PSYCHOPHYSICS
Method, Theory, and Application

Second Edition

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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.

METHOD OF CONSTANT STIMULI

Absolute Thresholds

The method of constant stimuli is the procedure of repeatedly using the same stimuli (usually between five and nine different values) throughout the experiment. The 50% threshold is located somewhere within the range of stimulus values—the lower end of which should be a stimulus that can almost never be detected, and the upper end of which should be a stimulus that is almost always detected. As the intensity level is increased within this range, the likelihood of detecting the stimulus will systematically increase. Through the method of constant stimuli, the percentage of detections as a function of stimulus intensity, ϕ is determined.

Preliminary observations are made for locating the approximate range of values in which the stimulus of lowest intensity is seldom perceived, and the stimulus of highest intensity is almost always perceived. The procedure requires that each stimulus be presented repeatedly, usually 100 times or more, but in a random order. During the experiment, a count of the number of yes or no responses for each stimulus intensity level is kept. For each stimulus value, the proportion (p) of yes responses is then computed, and a graph called a *psychometric function* is constructed. Stimulus intensity is plotted on the abscissa, and the proportion of yes responses is plotted on the ordinate. A psychometric function for a hypothetical experiment using nine stimulus intensities is seen in Figure 2.1. In this example, the absolute threshold (defined as the stimulus intensity for which the proportion of trials resulting in yes responses is .5) does not correspond to any of the stimuli used in the experiment. Therefore, a curve must be fitted to the nine data points and the threshold estimated by reading, from the curve, the stimulus intensity for the .5 point. In our example, the threshold is 12.3 units. It should be noted that the best fitting curve for the data points is an S-shaped function. If enough measurements are made, psychometric functions often follow a particular S shape called an *ogive*.

The procedure of fitting ogives to the points on a psychometric function is supported by theory as well as by experimental findings. Variation of biological and psychological measurements tends to be normally distributed; when the frequencies or proportions of measurements of various magnitudes are plotted against the dimension on which variation is occurring (e.g., height, weight, IQ, or sensory sensitivity), the result is usually the bell-shaped normal distribution curve. The ogive curve is a cumulative form of this distribution and describes how the proportion of cases below a point on the normal distribution increases as the magnitude of the measurement increases. Various techniques for fitting ogive functions to threshold data range from simply drawing the curve by eye to employing various elaborate mathematical techniques.

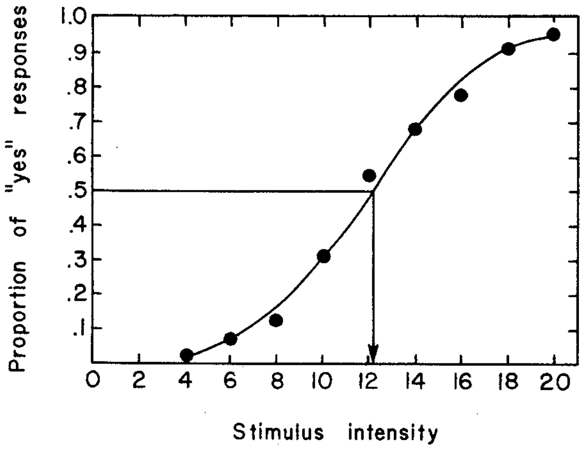

FIG. 2.1. Typical psychometric function obtained when the absolute threshold is measured by the method of constant stimuli. An ogive curve has been fitted to the points. The threshold is the stimulus intensity that would be detected 50% of the time.

One useful technique for fitting a particular mathematical function to pairs of numbers is to transform the numbers into units that should be linearly related if the mathematical function is appropriate. An ogive psychometric function has the convenient feature of becoming a linear function when the proportion of responses for each stimulus-value is transformed into a z score (Table 2.1). A normal distribution table is used to convert p values into z scores. The z-score values in Table 2.1 were obtained by using the abridged version of the normal distribution table found in Table A of the appendix of this book. The p values in Table A represent the proportion of the area under the normal distribution curve below a particular z-score value on the abscissa of this curve.

Figure 2.2 illustrates the reason that the shape of the cumulative normal distribution, where p is plotted as a function of X, changes from an ogive to a straight line when p values are converted to z scores. In this example, the values of X, a hypothetical set of measurements, are normally distributed. Thus, the abscissa of the normal distribution curve is expressed in both z scores and X units. The ogive curve in Figure 2.2 results when z scores are converted to p values and plotted as a function of corresponding z-score and X values. For example, it can be seen from Table A that a p value of .84 is associated with a z score of .99. The p value of .84 and the z score of .99 define a point on the ogive function. Furthermore, the p value of .84 constitutes the proportion of the area under the normal distribution that falls below a z score of .99 and an X value of 50. As the z scores and X values become higher, the proportion of area under the

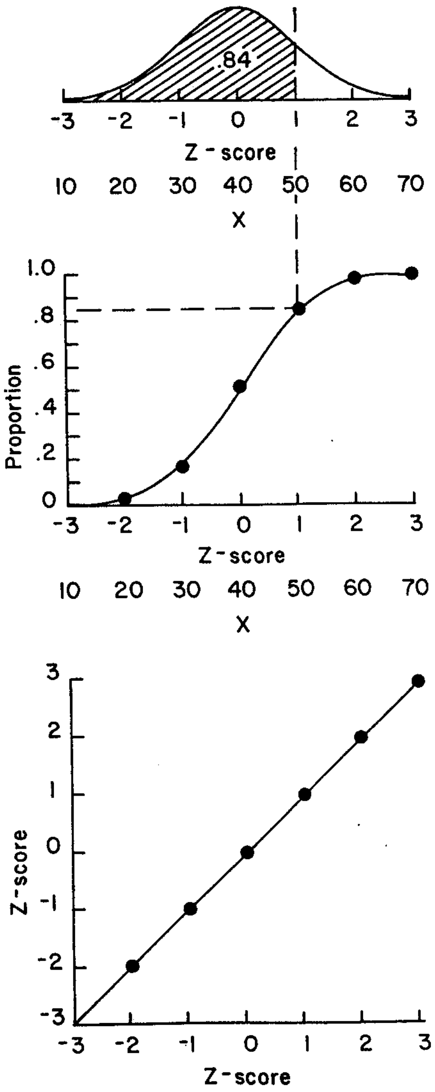

FIG. 2.2. Derivation of an ogive function from the normal distribution curve. Each point on the ogive specifies the proportion of the total area under the normal distribution that is below (to the left of) a specific point.

normal curve below z and X increases and approaches 1.0. The ogive, therefore, is a description of how the proportion of cases below a point on the abscissa of the normal distribution increases as z and X increase. The second graph in Figure 2.2 shows the linear relationship that must occur when p values are transformed back into z scores and plotted against themselves. It is noteworthy that z plotted against X is also linear. It is only when the relationship between p and X is an ogive that transforming p values to z scores results in a linear function. Consequently, a psychometric function where p is plotted against X can be identified as an ogive if the relationship between p and X becomes linear when p values are expressed as z scores.

In our problem, the proportion of detections, whether expressed as a z score or plotted on a normal probability ordinate, is seen to be a linear function of intensity, and therefore the ogive assumption is correct (Figure 2.3). A straight line can be drawn by eye through the data points to obtain the psychometric function. Given that threshold is defined as a stimulus which is detected in half of the trials, the measured threshold is the stimulus value for a z score of zero.

The psychometric function can be determined more precisely by determining the best-fitting straight line through a mathematical technique known as the *method of least squares*. In this method, the constants a and b of a straight-line equation $y = ax + b$ are determined. The resulting equation describes a line through the data points which minimizes the squared deviations of the empirical y values from the line. The following equations are used to determine a and b:

$$\text{(intercept) } b = \frac{(\sum X^2)(\sum Y) - (\sum X)(\sum XY)}{N(\sum X^2) - (\sum X)^2}, \tag{2.1}$$

$$\text{(slope) } a = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X^2) - (\sum X)^2}. \tag{2.2}$$

The value of b is equal to the Y intercept (the value of Y when X is zero) of the best-fitting straight line. The value of a is equal to the slope of the best-fitting straight line.

In our particular problem, X would be the ϕ value, Y would be the

TABLE 2.1
Proportion of Detections and Corresponding z Scores for Various Stimulus Intensity Values (Hypothetical Data)

Stimulus intensity (ϕ)	*Proportion detected*	*z score*
4	.04	−1.75
6	.07	−1.48
8	.13	−1.13
10	.31	−.50
12	.55	+.13
14	.66	+.41
16	.78	+.77
18	.93	+1.48
20	.98	+2.05

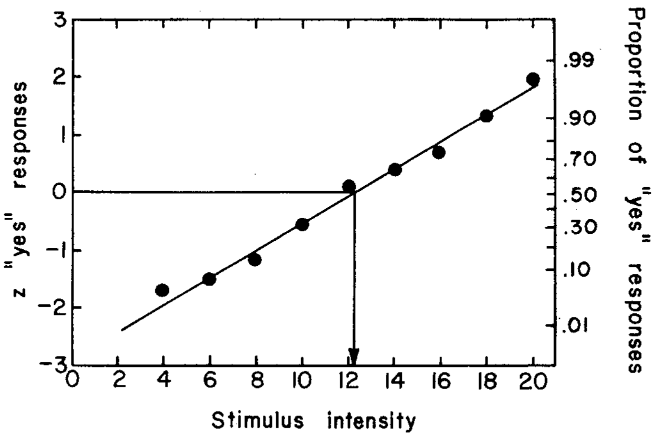

FIG. 2.3. Psychometric function in which the proportions of "yes" responses are expressed as z scores or are plotted on a normal probability ordinate. The linearity of the function indicates that the relation between the proportion of detections and stimulus intensity is an ogive.

corresponding z-score value, and N would be the number of pairs of ϕ and z-score values. When a and b have been calculated, the equation for a straight line that best fits the graph of z scores plotted against stimulus intensity is

$$z = a\phi + b. \tag{2.3}$$

The ϕ values for particular z scores can be determined by using the equation

$$\phi = \frac{z - b}{a}. \tag{2.4}$$

The threshold value would then be determined by calculating ϕ when $z = 0.0$.

Difference Thresholds

The method of constant stimuli can also be used to measure difference thresholds. The observer's task is to examine pairs of stimuli and to judge which stimulus produces a sensation of greater magnitude. One of the stimuli of the pair is given a fixed value and is called the *standard stimulus* (St). The value of the other stimulus, called the *comparison stimulus* (Co), is changed from trial to trial, being sometimes greater than, sometimes less than, and sometimes equal to the value of the standard stimulus. Usually five, seven, or nine values of the comparison stimulus, separated by equal distances on the physical scale, are employed. The values of the comparison stimuli are chosen so that the stimulus of greatest magnitude is almost always judged greater than the standard, and so that the stimulus of least magnitude is almost always judged less than the standard. There are usually an equal number of comparison stimulus values above and below the value of the standard stimulus. In a random sequence, each of the comparison stimuli is paired several times with the standard stimulus, and the observer reports which stimulus has the greater sensory value.

Under ideal conditions, standard and comparison stimuli would be presented together in space and time to permit optimal discriminability. This ideal is impossible, however, because sensations occurring at the same time and initiated at the same receptive areas would blend together and become completely indiscriminable. Therefore, the two stimuli must be presented to different receptive areas at the same time, or to the same receptive area, but at different times. The particular circumstances of an experiment usually determine whether the stimuli are presented simultaneously or successively and to the same or different receptive areas. In experiments on visual brightness discrimination, for example, stimuli are often presented simultaneously to adjacent or nearby areas of the retina; conversely, loudness discrimination is frequently measured by successively presenting the standard and comparison stimuli.

The necessity of presenting stimuli for comparison to different receptors or at different times may lead to certain errors of measurement, unless special precautions are taken in designing the experiment. If stimuli are presented to different receptive areas, judgments may be affected by differences between the receptive areas as well as differences between stimuli. In other words, it may be difficult or impossible to conclude anything about an observer's ability to discriminate stimuli. To control for the effects of the *space error,* the standard stimulus may be presented on half of the trials to one receptor area and on half of the trials to the other receptor area. In an experiment on the discrimination of line length, for example, the standard line would be presented equally often to the left and right of the comparison line, so that the effects of spatial location would be neutralized when the DL was determined. A *time error* may also confound experimental results when the standard and comparison stimuli are presented successively. In one form of the time error, the proportion of times for which the comparison stimulus is judged greater than the standard stimulus is found to be higher when the comparison stimulus is presented second than when it is presented first. Successive presentation makes it necessary for the observer to compare the second stimulus with the memory image of the first. In one interpretation of the time error, it is assumed that since the memory image may rapidly fade, the first stimulus may be judged less than the second stimulus, even when the physical intensities of the two stimuli are identical. Again, since the aim of the discrimination experiment is to study the ability of observers to detect differences in stimuli, certain precautions must be taken to eliminate the biasing effects of time errors. The most common procedure is to present the standard stimulus first on half of the trials and second on the other half of the trials. The method of counterbalancing spatial location or temporal order of standard and comparison stimuli is based on the assumption that, when the results from all of the trials are combined, the effects of the space or time errors will cancel, providing an unbiased estimate of the DL.

To understand the application of the method of constant stimuli, consider a hypothetical example where the purpose of the experiment is to measure the DL for weight discrimination when the standard stimulus is 80 gm and the comparison stimuli are 72, 74, 76, 78, 80, 82, 84, 86, and 88 gm. In this kind of experiment, care must be taken to make the weights identical in size and shape, so that the observer's discrimination will be based exclusively on heaviness. A blindfolded observer is asked to lift a weight placed in his hand. After the weight is removed, he is required to lift a second weight and to compare it with his impression of the first. Since the stimuli are presented successively, it is necessary to control for the effects of time errors. This control is established by presenting the standard stimulus (80-gm weight) first and the comparison stimulus second on half the trials and by using the reverse order on the other half of the trials. The standard stimulus must be paired with each comparison stimulus a sufficient number of times to obtain a reliable estimate of the proportion of "greater" responses for each comparison stimulus. The psychometric function with the proportion of greater responses plotted against values of the comparison stimuli is usually an ogive curve, as seen in Figure 2.4.

In a discrimination experiment, when the observer cannot perceive any difference, we expect the proportions of greater and less responses to be about equal. This .5 point on the psychometric function is called the *point of subjective equality* (PSE) and represents the value of the comparison stimulus which, over a large number of trials, is perceived subjectively as equal to the standard stimulus. In most cases, the PSE does not correspond exactly to the physical value of the standard stimulus. In our present example, the standard is 80 gm, but the PSE is 80.6 gm. The difference between the standard stimulus and the PSE is a psychophysical quantity called the *constant error* (CE):

$$\mathrm{CE} = \mathrm{PSE} - \mathrm{St}. \tag{2.5}$$

A constant error reflects some uncontrolled factor's systematic influence on the measurements being taken, so that numbers are consistently either too high or too low by a certain amount. Space and time errors are constant errors, since they systematically affect the observer's judgments. In the present example, a large negative constant error would probably occur if the standard weight were always presented first and the comparison weight second. The proportion of "greater than" responses for all comparison stimuli would tend to be too high because of a tendency to underestimate the sensory magnitude of the previously presented standard stimulus. The PSE would therefore have a value lower than that of the standard stimulus.

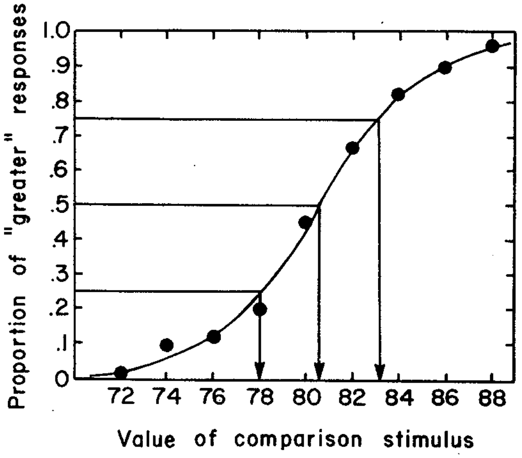

FIG. 2.4. Typical psychometric function obtained when the difference threshold is measured by the method of constant stimuli. An ogive curve has been fitted to the points.

Because the PSE represents a complete lack of discrimination, and because 0 or 1.0 greater than responding is perfect discrimination, the intermediate proportion points of .25 and .75 have been used to find the DL. It is possible to determine two DL's, an upper and a lower. The upper difference threshold (DL_u) is the stimulus range from the PSE to the .75 point. In our example, $DL_u = 83.3 - 80.6 = 2.7$ gm. The difference between the .25 point and the PSE yields a lower difference threshold (DL_l) of 2.6 gm. This method provides a measurement of one DL above the PSE and one below; therefore, the two are often averaged to give one DL for a particular standard stimulus.

The steepness of a psychometric function depends on the observer's differential sensitivity. From the manner in which the DL is derived from plotted data, it should be evident that psychometric functions with steep slopes yield small DL's. Therefore, the slope of the psychometric function and the DL are sometimes used interchangeably as measures of sensitivity.

As was true for measuring absolute thresholds, the psychometric function for the difference threshold can be expressed in z-score units as well

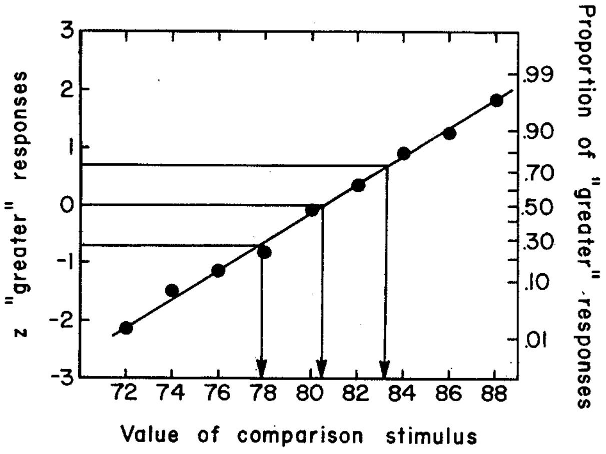

FIG. 2.5. Psychometric function for the measurement of the difference threshold in which the proportions of "greater" responses are expressed in z scores or are plotted on a normal probability ordinate. The linearity of the function indicates that the relation between the proportion of "greater" responses and the value of the comparison stimulus is an ogive.

as in response proportions. The advantage of the z-score plot, again, is in the ease of curve fitting, since the data points almost always form a straight line. The linear z-score psychometric function of Figure 2.5 indicates that our hypothetical data have the ogival form of the cumulative normal distribution. When this form is obtained experimentally, the most common interpretation is that fluctuations in differential sensitivity are normally distributed.

The line can be fitted to the data by eye or by a more precise technique, such as the method of least squares. The PSE corresponds to a z score of zero. The values of the lower and upper DL's can be determined by drawing vertical lines from the psychometric function when z is $-.67$ (.25 point) and $+.67$ (.75 point). If the values of a and b for the equation $z = a(\text{Co}) + b$ have been calculated by the method of least squares, then the Co values corresponding to z values of zero, $-.67$, and $+.67$, can be determined by using the equation

$$\text{Co} = \frac{z - b}{a}. \tag{2.6}$$

METHOD OF LIMITS

The method of limits is perhaps the most frequently used technique for determining sensory thresholds. It is an extremely efficient means of threshold measurement and usually yields satisfactory results if proper controls are used to correct for certain constant errors characteristic of the method. The method is less precise than the method of constant stimuli, but it is far less time consuming and is therefore used much more extensively. Furthermore, when choosing the values to be used for applying the method of constant stimuli, a few minutes taken to estimate the location of the threshold by the method of limits would be well spent.

Absolute Thresholds

In the measurement of absolute thresholds by the method of limits, the experimenter starts by presenting a stimulus well above or well below threshold; on each successive presentation, the threshold is approached by changing the stimulus intensity by a small amount until the boundary of sensation is reached. The stimuli are manipulated in either an *ascending series* or a *descending series*. If the series is ascending, the experimenter begins by presenting a very weak subthreshold stimulus to the observer. On each successive trial, the intensity of the stimulus is increased by a small amount until the observer eventually reports the presence of the sensation; at this point, the series is terminated. If the series is descending, the value of the stimulus is decreased in successive steps until the observer reports the disappearance of the sensation. Each transition point obtained from a number of ascending and descending series can be considered an estimation of the threshold, and the threshold is then designated as the average of these values.

The method of limits is often used in audiometry (i.e., the measurement of hearing) to determine the absolute threshold for hearing pure tones of various frequencies. Measurement of the threshold for perception of a 1000-Hz tone might be accomplished by applying a 1000-Hz signal generated by a pure tone oscillator to earphones worn by an observer. The intensity of the signal, as measured in decibels (dB), could be varied systematically by the experimenter. Typical results of the determination of an observer's hearing threshold for a 1000-Hz tone are shown in Table 2.2. Alternate ascending (A) and descending (D) series were administered for a total of ten series. In the case of the ascending series, the transition point between sensation and no sensation is taken as the point on the physical dimension which falls midway between the stimuli for the last no response and the first yes response. In the case of a descending series, the transition point is taken as midway between the last yes response and the first no response. In Table 2.2, the mean of the transition points was 4.1 dB, and the variability was considerable—the highest value being 5.5 dB and the lowest 2.5 dB. Here again, as is the case for the method of constant stimuli, the observer's behavior is characteristically variable.

Two constant errors may influence results obtained in using the method

TABLE 2.2
Determination of the Absolute Threshold for Hearing by the Method of Limits[a]

Stimulus intensity (dB)	*A*	*D*	*A*	*D*	*A*	*D*	*A*	*D*	*A*	*D*
10						Y				
9		Y				Y				Y
8		Y				Y				Y
7		Y		Y		Y				Y
6		Y		Y	Y	Y		Y		Y
5	Y	Y		Y	N	Y	Y	Y		Y
4	N	Y	Y	N	N	N	N	Y	Y	N
3	N	N	N		N		N	Y	N	
2	N		N		N		N	N	N	
1	N		N		N		N		N	
0	N		N				N		N	
−1	N		N				N			
−2	N						N			
−3	N						N			
−4	N									
−5	N									
−6	N									
−7	N									
−8	N									
−9	N									
−10	N									
Transition points =	4.5	3.5	3.5	4.5	5.5	4.5	4.5	2.5	3.5	4.5

[a] Mean threshold value = 4.1

of limits. Since the stimulus is gradually changed in the direction of threshold over several trials, there may be a tendency for an observer to develop a habit of repeating the same response. This habit may result in his continuing to make the response for a few trials after the threshold point has been reached. The constant errors resulting from this tendency are called *errors of habituation* and affect the data by falsely increasing thresholds on ascending trials and by falsely decreasing thresholds on descending trials. In opposition to this constant error, an observer may falsely anticipate the arrival of the stimulus at his threshold and prematurely report that the change has occurred before it really has, thus making an *error of expectation*. In this case, thresholds on ascending trials will be deceptively low, and thresholds on descending trials will be too high. If errors of habituation and expectation were of equal magnitude, they would cancel each other, but this condition is unlikely in most experimental situations. One technique to prevent anticipatory tendencies is to vary the starting point for successive series, so that the observer cannot predict the number of trials necessary for reaching threshold. To minimize

habitual tendencies, experimenters often try to avoid the use of excessively long trial series. Preliminary training and careful instructions may also help to eliminate, or at least to minimize, the effects of these two tendencies.

Difference Thresholds

The method of limits is also useful for measuring difference thresholds. For this application, standard and comparison stimuli are presented in pairs, and on successive presentations the comparison stimulus is changed by a small amount in the direction of the standard stimulus. For example, if the standard is a 20-dB tone, the experimenter might start with a 15-dB tone and move in .5-dB increments, or might start with a 25-dB tone and move in .5-dB decrements. During each series, whether ascending (A) or descending (D), two transition points are obtained which are termed the *upper limen* (L_u) and *lower limen* (L_l). The upper limen is the point on the physical dimension where "greater" responses change to "equal" responses. Similarly, the lower limen is the point where the "less" responses change to "equal" responses. If an ascending series is given, for example, the first tone would be obviously weaker than the standard, and the observer would say "less" and would continue to say "less" until the experimenter had increased the comparison stimulus sufficiently to be indiscriminable from the standard, at which point the response would change to "equal." The physical value of the stimulus at this point would define the lower limen. As the experimenter further increased the intensity of the comparison stimulus, the observer would continue to say "equal" until the comparison stimulus became discriminably louder than the standard. The response would then change to "greater," which would establish the upper limen and end the series.

Table 2.3 contains results of an experiment in which the DL was measured for loudness when the standard stimulus was a 20-dB, 1000-Hz tone. The mean upper limen was 22.00 dB, indicating that on the average the observer perceived a 22.00-dB tone as just noticeably louder than a 20-dB tone. On the average, a tone of 17.95 dB (the lower limen) was perceived as just noticeably weaker than the 20-dB standard. The range on the stimulus dimension over which an observer cannot perceive a difference between the comparison and the standard stimuli is called the *interval of uncertainty* (IU) and is computed by subtracting the mean lowerlimen ($\bar{L}_l$) from the mean upper limen ($\bar{L}_u$). The best estimate of the difference limen (DL) is taken as half the IU, and the point of subjective equality is obtained by finding the midpoint of the IU [$\text{PSE} = \frac{1}{2}(\bar{L}_u + \bar{L}_l)$]. In the present example, the IU was 4.05; the DL is therefore half of this value, or 2.025, and the PSE is 19.97.

TABLE 2.3
Determination of the Difference Threshold for Hearing by the Method of Limits[a]

Stimulus intensity (dB)	*A*	*D*	*A*	*D*	*A*	*D*	*A*	*D*	*A*	*D*
24.5						G				
24.0		G				G		G		
23.5		G				G		G		G
23.0		G		G	G	G		G		G
22.5		G	G	G	E	G	G	G		G
22.0	G	E	E	G	E	G	E	G	G	E
21.5	E	E	E	E	E	G	E	E	E	E
21.0	E	E	E	E	E	E	E	E	E	E
20.5	E	E	E	E	E	E	E	E	E	E
20.0	E	E	E	E	E	E	E	E	E	E
19.5	E	E	E	E	E	E	E	E	E	E
19.0	E	E	E	E	E	E	E	E	E	E
18.5	E	L	E	E	E	E	E	E	E	E
18.0	E		E	L	E	L	E	L	E	E
17.5	L		L		E		L		L	L
17.0	L		L		L		L		L	
16.5	L		L		L		L		L	
16.0	L				L				L	
15.5	L				L				L	
Upper limen	21.75	22.25	22.25	21.75	22.75	21.25	22.25	21.75	21.75	22.25
Lower limen	17.75	18.75	17.75	18.25	17.25	18.25	17.75	18.25	17.75	17.75

[a] Interval of uncertainty = IU = $\bar{L}_u - \bar{L}_l = 22.00 - 17.95 = 4.05$. Difference limen = DL = ½IU = ½(4.05) = 2.025. Point of subjective equality = PSE = $\frac{1}{2}(\bar{L}_u + \bar{L}_l = \frac{1}{2}(22.00 + 17.95) = 19.97$.

It is important to note that in measuring the DL, as in measuring absolute thresholds by this method, care must be taken to control for the effects of errors of habituation and of expectation. In addition, since two stimuli are presented to the observer for comparison when this method is used to measure DL's, controls must be employed to prevent contamination of results by space and time errors. The same procedures suggested for use with the method of constant stimuli—counterbalancing spatial position or temporal order of stimuli—should also be sufficient when using the method of limits.

Variations of the Method of Limits

A variation of the method of limits is the *up-and-down* or *staircase method* (Cornsweet, 1962). One begins by presenting a sequence of stimuli which progressively increase or decrease in value. When the observer's response changes, the stimulus value is recorded, and the direction of the stimulus sequence is reversed from ascending to descending, or vice versa. For example, when the observer first says yes in an ascending sequence, the experimenter will start a descending sequence which is terminated when the observer first says no, at which point the sequence is reversed again. This procedure continues until a sufficient number of response-transition points has been recorded. The threshold is taken as the average of the transition points. This method saves time because stimuli that are much below or above threshold are never presented. Because of its efficiency, the staircase method has been of value to clinicians.

The staircase method resembles the *threshold tracking method* Békésy (1947) used with an audiometer to test hearing. However, in the threshold tracking method the stimulus is continuously variable. The observer controls its intensity, and the results are usually recorded by a graphic recorder. Observers track their own threshold continuously. As long as the observer presses a switch, the stimulus will gradually decrease in intensity; as long as the observer keeps the switch open, the stimulus will gradually increase in intensity. If the trial starts with the switch depressed, the observer will keep it depressed until the sensation first disappears, at which time the switch is released, which causes the intensity of the stimulus to begin to gradually increase. When the stimulus is again detected, the observer presses the switch and keeps it closed until the stumulus can no longer be detected. The observer continues in this manner until performance becomes stable for some specified period of time. A record of the up and down fluctuations in stimulus intensity produced by the observer's tracking is made by a graphic recorder. A sample record from a Békésy audiometer is seen in Figure 2.6. Since the output of an audiometer that is applied to an earphone can be made to change frequency continuously over a 125–10,000-Hz range in a period of a few minutes, a complete record of the observer's threshold as a function of frequency can be made in a very short time. The method has been extremely useful in clinical audiometry, and it also has been successfully adapted to measure thresholds in modalities other than hearing.

The method of threshold tracking has also been useful in animal psychophysics inasmuch as animals can be trained to make a different response when a stimulus is detected than when it is not detected. After training pigeons to peck one key when a light was visible and another key when it was not visible, Blough (1958) obtained a dark-adaptation curve as the bird tracked its threshold in a dark chamber following exposure to intense light (Figure 2.7).

Another variation of the method of limits is the *forced choice method* first used by Blackwell (1953) for experiments on vision and by Jones (1956) for experiments on taste and smell. The observer's task is to

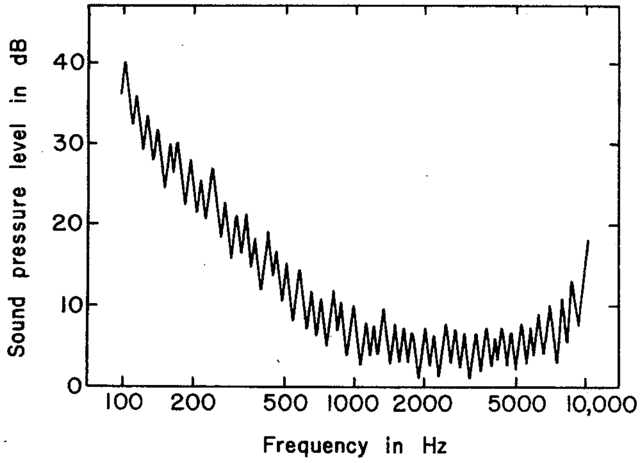

FIG. 2.6. Record of observer's responses as he continuously tracked his auditory threshold as the frequency changed.

choose among several carefully specified observations, only one of which contains the stimulus. Observations may be sequential, as in *temporal-forced choice,* where they are made one after another; or observations may be simultaneous, as in *spatial-forced choice,* where they are made at several different locations. In a four-interval, temporal-forced choice experiment, the observer would be required to make four observations and then to choose the observation which contained the stimulus. In a spatial-forced choice experiment, the observer might be required to view a display on which a stimulus would be presented in one of four quadrants. In this case, the task would be to choose which quadrant contained the stimulus. In both cases, stimulus intensity is increased by discrete steps on successive trials. The stimulus intensity corresponding to a specified performance level, such as two correct responses in succession, is defined as the threshold. The method can be used to measure the difference threshold as well as the absolute threshold by presenting the comparison stimulus for one observation and the standard stimulus for all other observations. The observer is required to pick the comparison stimulus from among the several observations.

METHOD OF ADJUSTMENT

The method of adjustment has been used primarily for measuring difference thresholds but can also be applied to problems of absolute sensitivity. One of the main features of this method is the opportunity afforded an observer to control the changes in the stimulus necessary to measure a threshold.

Absolute Thresholds

In measuring absolute thresholds by the method of adjustment, the general procedure is to set the stimulus intensity level either far below or far above threshold and to ask the observer either to increase the intensity level until it is just perceptible, or to decrease the intensity until the sensation just disappears. Usually, the stimulus intensity is continuously variable. Experiments generally require an observer to make a fairly large number of ascending and descending settings, and the absolute threshold is taken as the mean of these settings. One advantage of this method is that it gives the observer an unusually large amount of active participation in the experiment, which may help to prevent boredom and, therefore, to maintain high performance.

Difference Thresholds

When the method of adjustment is applied to the measurement of difference thresholds, the observer is instructed to adjust a comparison stimulus until it seems equal to some standard stimulus. This is often called the *method of average error,* since the experimenter is primarily interested in the discrepancies between the observer's settings of the

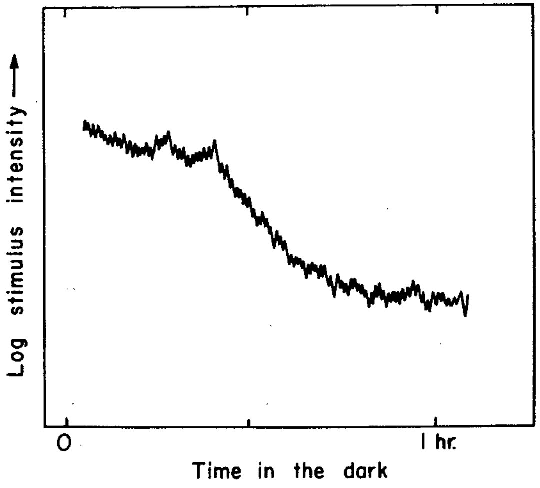

FIG. 2.7. Record of pigeon's responses during dark adaptation. (From Blough, 1958. Copyright 1958 by the Society for the Experimental Analysis of Behavior, Inc.)

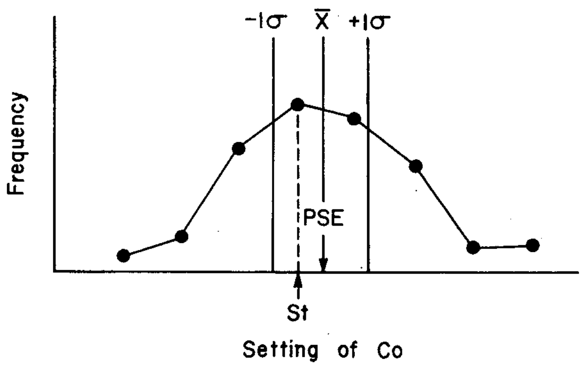

FIG. 2.8. Frequency distribution of setting of the comparison stimulus when the method of adjustment is used to measure the difference threshold. The mean of the distribution is the point of subjective equality, and the standard deviation is used as the difference threshold.

comparison stimulus and the physical value of the standard stimulus. In a large number of settings, an observer will sometimes underestimate and sometimes overestimate the standard by a considerable amount, but most of the matches typically tend to cluster closely around the value of the standard stimulus. As is true for the hypothetical data in Figure 2.8, a frequency distribution of the results will most likely be symmetrical and, if enough trials have been administered, will approximate a normal distribution.[1] The mean ($\bar{X}$) of this distribution (the mean of all the settings of the comparison stimulus) is the PSE. If there are no constant errors, the PSE should correspond closely to the value of the standard. The constant error (CE) is computed by subtracting the value of the standard from the PSE (CE = PSE − St).

Whether or not there is a constant error, the frequency distribution will have a high degree of central tendency when discrimination is good; when discrimination is poor, the settings will tend to be quite variable. A measure of dispersion such as the standard deviation (σ), therefore, is used as the DL. One frequently used formula for the standard deviation is

$$\sigma = \sqrt{\frac{N\sum X^2 - (\sum X)^2}{N^2}}. \qquad (2.7)$$

where X is the value of a particular Co setting and N is the number of settings. A large standard deviation would indicate that, over a wide range

of stimulus values, the two stimuli appeared equal and that discrimination was poor. If discrimination is precise, the two stimuli will appear equal only over a narrow range of stimulus values; judgments will tend to cluster together, and the standard deviation of the distribution of judgments will be relatively small.

The method of adjustment is difficult to apply when stimuli are not continuously variable, or when pairs of stimuli cannot be presented simultaneously. When stimuli are varied in steps rather than continuously, DL measurements are somewhat inacurrate. In experiments in which the standard stimulus must be presented first and is followed by the comparison stimulus for the observer to adjust, it is impossible to counterbalance or measure stimulus order effects. A final shortcoming of the method results from giving the observer control of the stimulus: this procedure makes it difficult to maintain constant conditions during threshold measurement.

APPLICATION OF CLASSICAL PSYCHOPHYSICAL METHODS TO PROBLEMS OF STIMULUS MATCHING

A stimulus critical value function, in which absolute threshold is plotted against some property of the stimulus, can be thought of as an *equal sensation contour*. The function describes how stimulus intensity must be adjusted to maintain sensory intensity at absolute threshold as other properties of the stimulus are changed. Figure 1.10 illustrates how sound pressure must be changed in order to keep the sensory magnitude of the sound at a just audible level as the frequency of the stimulus is changed. Often, it is in our interest to determine an equal sensation contour for suprathreshold levels of stimulation. In the case of hearing, the function would specify the sound pressure necessary at various frequencies to keep the psychological loudness of the sound at some constant level.

Figure 2.9 illustrates equal loudness contours obtained by Robinson and Dadson (1956). Each contour represents a different loudness level. Loudness level, in units called *phons*, is the sound pressure level in dB of a 1000-Hz tone which sounds equal in loudness to a given tone. In determining equal loudness contours, a 1000-Hz tone is set to a particular loudness level, and the intensity of a comparison tone of another frequency is adjusted so that its loudness matches that of the standard 1000-Hz tone of fixed intensity. This procedure is repeated for a number of comparison tones of different frequencies, and the plotted results constitute one equal loudness contour. The results of Robinson and Dadson indicate that, to maintain sound at the same loudness level, both low- and high-frequency tones must be considerably more intense than those in the

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[1] A normal distribution of comparison stimulus settings is sometimes obtained only after some transformation is made on the stimulus units. Often a logarithmic transformation of the stimulus values results in a normal distribution of responses.

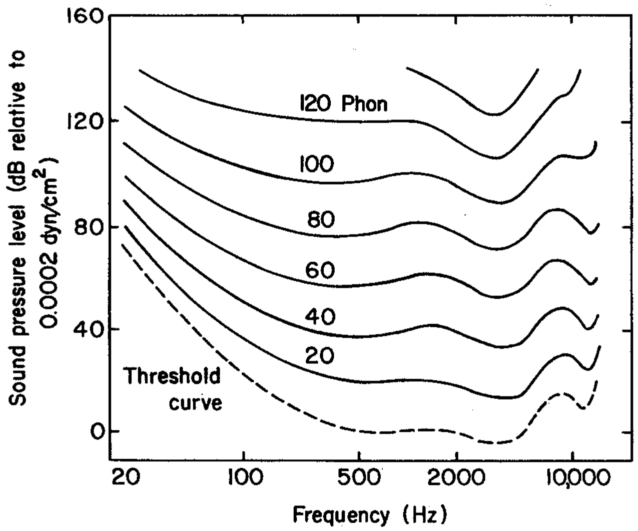

FIG. 2.9. Equal loudness contours. Each curve describes the intensity levels to which tones of various frequencies must be adjusted to keep loudness constant. Each curve was obtained at a different loudness level. (From Robinson & Dadson, 1956. Copyright 1956 by the Institute of Physics.)

midrange of frequencies. The shapes of the equal loudness contours are not unlike that of the threshold curve. However, it can be seen that the equal loudness contours become somewhat flatter at higher loudness levels. The results of this experiment indicate that the relative deficiency of the auditory system at low frequencies is much more severe at low intensity levels of stimulation. For this reason, high quality stereophonic sound equipment is usually designed to produce a relatively more intense bass response when the volume control is turned down.

The method of adjustment provides perhaps the most efficient technique for determining an equal sensation contour. As in measuring the DL, an observer is required to adjust the value of a comparison stimulus to match that of the standard stimulus. The values plotted on the equal sensation contour would consist of PSE values for several different stimuli that had been matched to the standard stimulus. The PSE values could also be obtained by other psychophysical methods, such as the method of limits or the method of constant stimuli.

In constructing equal sensation contours, psychophysical matching procedures are employed to determine the stimulus values necessary to keep sensation magnitude constant for various conditions of stimulation. All matches of a number of comparison stimuli are made to a common standard stimulus of constant value. Therefore, each match should yield a

value of the comparison stimulus that produces the same sensation magnitude as that of the standard stimulus. Another equally useful matching method is to employ a single comparison stimulus which is adjusted by the observer to match changing sensation magnitude as some parameter of the standard stimulus is changed. For example, increasing the loudness of a tone as its duration is increased could be specified in terms of the intensity of a comparison stimulus of fixed duration needed to match the loudness of tones of fixed intensity and variable duration.

The measurement of loudness enhancement also provides an example of matching with a single comparison stimulus. A sound may be perceived as louder when paired with a more intense sound than when presented alone. Loudness enhancement refers to the increment in loudness of a sound caused by the presentation of another sound. For example, Zwislocki and Sokolich (1974) found that the loudness of a 10-msec tone burst was enhanced by preceding it with a more intense burst. By requiring the observer to adjust the intensity of a comparison stimulus so that its loudness was the same as that of a test stimulus, Zwislocki and Sokolich measured the loudness-enhancing effects of a conditioning stimulus. The test stimulus was presented within a 500-msec period following the presentation of the conditioning stimulus (Figure 2.10). Loudness enhancement was indicated when the observer adjusted the comparison stimulus to an intensity that was higher in the presence than in the absence of the conditioning stimulus. The amount of loudness enhancement was the difference in intensity of the matches made to the test stimulus in the presence and in the absence of the conditioning stimulus. Enhancement was found to be greatest when the conditioning and test stimuli were nearly simultaneous. The result indicates that persisting after effects of brief sounds may outlast the stimulus by as long as 400 to 500 msec and have the effect of enhancing the loudness of other sounds.

Analogous experiments on the perception of brief vibrotactile stimuli applied to the hand reveal an interesting similarity between auditory and

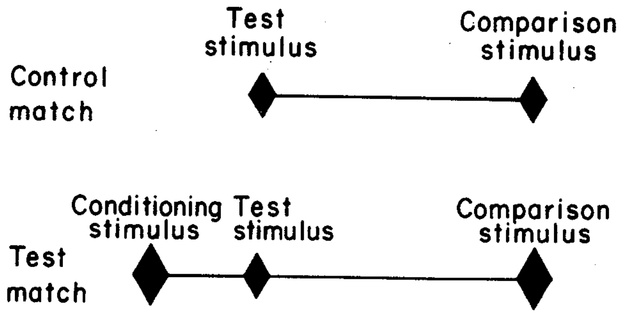

FIG. 2.10. Stimulus-matching method for investigating sensation magnitude enhancement.

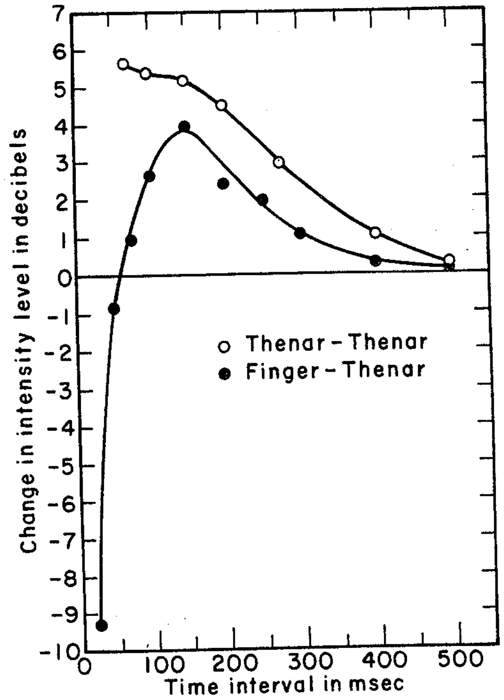

FIG. 2.11. Vibrotactile enhancement expressed as the difference between the test match and the control match as a function of the time interval between the conditioning and test stimulus. (From Verrillo & Gescheider, 1976.)

tactile modalities. For both hearing and touch, enhancement was maximal when the frequencies of the two stimuli were identical and the time between them was brief (Gescheider, Verrillo, Capraro, & Hamer, 1977; Verrillo & Gescheider, 1975). As seen in Figure 2.11, when the conditioning stimulus was on the finger and the test stimulus was on the fleshy pad below the thumb (thenar eminence), the sensation magnitude of the test stimulus was suppressed for trials with very short time intervals between stimuli and enhanced for trials with longer time intervals between stimuli. Suppression was not observed when both stimuli were on the thenar eminence. These results suggest that the psychophysically measured interaction effects between sensory tactile stimuli are based on inhibitory and excitatory neural processes.

CONCLUSION

The temptation to conclude that sensations can be directly measured by the procedures outlined in this chapter must be avoided; sensations cannot be measured in units of sensory magnitude by using these methods. Instead, sensation must be expressed in terms of the amount of stimulus energy necessary to prompt specific changes in the observer's responses. Sensation is thus treated as a concept which must be defined in terms of stimulus-response relationships. Inferences about the operation of sensory processes within the observer from measurements of thresholds or values of a matching stimulus are only as valid as the care in measurement and control over conditions employed in the experiment.

Techniques for measuring psychophysical responses are continually being improved upon, and recent advances in this area are described in Chapters 4 and 5. Chapters 3 through 5 provide descriptions of how failure of the classical threshold concept and the emergence of the theory of signal detection resulted in improved techniques for measuring an observer's sensitivity to stimulation.

PROBLEMS

2.1. In a hypothetical experiment, the method of constant stimuli was used to measure the absolute threshold. The results are presented below.

	Stimulus Intensity								
	2	4	6	8	10	12	14	16	18
p yes	.04	.05	.20	.34	.53	.72	.94	.96	.99

Plot the psychometric function. Fit a smooth curve to the data points and estimate the absolute threshold.

2.2. Convert the *p* yes values in problem 2.1 to *z*-score units and plot the psychometric function. Determine the best-fitting straight line for the data by the method of least squares and write the equation. Draw the line through the data points. Estimate the absolute threshold.

2.3. In an experiment on discrimination, the method of constant stimuli was used to measure the DL. The results are presented below.

	Comparison Stimulus								
	60	70	80	90	100	110	120	130	140
p greater	.02	.08	.15	.30	.53	.68	.87	.91	.98

Convert *p* values to *z* scores. Plot the psychometric function in *z*-score units. Determine the best-fitting straight line by the method of least squares. Determine PSE, CE, upper DL, lower DL, and mean DL. The standard stimulus had a value of 100.

2.4. In the table below are the results of a discrimination experiment in which the method of limits was used. The value of the standard stimulus was 100.

Stimulus Intensity	A	D	A	D	A	D
140				G		
135		G		G		G
130		G		G	G	G
125	G	G		G	E	G
120	E	G		G	E	E
115	E	E	G	E	E	E
110	E	E	E	E	E	E
105	E	E	E	E	E	E
100	E	E	E	E	E	E
95	E	E	E	E	E	E
90	L	E	L	E	E	E
85	L	L	L	E	L	E
80	L		L	L	L	E
75	L		L		L	L
70	L		L		L	
65					L	
60						

Determine IU, PSE, CE, and mean DL.

2.5. In an experiment on discrimination, the method of adjustment was used to determine the DL. The standard stimulus was 100, and the settings of the comparison stimulus are in the table below.

Setting of the Comparison Stimulus				
85	105	97	95	98
105	110	98	104	82
112	95	107	109	96
65	93	102	91	108
94	108	138	79	117
98	125	102	131	94
118	99	85	100	99
135	80	73	107	104
102	115	96	120	101
88	103	67	104	94

Determine the DL, PSE, and CE.

3

Classical Psychophysical Theory

The application of the methods described in Chapter 2 yields a quantity which is expressed in physical units and called the threshold. The concept of the threshold as an index of absolute and differential sensitivity has been extremely useful in the study of sensory systems. Through the use of this quantity, investigators have been able to discover the stimuli to which our sensory systems are the most and the least sensitive. But psychophysicists have not restricted their work to this descriptive level: they have also gone beyond this level to propose theories concerning the underlying mechanisms of sensory thresholds. Each theory was proposed to account for empirical data obtained in psychophysical experiments. The theorists hoped to describe the neurophysiological or psychological processes within the observer which may have determined the observer's behavior. The validity of each theory must be evaluated by determining the degree to which precise quantitative deductions from the theory are confirmed by experimental data.

CLASSICAL THRESHOLD THEORY

Early threshold theories were based upon the assumption that the measurements obtained in psychophysical experiments were estimates of a neural threshold in the observer which could not be measured directly. It was thought that the threshold was a sharp transition point between sensation and no sensation, and that a specific, critical amount of neural activity must result from stimulation for the threshold to be exceeded.