and intensity of light will produce identical responses in the nervous system. Indeed, it has been discovered that the number of photons that must be absorbed by the photochemical pigment in rods, rhodopsin, is identical at any wavelength—about 10 photons—for the observer to detect light. Specifically, as illustrated in Figure 1.15(a), the number of photons incident on the cornea of the eye at the detection threshold varies as a function of the wavelength of the stimulus. Since the lens and other ocular media of the eye absorb light, the number of photons at the retina needed for detection must be less than that measured at the cornea. The number of photons at the retina can be calculated at all wavelengths from the absorption spectrum of the ocular

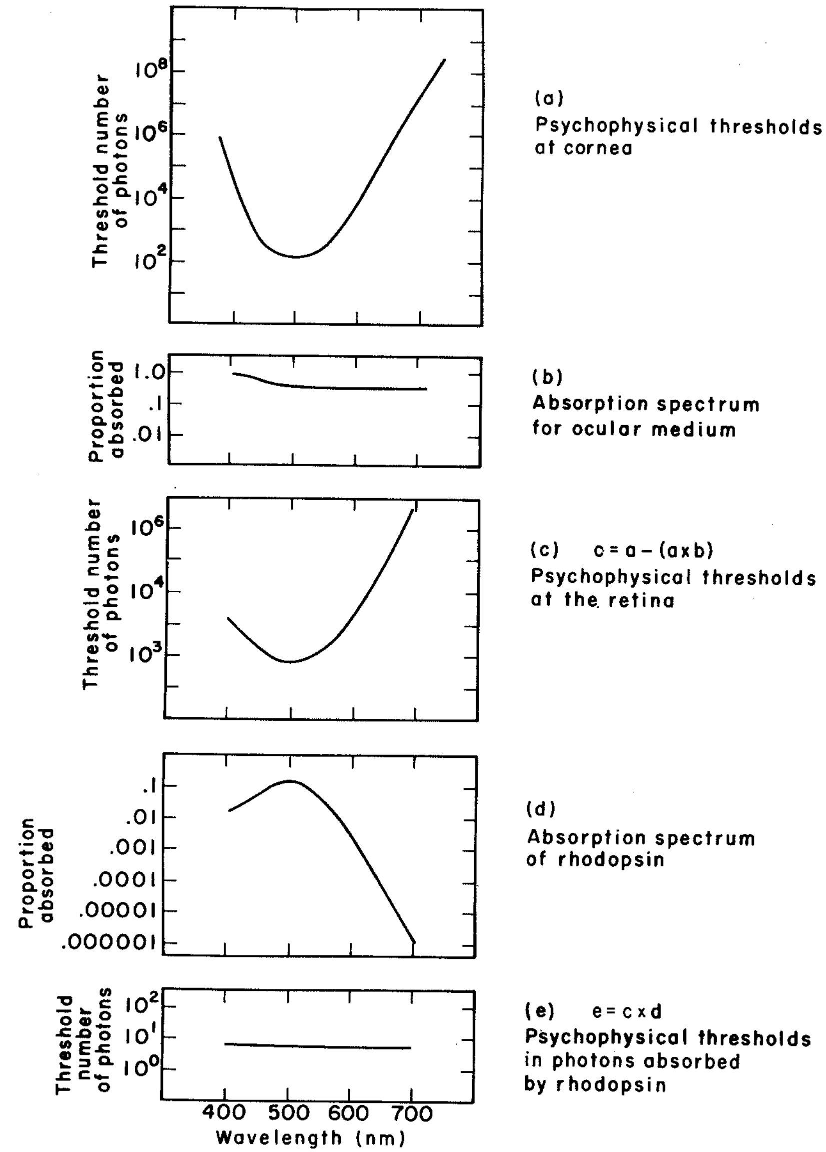

FIG. 1.15. Absolute threshold measured at the cornea of the eye as a function of the wavelength of light (a). Absorption spectrum of the ocular medium of the eye (b). Absolute threshold at the retina of the eye as a function of wavelength of light (c). Absorption spectrum of rhodopsin (d). Absolute threshold expressed as photons absorbed by the photochemical pigment rhodopsin contained in rod receptors in the retina (e).

media. The values in (a) multiplied by the corresponding values in (b) gives the number of photons absorbed by the ocular media. Subtracting these values from (a) gives the number of photons at the retina needed for vision. The results of this calculation are plotted in (c). Of the photons reaching the retina, the number absorbed by the photochemical pigment rhodopsin (e) is determined for each wavelength of light by multiplying the number of photons at the retina needed to exceed threshold (c) by the absorption spectrum of rhodopsin (d). It can be seen in Figure 1.15(e) that the number of photons that must be absorbed by rhodopsin in order to exceed the threshold for vision is exactly the same at all wavelengths of light. Thus, combinations of stimulus intensity and wavelength that produce identical sensations also produce identical photochemical reactions. A fundamental fact of visual science was discovered through integration of data from two fields as different as psychophysics and photochemistry.

More generally, it is by assuming the reflexive Principle of Nomination that it is possible to bridge the gap between psychophysical and biological facts. Because identical sensations are based on identical physiological reactions, a physiological hypothesis can be tested by a psychophysical procedure. Without this principle, the task of correlating sensory experience with physiology would probably be impossible. A biochemist studying visual pigment and a visual psychophysicist studying absolute thresholds would have no common language through which to inter-relate their findings. Because of differences in language, the two scientists would be restricted to working on problems within their own mutually exclusive subdisciplines of visual science. The research described above on the photochemical basis of the spectral sensitivity curve illustrates how the language barrier can be crossed. The hypothesis that changes in an observer's visual sensitivity with changing wavelengths of light are caused by corresponding changes in the degree to which the ocular media and photochemical pigments of the visual receptors absorb light was tested through the *method of response invariance*. In this method, termed by Rodieck (1973), the investigator seeks to discover, not how the response changes as the stimulus is varied, but rather the combinations of stimulus variables that generate identical responses. Threshold responses are considered identical because, within an experiment, the same criterion of performance (e.g., detecting the stimulus 50% of the time) is always used. The intensities of light needed to produce threshold responses were determined for a wide range of wavelengths of light. These combinations of light intensities and wavelengths were also found to result in identical physiological responses (10 photons absorbed by the photochemical pigment of the receptors).

Although this approach has been known for many years, it was Brindley (1960) who first explicitly stressed its importance for psychophysics.

Class A Observation

Stimulus A → Neural Response X → Sensation Y

Stimulus B → Neural Response X → Sensation Y

Class B Observation

Stimulus A → Neural Response X → Sensation Y

Stimulus P → Neural Response Q → Sensation R

FIG. 1.16. Distinction between Class A and Class B observations as described by Brindley (1960).

Brindley distinguished between two general types of psychophysical observations, termed Class A and Class B observations (Figure 1.16). Class A observations are those in which the two stimuli are adjusted so that they elicit the same response from the observer. Threshold experiments and matching experiments in which two stimuli are adjusted to produce identical sensations consist of Class A observations. In both cases, the experimenter determines stimulus conditions needed to produce identical responses and, according to the reflexive Principle of Nomination, identical neural responses. Any observations that cannot be expressed as the identity or nonidentity of two sensations is a Class B observation. Class B observations are those in which the experimenter determines how the sensory response of the observer changes as the stimulus changes. Included as Class B observations are all those in which an observer reports that his sensation changes from blue to green when the wavelength of light is changed, or that a light has become twice as bright when its intensity is increased. That observers can reliably make these kinds of judgments forms the basis of many of the psychophysical scaling procedures discussed in Chapters 6 and 7. Although Class B observations can be made reliably, they lack what Brindley calls a *psychophysical linking hypothesis,* which would provide a rigorous means by which psychophysical observations could be used to test hypotheses about underlying physiological mechanisms. Class A observations, on the other hand, coupled with the assumption that identical sensations are based on identical physiological events, provide a means for testing a physiological hypothesis with a psychophysical procedure. By using the method of response invariance for both the domains of sensation and physiology, it is possible to look for physiological responses that are absolutely identical when different stimuli produce sensations that are absolutely identical. Many psychophysicists have argued that it is only from such invariances that the physiological bases of sensation will be discovered. At the very least, the method of response invariance has made explicit certain methodological implications of the philosophy of materialism and has provided a powerful tool for the scientific study of sensory processes.

A second example of the use of the method of response invariance is seen in the work of Verrillo on the neurophysiological basis of the detection of vibration of the skin. In examining the absolute sensitivity for touch, we saw that the threshold for detecting vibration is independent of stimulus frequency at low frequencies and is a U-shaped function of frequency for higher frequencies (Figure 1.11). To account for this observation, Verrillo (1963) proposed a duplex theory of mechanoreception, in which he hypothesized that one type of receptor was responsible for detecting low frequencies and another for detecting high frequencies.

A sharp break in a psychophysical threshold function often represents a transition from the operation of one type of sensory receptor to another. In using psychophysical threshold functions to identify receptor systems, the assumption is made that the psychophysical threshold is always determined by the receptors that have the lowest threshold. Recall that the initial segment of the dark adaptation curve of Figure 1.8 was determined by cones because immediately after exposure to the adapting light their thresholds are lower than rod thresholds. However, after several minutes in the dark, the reverse was true and rods determined the threshold for the remainder of the experiment.

Verrillo (1966) subsequently identified the Pacinian corpuscle as the receptor responsible for detecting high frequency vibration. Verrillo's comparison of psychophysical threshold functions for human observers with neural threshold functions of Pacinian corpuscles is an example of the method of response invariance. Both functions seen in Figure 1.12 represent combinations of stimulus intensity and frequency needed to produce threshold responses. Because of the close correspondence between the U-shaped segment of the psychophysical function and the neural threshold function, Verrillo concluded that high frequency vibration is detected exclusively through stimulation of Pacinian corpuscles. Recent evidence strengthening this argument comes from Bolanowski and Verrillo (1982), who compared psychophysical thresholds for humans with neural thresholds for Pacinian corpuscles of cats. As in the Verrillo (1966) study, the relationship between threshold and stimulus frequency was examined. In addition, the skin temperature of the observer's hand and the temperature of the bathing solution of the cat's Pacinian corpuscles were experimentally varied. The results seen in Figure 1.17 show that

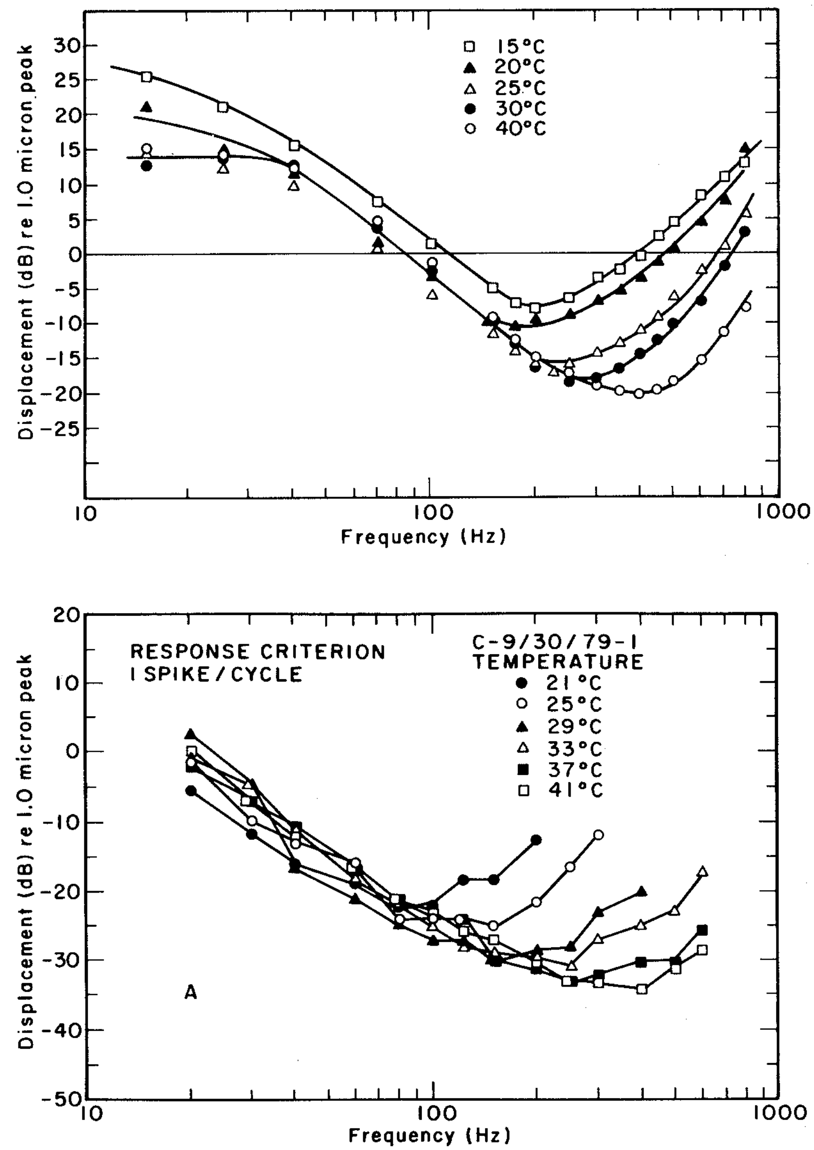

FIG. 1.17. Psychophysical threshold for detection of vibration on the hand as a function of frequency and skin temperature (top). Neural threshold of Pacinian corpuscle as a function of frequency and temperature of bathing solution (bottom). (From Bolanowski & Verrillo, 1982.)

variation in temperature has a strikingly similar effect on psychophysical and neural thresholds. In both cases, the frequency of maximum sensitivity (i.e., the frequency with the lowest threshold) shifted to higher frequencies as temperature increased. Thus, a correspondence between psychophysical and neural threshold functions was observed over a wide range of temperatures, even though the shape of the functions changed with temperature. This result is expected if a single receptor-type mediates the detection of high frequency vibration. When the frequency response of the Pacinian corpuscle is changed by manipulation of a variable such as temperature, there should follow a corresponding change in psychophysical thresholds. Bolanowski and Verrillo's findings strongly support this hypothesis.

When it is not possible to compare psychophysical and neural threshold functions, the full power of the method of response invariance cannot be exploited. Nevertheless, in the absence of neural response data it may be possible to identify underlying neural mechanisms from psychophysical data. For example, the *method of selective adaptation* has been used to study the properties of sensory receptors. When using this method, the assumption is made that, by exposing the observer to a carefully selected adapting stimulus, the thresholds of all types of receptors but one are sufficiently elevated so that the one type of receptor that remains sensitive will determine the psychophysical threshold. This method has been successfully used to study how the sensitivity of visual receptors changes as the wavelength of light changes (Stiles, 1959; Wald, 1964). Spectral sensitivity curves, as determined psychophysically under conditions of adaptation, were found to be in substantial agreement with those determined physiologically for individual receptors.

In Wald's (1964) experiment, the observer was required to detect a small circle (1.0°) of variable wavelength presented against a larger (3.5°) illuminated background of fixed wavelength. By having the observer visually fixate a small point where the test stimulus was presented, no rods, and only the cones of the fovea, were stimulated. The objective of the experiment was to measure, through psychophysical procedures, the spectral sensitivity of each of the three types of cones in the fovea.

Spectral sensitivity curves, where sensitivity is plotted as a function of the wavelength of the test stimulus, had to be determined for each type of cone. The wavelength and intensity of the background were carefully chosen so that the background, through sensory adaptation, would cause substantial elevations in the thresholds of two types of cones, but have little effect on the third. Thus, measurements of psychophysical thresholds for detecting test stimuli of varied wavelength should reveal the spectral sensitivity of a single type of cone. The psychophysical thresholds for detecting light would always be determined by the cone with the lowest neural threshold.

To obtain the spectral sensitivity curve for the blue-sensitive cone, Wald's observers detected stimuli of variable wavelength presented against a bright yellow background containing all visible wavelengths longer than 550 nm. A yellow background stimulus such as this should elevate the neural thresholds of red-sensitive and green-sensitive cones, while having little effect on the thresholds of blue-sensitive cones. Psychophysical thresholds for detecting stimuli of varied wavelength presented against the yellow background should reveal the spectral sensitivity of the blue-sensitive cone. On the other hand, having the observer detect the test-lights against a blue background should elevate the thresholds of the blue-sensitive and green-sensitive cones, while having little effect on the sensitivity of the red-sensitive cone. The spectral sensitivity of the red-sensitive cone should be revealed by measuring psychophysical thresholds for detecting lights of varied wavelength presented against the blue background. Finally, to isolate the spectral sensitivity of the green-sensitive cone, Wald had observers detect lights of varied wavelength presented against a purple background containing wavelengths in both the blue and red regions of the visual spectrum. In this condition, the green-sensitive cone should be much more sensitive than the adapted blue-sensitive or red-sensitive cones, and consequently, the psychophysical thresholds should reveal the spectral sensitivity of the green-sensitive cones.

The results obtained for one of Wald's observers are presented in Figure 1.18. Sensitivity was expressed as the reciprocal of the measured threshold (1/threshold). The logarithm of sensitivity is plotted as a function of the wavelength of the test stimulus. The absolute height of each curve was not determined, and thus a measure of relative sensitivity (i.e., sensitivity changes of a cone with changes in wavelength) was plotted. It can be seen that foveal spectral sensitivity curves obtained with different adapting backgrounds peaked at different wavelengths of the spectrum. After adaptation by yellow light, the curve peaked in the blue region of the spectrum. Presumably, this curve was determined entirely by the blue-sensitive cone. When the eye was adapted to purple light, the curve peaked in the green region of the spectrum, presumably reflecting the sensitivity of the green-sensitive cone. Adaptation to blue light resulted in a spectral sensitivity curve which peaked in the red region of the spectrum. Presumably, this curve was determined by the red-sensitive cone.

It must be pointed out that the measurements of light corresponding to the absolute threshold were made at the cornea of the eye and not inside the eye at the receptors. Consequently, the spectral sensitivity curves in Figure 1.18 might not be entirely accurate indicators of the spectral sensitivity of the cones. Wald thought that each of the three spectral sensitivity curves obtained in the presence of adapting background stimuli

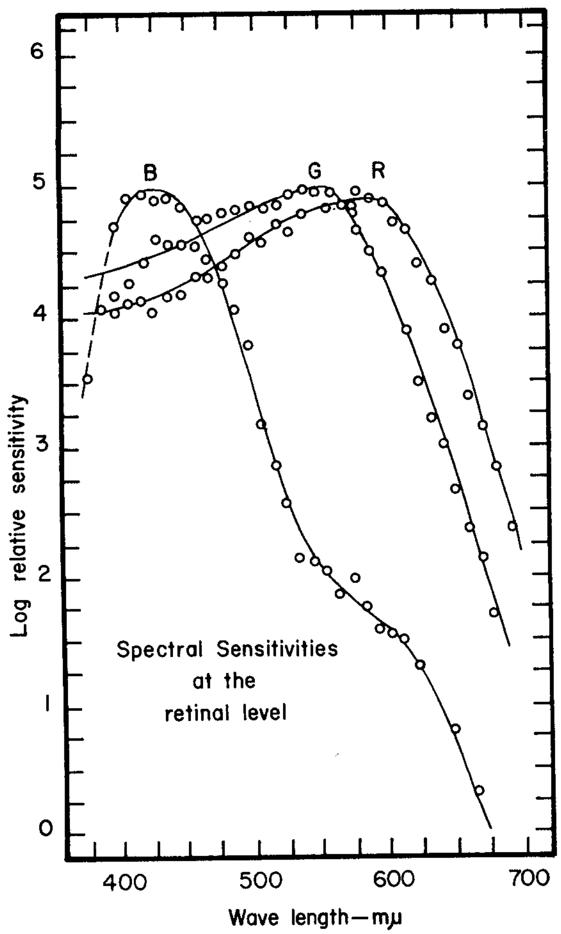

FIG. 1.18. Visual sensitivity (1/threshold) for stimuli presented to the fovea after adaptation. The blue curve (B) represents the psychophysical thresholds measured after adaptation to a yellow light. The green curve (G) represents the psychophysical thresholds measured after adaptation to a purple light. The red curve (R) represents the psychophysical thresholds measured after adaptation to blue light. (From Wald, 1964.)

reflected the sensitivity curve of the cone plus the filtering action of nonneural structures in the eye. In other words, the psychophysical threshold measured at the cornea, in addition to being influenced by the sensitivity of the receptor, was also influenced by how much light reached the receptor after passing through the eye. Wald used absorption curves for nonneural structures in the eye (e.g., cornea, lens, ocular media, and nonvisual pigments of the fovea) to correct psychophysical thresholds measured at the cornea, so that they became psychophysical thresholds at the

receptors. Under conditions of selective adaptation, having specified the amount of light of various wavelengths that must reach the receptor in order for the observer to see, Wald was able to estimate the spectral sensitivity curve of the cone. Psychophysically measured spectral sensitivity curves for the three types of cones are seen in Figure 1.19.

Recently, the method of selective adaptation has been used to study the characteristics of mechanoreceptors in the skin (Gescheider, Frisina, & Verrillo, 1979; Verrillo & Gescheider, 1977). In the study by Verrillo and Gescheider (1977), psychophysical thresholds for detecting vibration on the hand were measured before and after adaptation. Adaptation consisted of applying an intense 10-Hz stimulus to the skin for a period of 10 min. It can be seen in Figure 1.20 that adaptation by the 10-Hz stimulus had the selective effect of elevating thresholds at low, but not high, fre-

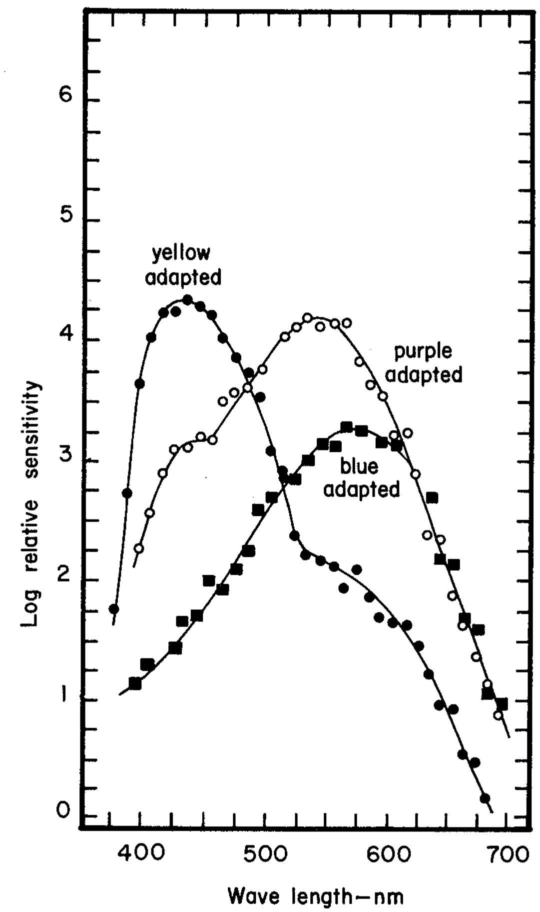

FIG. 1.19. Visual sensitivity corrected for absorption of light by elements of the eye before the retina. The three curves represent sensitivity functions for blue, green, and red sensitive cones in the fovea of the human eye. (From Wald, 1964.)

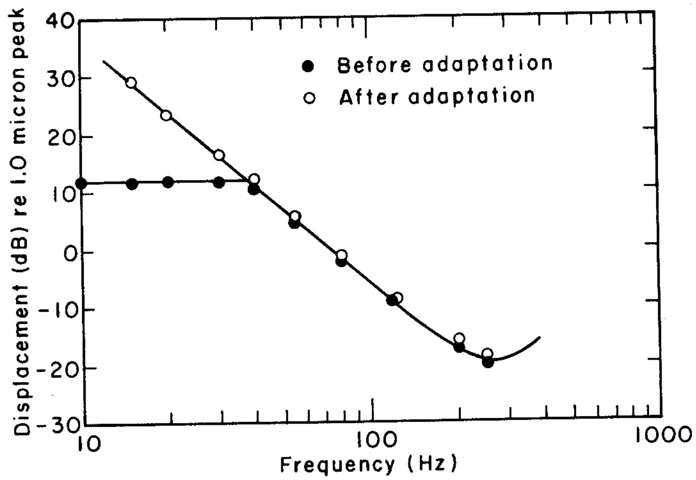

FIG. 1.20. Vibrotactile thresholds on the hand as a function of frequency measured before and after adaptation. (From Verrillo & Gescheider, 1977.)

quencies. Presumably, the low frequency adapting stimulus elevated the thresholds of all receptors except Pacinian corpuscles. Under these conditions, the frequency response of a single receptor type—the Pacinian corpuscle—could be examined over a wide range of frequencies through the measurement of psychophysical thresholds. As a consequence of elevating the thresholds of the non-Pacinian receptors, the flat portion of the psychophysical curve was eliminated, and what remains is the entire U-shaped threshold curve of the Pacinian corpuscle.

From this brief exposure to analytical psychophysics, it should be clear how the reflexive Principle of Nomination that identical sensations produced by stimuli are mediated by identical neural responses has provided the philosophical foundation for a very ambitious approach to psychophysics, the goal of which is no less than to determine the neural basis of sensation. According to the analytic psychophysicist, the method of response invariance must be used to determine combinations of stimulus variables that result in identical sensations. Identical sensations are specified through invariant sensory responses, such as the absolute threshold or a psychophysical match of sensations above absolute threshold. Thus, the experimental data always consist of measurements of properties of the stimulus (e.g., intensity and wavelength) that correspond to a constant sensory response. Only after the stimulus conditions that produce identical sensation have been determined is it possible to

discover the underlying neural response. After the psychophysical measurements are made, the investigator may then proceed to search for neural responses that remain constant under the same stimulus conditions that resulted in constant sensation. The discovery of such invariances in neural response has greatly enhanced our understanding of the neural basis of sensation and has provided strong support for the basic assumption and procedures of analytic psychophysics.

We have considered the methodological assumptions for investigating the biological bases of psychophysical responses. It is appropriate to turn now to the various techniques for measuring sensory thresholds.

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.

1.2. If, in an experiment, you found $\Delta\phi$ to be 2.4 when ϕ was 10.0, and you assumed the validity of Weber's law, $\Delta\phi = c\phi$, what values of $\Delta\phi$ would you expect if you repeated the experiment for ϕ values of 3.0, 5.0, 20.0, and 30.0? Plot the expected values of $\Delta\phi$ as a function of ϕ.

1.3. Experimentally determined values of $\Delta\phi$ can seldom be accurately predicted from the equation $\Delta\phi = c\phi$. For example, the values of $\Delta\phi$ presented below could represent the typical results of a discrimination experiment.

ϕ	$\Delta\phi$
3.0	1.0
5.0	1.4
10.0	2.4
20.0	4.4
30.0	6.4

On the graph used for problem 1.2, plot these experimentally determined values of $\Delta\phi$ and compare them to those predicted from the Weber equation, $\Delta\phi = c\phi$.

1.4. For the experimentally determined values of $\Delta\phi$ given in problem 1.3, calculate the Weber fraction, $\Delta\phi/\phi$, and plot it as a function of ϕ. How does this function deviate from that expected from the Weber equation $\Delta\phi/\phi = c$?

1.5. Test the hypothesis that the equation $\Delta\phi/(\phi + a) = c$ is a better description of the hypothetical data of problem 1.3 than the Weber equation $\Delta\phi/\phi = c$. Assume a value of 2.0 for a and calculate c from $\Delta\phi/(\phi + a) = c$ for each value of ϕ. Plot $\Delta\phi/(\phi + a)$ as a function of ϕ.

1.6. In deriving his law, Fechner assumed Weber's equation, $\Delta\phi = c\phi$, was correct. Assuming c to be .1, determine the values of ϕ corresponding to the first 10 jnd's above an absolute threshold of 5.0. Using the logic of Fechner, make a graph of sensation magnitude, ψ, as a function of stimulus intensity, ϕ. Repeat the procedure for $c = .2$.

1.7. Convert the ϕ values of problem 1.6 to logarithms and plot sensation magnitude as a function of log ϕ. Write equations for the functions obtained for the two values of c in the Weber equation.

1.8. Upon what two basic assumptions is Fechner's law based? Evaluate the validity of these assumptions.

2 The Classical Psychophysical Methods

The experiments described in Chapter 1 are examples of how psychophysics has been used to determine the sensitivity of perceptual systems to environmental stimuli. In Chapter 2, the specific methods for measuring sensitivity are discussed in detail.

Presenting a stimulus to observers and asking them to report whether or not they perceive it is the basic procedure for measuring thresholds. Biological systems are not fixed, however, but rather are variable in their reaction. Therefore, when an observer is presented on several occasions with the same stimulus, he is likely to respond yes on some trials and no on other trials. Thus, the threshold cannot be defined as the stimulus value below which detection never occurs and above which detection always occurs. The concept of the threshold has obviously been, and still is, useful, since it affords a technique for quantifying the sensitivity of sensory systems. But since reactions to stimuli are variable, the threshold must be specified as a statistical value. Typically, the threshold has been defined as the stimulus value which is perceptible in 50% of the trials.

Fechner recognized the statistical nature of thresholds and the necessary methodological consequences. Psychologists are indebted to him for developing three methods of threshold measurement: the methods of constant stimuli, limits, and adjustment. Each of these methods consists of an experimental procedure and a mathematical treatment of data. These extremely valuable techniques for obtaining absolute and difference thresholds (RL's and DL's) are still used today.