Chapter 1
Psychophysics

A field of psychology, *psychophysics* has as main concern the understanding of the passage of a physical event into a psychological reality. Researchers in psychophysics examine the link between the physical measurement of a stimulation and the psychological measurement of this stimulation. Psychophysicists are primarily interested in three types of capabilities: detecting stimuli, discriminating them, and estimating their value (scaling). The first two types are associated with the fundamental concepts of absolute threshold and differential threshold, respectively.

1.1 Detection

The different sensory systems provide information on the physical and chemical changes that may occur in the environment. A fundamental objective of psychophysics is to assess the minimum amplitude that these changes must have so that an individual can be notified. This minimum amplitude, that is to say the smallest amount of energy that can be detected in the absence of any stimulation, is called *absolute threshold*. Below this threshold, sensation is not possible. However, this threshold is a point whose identification corresponds to an operational definition for a given method. Traditional psychophysics offers several methods for estimating a threshold. The most conventional are the method of constant stimuli, the method of limits, and the method of adjustment. For now, only the constant method is presented:

Gustav Fechner

One could say that psychophysics started in 1860 with the publication of the book *Elements of psychophysics* by the German researcher Gustav Theodor Fechner (1801–1887). Philosopher and physicist, the founder of psychophysics wanted to study the links between the inner world and the outer world. Also known under the pseudonym of "Dr. Mise", Fechner, who worked in Leipzig, had quite a special mind. We owe him various experimental methods still used in psychophysics, but he was also interested in, for example, the properties of the electric current, experimental aesthetics, and even life after death. Note

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that there is an annual meeting of psychophysics, usually held in October, called Fechner Day (October 22). This meeting is held in different locations around the world under the supervision of the International Society for Psychophysics (http://www.ispsychophysics.org/), founded in 1985 in southern France.

1.1.1 Absolute Threshold and Method of Constant Stimuli

For measuring an absolute threshold with the method of constant stimuli, also called the constant method, one must first determine the threshold roughly by locating a region for which a stimulus is almost never perceived and for which a stimulus is almost always perceived. Then, we generally select from five to nine stimuli located between these regions. After this selection, the selected stimuli are presented repeatedly in random order. The method requires an observer to make at least a hundred judgments, but of course, increasing the number of trials for estimating a threshold decreases the risk that the estimated value is far from what the real threshold is.

At each presentation, an observer has to indicate whether or not the stimulus is perceived. It becomes then possible to obtain a discrete (not continuous) frequency distribution, each point representing the number of times a stimulus was detected. These frequencies have to be transformed into probabilities. It is on the basis of these probabilities that the threshold value will be estimated. The probability calculated for each stimulus can be reported on a figure. As shown in Fig. 1.1, the percentage of

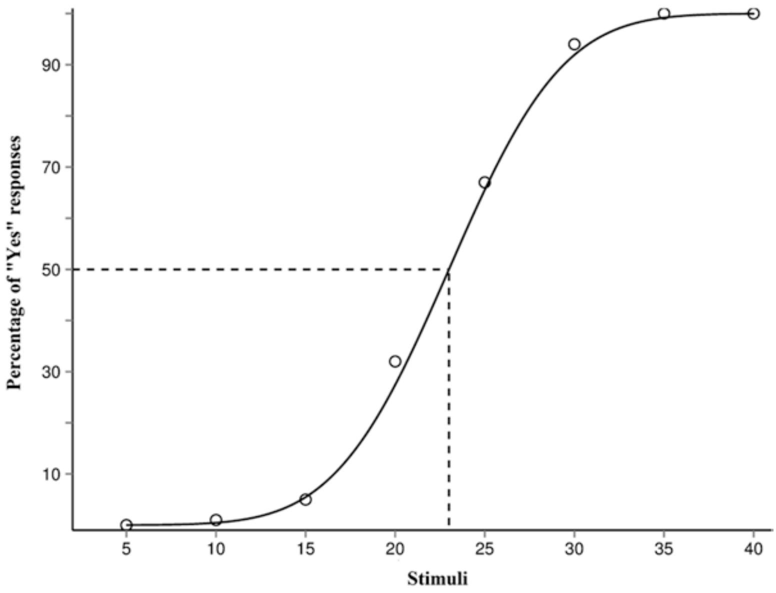

Fig. 1.1 Illustration of a hypothetical psychometric function for absolute threshold. On the y-axis is the percentage of times where the observer reports perceiving the stimulus. The *dotted vertical line* reaching the x-axis indicates the absolute threshold

times the stimulus is detected is placed on the *y*-axis and is plotted as a function of the magnitude of the stimuli, placed on the *x*-axis, in ascending order. The function that relates the probability of detecting to the magnitude of a physical continuum is called a psychometric function. Such a function generally has the shape of an ogive—a kind of S—and the threshold is operationally defined as the point corresponding to an ability to perceive the stimulus 50 % of the time. This value, 50 %, represents the point for which an observer is able to detect the stimulus at a level higher than what would provide responses made randomly in a procedure involving two responses, yes or not.

For drawing a function on the basis of a series of points, it is necessary to posit some assumptions. First, the phenomenon under investigation is assumed to be a continuous random variable. Thus, we shall believe that the discrete distribution obtained (series of points) is an approximation of a continuous function. Also, it is necessary to make an assumption about the shape of this function. Mathematics offers several possibilities, but a function often used in psychology is the normal distribution. The reader is probably already familiar with the concept of normal distribution (normal or Gaussian curve or bell-shaped curve). The function used to draw a psychometric function is derived from the bell-shaped function (probability density function) and is called cumulative normal function. It is after drawing this function that it becomes possible to estimate the threshold value accurately. Besides the cumulative Gaussian function, Weibull and logistics functions are probably the most likely ones to be used (Macmillan & Creelman, 1991).

1.1.2 Signal Detection Theory

Despite the rigor used to estimate the ability to detect a stimulus with the constant stimuli method, a major problem may arise. The estimated capacity may depend not only on the sensitivity of an observer but also on the way in which this observer makes decisions. An observer might as well wait to be sure before making a decision, before declaring that a stimulus is perceived, whereas another observer, in spite of doubt, would tend to say “yes, I perceive” (Macmillan & Creelman, 1991).

There is a method, developed in the 1940s, to determine the sensitivity of the observer to detect a stimulus while correcting the problem associated with the involvement of decision making. Thus, the signal detection theory (SDT), also known as sensory decision theory, uses two parameters to describe the performance: one describing the sensitivity level and the other describing the way an observer makes a decision (Macmillan & Creelman, 1991).

1.1.2.1 Basic Concepts

To understand the SDT, we must first know two fundamental concepts: signal and noise. Signal (*S*) and noise (*N*) are the parts of any sensory message. The stimulus that one attempts to detect, called signal, has precise and stable characteristics.

Noise is rather defined as a random variable that is constantly changing. This variable takes different values which are usually assumed to be normally distributed. Noise is a background against which a signal to be detected is sometimes added. This noise includes an external activity (controlled by the experimenter) and internal physiological activity (generated by the nervous system).

In a typical SDT task, an observer must make the following decision about what was presented: was it noise only (N) or noise with the addition of a signal ($S+N$)? For a given amount of noise, the more a signal generates internal activity (the stronger it is), the easier it is to detect it. These two concepts, N and $S+N$, are generally represented with two normal frequency distributions (Fig. 1.2).

An observer subjected to a signal detection task should adopt a decision criterion. This criterion is often measured with the index beta (β). The adoption of a criterion generates four typical conditions (Table 1.1). From these four conditions, two are linked to the presence of the signal and two to its absence. When the signal is present and an observer reports to have perceived it, it is a case of correct identification called a *hit*. When the observer does not detect the presence of a signal when it is presented, we have a case called *miss*. If the signal is not presented but the observer reports that it was, it is a *false alarm*. Finally, not perceiving a signal when actually there was only noise is a condition called *correct rejection*. Table 1.1 summarizes these four typical situations.

Some people prefer waiting to reach some level of certainty before reporting that they have perceived the presence of a signal. These people are referred to as conservative observers, as opposed to lax observers. Two observers may eventually have

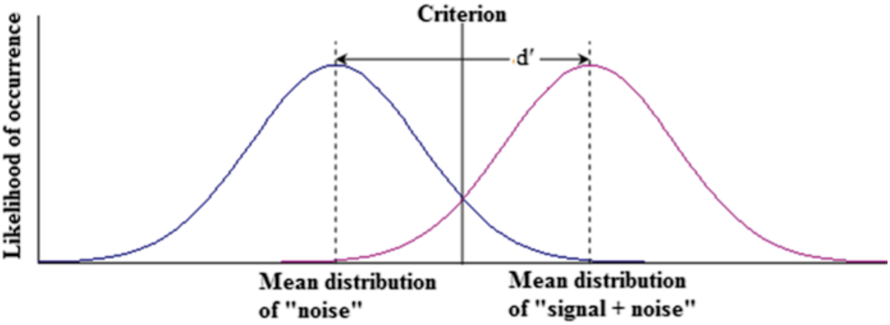

Fig. 1.2 Distributions of noise and signal + noise of the signal detection theory. The *continuous vertical line* represents the criterion. The distance between *dotted lines* represents d', an index of sensitivity

Table 1.1 The four typical situations of the signal detection theory

		Signal	
		Present	Absent
Response	Present (yes)	Hit	False alarm
	Absent (no)	Miss	Correct rejection

similar sensitivities, but adopt different decisional strategies. Compared with a lax observer, the number of hits of a conservative observer might be lower, but the latter would commit fewer false alarms. In short, for a given level of sensitivity, the number of false alarms and the rate of hits may vary, and this is depending on the decisional style of the observer (see Appendix A).

1.1.2.2 Units of Measurement

There are various indices associated with SDT that allow to quantifying the sensitivity of an observer and the criterion adopted. Among the performance indicators used to measure the sensitivity, d' (pronounced *d* prime) is probably the most common. d' can be defined as the difference between the means of N and $S+N$ distributions, divided by the standard deviation of the noise distribution; d' is a pure index of detectability in that it is not affected by the observer's criterion.

One can easily calculate d' on the basis of hits and false alarms obtained empirically. We obtain an assessment of d' with the transformation into Z-scores of the probabilities of obtaining a hit and a false alarm:

$$d' = Z(\text{Hit}) - Z(\text{False Alarm})$$

For instance, suppose an observer detects correctly the presence of a signal for 90 % of the trials, but commits 25 % of false alarms. Given that the Z-score value for 90 % is 1.28 and the Z-score value for 25 % is −0.67, the sensitivity, d' value, is $1.28-(-0.67)=1.95$.

It is important to emphasize that this transformation of percentages into Z-scores is based on the assumption that the N and $S+N$ distributions are normal. Note that there are other performance indices, like Δm or d_e', for estimating sensitivity. Another index, A', is particularly interesting because it allows to estimate sensitivity without having to posit the hypothesis that the distributions are normal. We obtain A', using the following equation:

$$A' = \tfrac{1}{2} + \frac{\big(p(H) - p(\text{FA})\big) \times \big(1 + p(H) - p(\text{FA})\big)}{\big(4p(H)\big) \times \big(1 - p(\text{FA})\big)}$$

where $p(H)$ is the probability of a hit and $p(\text{FA})$ the probability of a false alarm.

Regarding the criterion, it may be estimated using β. This index is a ratio of the ordinates for each distribution (N and $S+N$) corresponding to the location of the criterion. Thus, the calculation of the β criterion is as follows:

$$\frac{\text{Ordinate of the } S+N \text{ distribution}}{\text{Ordinate of the } N \text{ distribution}}$$

So, in the preceding example, the value of β is 0.552:

Ordinate of 90 % = 0.176 and ordinate of 25 % = 0.319.
Therefore, $\beta = 0.176/0.319 = 0.552$.

A high value of β means that the observer is very conservative when making decisions, but conversely, a low β value (<1), as is the case in this example, indicates that the observer tends to be lax. Finally, note that there are also other indicators to express the criterion, including *c* (Macmillan & Creelman, 1991).

1.2 Discrimination

Another fundamental sensory ability is at play when someone tries to find out if two stimuli are different from each other. The minimum intensity difference required for differentiating two stimuli is called *difference threshold*. As was the case for the absolute threshold, the difference threshold is defined arbitrarily; the threshold value depends on the method used, i.e., on an operational definition. This threshold, the point at which an observer is able to tell the difference between two stimuli, is sometimes called the *just noticeable difference* (JND).

1.2.1 Difference Threshold and Method of Constant Stimuli

For estimating a differential threshold with the constant stimuli method, an observer is presented with two stimuli and must determine which of the two stimuli is of greater magnitude. The method includes the presentation on each test of a standard stimulus and of a comparison stimulus. The comparison stimulus usually takes one of seven to nine values distributed around the standard. The standard and one of the comparison stimuli are presented several times, concurrently or sequentially, depending on the nature of the sensory continuum investigated (Grondin, 2008).

In the following example, the purpose is to determine the difference threshold for a standard weight of 250 g with successive presentations of the standard and of a comparison stimulus. The comparison stimulus may take one of the following values: 230, 235, 240, 245, 250, 255, 260, 265, and 270 g. An observer has to indicate on each trial whether the comparison stimulus is lighter or heavier than the standard. After several judgments, it is possible to construct a psychometric function (Fig. 1.3). On the *x*-axis of the function, the different values of the comparison stimuli are placed in ascending order. On the *y*-axis, the probability to report that the comparison stimulus is heavier than the standard is reported.

This function enables the identification of two variables that may be important when studying sensation: the *point of subjective equality* (PSE) and the *difference threshold*. The PSE is the point on the *x*-axis corresponding to 0.50 on the *y*-axis: the probability to respond that the standard is heavier than the comparison stimulus is the same as the probability to respond that the comparison stimulus is heavier

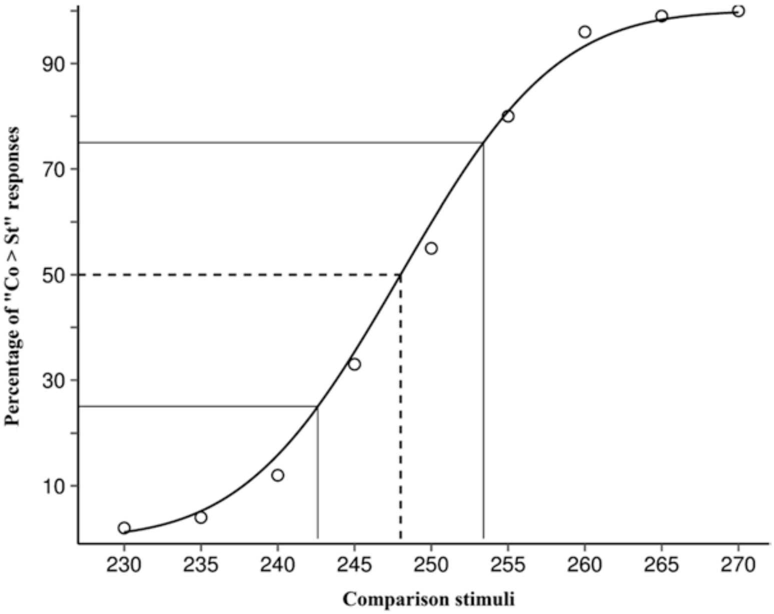

Fig. 1.3 Illustration (hypothetical case) of a psychometric function for difference threshold for weight (standard = 250 g). On the *y*-axis is the percentage of times where the observer indicates that the comparison (Co) is heavier than the standard (St). The *vertical and dotted line* indicates the point of subjective equality on the *x*-axis. The other two lines indicate the values that are used for calculating the difference threshold (see text)

than the standard. Furthermore, we call *constant error* the difference between the PSE and the value of the standard.

Two difference thresholds, one above and one below, can be extracted on this function. For the first, we need to subtract the points on the *x*-axis which, on the function, correspond to 0.75 and 0.50 on the *y*-axis. The rationale is the following one: this value, 0.75, is the middle point between a perfect discrimination (100 %) and total inability to discriminate (50 %). In the same way, there is a lower difference threshold: points on the *x*-axis which, on the function, correspond to 0.50 and 0.25 on the *y*-axis. The 0.25 is in the middle of the inability to discriminate (50 %) and a perfect discrimination (0 %). We can obtain a single threshold value by calculating the mean of the two thresholds. It is also possible to calculate directly this difference threshold by subtracting the points on the *x*-axis corresponding to 0.75 and 0.25 on the *y*-axis and then by dividing this value by two.

Finally, it should be noted that classical errors can occur in the determination of difference thresholds with the constant stimuli method. When the stimuli are presented simultaneously, i.e., at the same time, there is a need to vary randomly the side, to the left or to the right, where the standard is presented. This variation seeks to prevent cases where there will be a strong preference for one side or the other. This preference causes what is referred to as the spatial errors. When the stimuli to discriminate are compared sequentially, rather than simultaneously, there may occur a type of bias called a temporal order error. In such a case, the observer will have a more or less marked tendency to judge whether the first or the second stimulus has a greater magnitude. There is often an underestimation of the value of the first stimulus, which could be interpreted as a decrease of the memory trace left by this stimulus (Hellström, 1985).

1.2.2 Weber's Law of Discrimination and Its Generalized Form

There is not only one difference threshold value for a particular sensory modality. In fact, this value varies according to the magnitude of the stimuli used for a given investigation (Grondin, 2001, 2010, 2012). According to Weber's law, sometimes also called the Bouguer-Weber's law (Bonnet, 1986), the difference threshold increases as a function of the intensity of the stimuli being studied. This law states that the minimal magnitude difference, or difference threshold ($\Delta\phi$), necessary to distinguish two stimuli, depends on their magnitude (ϕ). In other words, according to this law, the relationship between $\Delta\phi$ and ϕ is proportional:

$$\Delta\phi = K\phi \ \left(\text{or } \Delta\phi / \phi = K\right)$$

where K, the Weber fraction, is constant. This Weber's law is indeed a principle that provides a tool for looking at the mechanisms involved in the discrimination of sensory quantities in a given sensory modality.

An example will allow grasping fully this relatively simple law. In the previous section, a standard of 250 g was used. If it is known that the difference threshold for a weight of 250 g is 25 g, it can be predicted, on the basis of Weber's law, that the minimal difference to distinguish two weights is 50 g if the standard is 500 g. In other words, the ratio between the difference threshold and the standard will remain the same, 10 % (50/500 or 25/250) in this example.

Although Weber's law may be right for a certain extent of a given sensory continuum, it proves to be incorrect for some values of this continuum. This failure of the strict form of Weber's law has led to a reformulation of the relationship between the difference threshold and the magnitude of the stimulus.

In fact, the Weber fraction is valid only for a limited range on a sensory continuum. For very low or very high values, the Weber fraction is higher. For low values, the increase of the fraction can be easily described based on a transformation of Weber's law. All of what is required is the addition of a constant, a, interpreted as the result of sensory noise:

$$\Delta\phi = K\phi + a$$

Returning to the example above, we can easily understand that for low values, a has a lot of weight in the equation, which is not the case for larger values.

If a takes a value of 10, the threshold calculated for a standard, ϕ, of 250 g, is 35 instead of 25, as it would have been the case without the additional noise (a). Therefore, the Weber fraction goes from 10 to 14 %. However, for a standard, ϕ, of 2500 g, the calculated threshold is 260 rather than 250. The Weber fraction goes from 10 to 10.4 %.

1.3 Other Methods for Estimating Thresholds

There are many other methods for estimating the value of thresholds, absolute and differential. We describe only two of these below, the method of adjustment and the method of limits.

1.3.1 The Method of Adjustment

With the method of adjustment, the observer has an active participation. On each trial, the observer proceeds to a change. In the case of the determination of the absolute threshold, the observer is presented with a stimulus whose intensity is far below or above the threshold level. The task is to adjust the intensity of the stimulus, either by increasing or decreasing it, so that it is just at the limit of what could be perceived. This method involves a series of ascending and descending trials. It is the average of all observed transition points, between what is perceivable and what is not, which is the estimated value of the absolute threshold. This method is also called the "method of mean errors."

This method of adjustment is not really used to determine an absolute threshold; it is rather useful for the determination of a difference threshold. In the latter case, an observer must adjust a comparison stimulus such that it appears equal to a standard stimulus. To use this method, it is imperative that the stimuli in the study may vary continuously (for estimating both absolute and difference thresholds) and can be presented simultaneously (for difference threshold). The choice of the method of adjustment would not be appropriate, for example, for trying to estimate the difference threshold for auditory intensity. So, after several trials, we can extract two key pieces of information by averaging the points of equality and by calculating the standard deviation of the distribution of points. By subtracting the standard stimulus value from the calculated mean, the constant error is obtained; and the difference threshold will be revealed by the standard deviation. We understand the spirit of this operational definition of the threshold: the greater the standard deviation, the higher the threshold (i.e., poorer discrimination or lower sensitivity). In other words, this means that two stimuli will appear equal over a large range of values.

Consider the following example where two observers, A and B, try to adjust the intensity of a light source to the same level as another source having a fictitious value of 100. The adjustment of each observer at each trial is reported in Table 1.2.

Table 1.2 Adjusted value of the comparison stimulus obtained on each trial with a standard having a value of 100

Observer/trial	1	2	3	4	5	6	7	8	9	10
A	98	99	104	97	102	103	97	102	93	101
B	91	97	89	108	111	99	93	108	95	100

Point of subjective equality of Observer A, 99.6; for Observer B, 99.1
Difference threshold of Observer A, **3.41**; for Observer B, **7.65**

We can see that, on average, there is little difference between them, but we understand that there is much more variability in the scores of Observer B. It is the estimate of this variability that is used to establish the sensitivity level, i.e., the difference threshold.

1.3.2 The Method of Limits

One can just as easily measure an absolute threshold or a difference threshold with the method of limits. In both cases, the method requires the presentation of two types of series of stimuli, one ascending and the other descending. However, in addition to presenting one stimulus at a time (absolute threshold) rather than two (difference threshold), the moment for stopping ascending and descending series depends on the type of threshold under investigation.

Thus, for estimating an absolute threshold specifically, it is necessary to identify in advance a series of stimuli that are more or less close to what is believed to be the threshold. These stimuli are presented one at a time, sometimes in ascending order, sometimes in descending order, alternating from one order to another. In a series of ascending presentations, the first stimulus presented is significantly below the absolute threshold; then the intensity is increased gradually from one trial to another, until the observer reports having perceived the stimulus. Similarly, during a series of descending trials, we first use a stimulus that can be perceived easily, and then the intensity is gradually decreased, until reaching the moment of a transition from a trial where the stimulus is perceived and a trial where it is not. Note that the ascending and descending series do not all begin at the same point (Table 1.3). The purpose of this strategy is to circumvent the problem caused by the possibility of committing the so-called anticipation and habituation errors. To determine the absolute threshold, it is necessary to average the transition points, from not perceived to perceived in the ascending series and from perceived to not perceived in the descending series.

We commit a habituation error when we take the habit of answering “no” during an ascending series or “yes” during a descending series. This type of error will result in the first case in an overestimation of the actual value of the absolute threshold and in the second case in an underestimation. An anticipation error occurs when an observer, knowing that there will be a transition point, passes too quickly from “yes” to “no” (descending series) or from “no” to “yes” (ascending series).

Table 1.3 Determination of an absolute threshold with the method of limits (fictitious values) where the observer indicates whether or not a stimulus is perceived

Intensity/series						
	Ascending	Descending	Ascending	Descending	Ascending	Descending
16				Yes		
14				Yes		Yes
12		Yes		Yes		Yes
10		Yes	Yes	No		Yes
8	Yes	Yes	No		Yes	No
6	No	Yes	No		No	
4	No	No	No		No	
2	No		No		No	
0			No		No	
0					No	
Points of transition	7	5	9	11	7	9

Threshold value: (7 + 5 + 9 + 11 + 7 + 9)/6 = **8**

In the first case, the anticipation error will result in an overestimation of the threshold value compared with the real threshold value and will result in an underestimation in the second case.

In the case of a difference threshold estimated with the method of limits, two stimuli are used, a standard and a comparison stimulus (Table 1.4). These stimuli are presented in pairs, either simultaneously or successively. It is the nature of the evaluated sensory continuum that determines the relevance of the presentation mode. For sound, for example, it is better to present the stimuli successively.

After the presentation of the two stimuli, the observer must determine if this stimulus is smaller or larger than the other or if those stimuli appear to be equal. Comparison stimuli vary from one trial to another so that the difficulty of discriminating is gradually increased. If it is an ascending series, the magnitude of the comparison stimuli is increased; for a descending series, the magnitude is decreased.

Determining the difference threshold with the method of limits, instead of the absolute threshold, is particular for not having a series, either ascending or descending, being stopped when a transition point is observed. In fact, in the case of an ascending series, for example, the first transition that the observer meets is when the comparison stimulus appears to be smaller than the standard and then, the following trial, the stimuli appear equal. It is necessary to continue to increase the value of the comparison stimuli until the standard and comparison stimuli stop appearing equal. It is necessary to reach the transition that leads to the impression that the comparison stimulus is larger than the standard. Once this response is made for the first time, the series ends (Table 1.4). The same process is followed with the descending series. Also, just as was the case for the absolute threshold, ascending and descending series have to be alternated, and the starting value of a series should also vary from one time to another, for the ascending and for the descending series.

Table 1.4 The difference threshold with the method of limits is based on conditions where the observer indicates that a comparison stimulus is lesser (*L*) or greater (*G*) than a standard (of 10, fictitious values) or of equal (*E*) value

Intensity/series						
	Ascending	Descending	Ascending	Descending	Ascending	Descending
18				*G*		
17				*G*		*G*
16		*G*		*G*		*G*
15		*G*	*G*	*E*		*G*
14	*G*	*G*	*E*	*E*	*G*	*E*
13	*E*	*G*	*E*	*E*	*E*	*E*
12	*E*	*E*	*E*	*E*	*E*	*E*
11	*E*	*E*	*E*	*E*	*E*	*E*
10	*E*	*E*	*E*	*E*	*E*	*E*
9	*E*	*E*	*E*	*L*	*L*	*E*
8	*E*	*E*	*L*		*L*	*L*
7	*L*	*L*	*L*		*L*	
6	*L*		*L*			
5	*L*		*L*			
4	*L*		*L*			
3			*L*			
2			*L*			
Upper limit	13.5	12.5	14.5	15.5	13.5	14.5 ($M=14$)
Lower limit	7.5	7.5	8.5	9.5	9.5	8.5 ($M=8.5$)

Point of subjective equality: (14 + 8.5)/2 = 11.25
Uncertainty interval: 14 − 8.5 = 5.5
Difference threshold: 5.5/2 = **2.75**

For each series, there are therefore two transition points. These points make it possible to identify an upper limit (uL) and a lower limit (lL). For example, in the case of a descending series, the uL is reached when, after the comparison stimulus was perceived as being greater than the standard, these stimuli are now perceived as equal. Similarly, the lL is reached when, after being perceived as being equal to the standard during a trial or several trials, the comparison stimulus is now perceived as being lesser than the standard. An uncertainty interval can be calculated by subtracting the average of uL from the average of lL; the difference threshold is then calculated by dividing this uncertainty interval by 2. A PSE is estimated as follows: (uL + lL)/2.

1.3.3 Adaptive Methods

Although we will only touch on the subject, it should be noted that there are a series of so-called adaptive procedures for estimating thresholds. In general, these methods allow to make good estimates of thresholds in a lesser number of trials, in particular by reducing the number of trials involving stimulus values that are far from the threshold.

One of these procedures is the staircase method (Bonnet, 1986). For using it, it is necessary to choose a starting level (more or less close to the threshold) and a step value allowing to change the difficulty level, by decreasing or increasing the magnitude of the stimulus, depending on whether there is a change from "I do not perceive" to "I perceive" or from "I perceive" to "I do not perceive." It is also necessary to decide whether or not the magnitude should be changed as soon as a response indicates the transition from one state to another. Finally, it is also necessary to decide when to stop the procedure, for example, after a number of state changes or after a fixed number of trials. With the staircase procedure, one can use a single staircase having only one set of variations, a double staircase involving two independent series, a series starting well above the threshold, and the other way below.

Another well-known adaptive method is called *parameter estimation by sequential testing* (PEST). Generally, with this procedure, at every reversal in the opposite direction, the step value adopted at the beginning is halved. Also, this step remains the same when there is a change in the same direction or may even increase (be doubled) if, for example, the observer provides a response in the same direction in three consecutive trials (Macmillan & Creelman, 1991). Finally, note that there are other adaptive methods such as those based on a Bayesian procedure or maximum likelihood (Shen, 2013; Shen & Richards, 2012).

1.4 Scaling

A third fundamental question in the field of psychophysics is that of the relationship between the magnitude of a physical stimulus and its psychological magnitude. Such a question is significantly different from that which arose in the context of Weber's law that relates two physical quantities. The questioning is along the line started by Fechner who proposed, using an indirect method, that the relationship between the magnitude of a physical stimulus and the psychological magnitude would necessarily be logarithmic (Appendix B).

For conducting an empirical verification of a law on the relationship between physical quantities, for a given sensory continuum, and the sensory experience that is made, we first have to try to quantify this experience. Stanley Smith Stevens proposes to adopt different methods to measure the experience as directly as possible:

The American Stanley Smith Stevens (1906–1973) is a prominent figure in psychophysics. He obtained a PhD from Harvard University, where he worked for many years. He is of course well known for Stevens's law and for the development of methods for studying the link between the magnitude of a physical stimulus and its psychological magnitude. What is less known is his contribution extending to other fields, particularly in the field of hearing. We owe him in particular the identification of different measurement scales.

1.4.1 Methods

The empirical demonstrations of Stevens rely on several scaling methods. Essentially, we can distinguish the “partition scale” and “ratio scale.”

Among the partition scales, there are category scales and equisection scales. In the first case, an observer must assign each stimulus a set of stimuli in certain categories (for instance, from 1 to 5). The number of stimuli in the set and the number of categories are determined in advance. As for the equisection scales, an observer must divide his psychological continuum into a series of distances considered as equal. For example, the observer may need to determine that the distance between the sensations created by stimuli A and B on a sensory continuum is smaller than, equal to, or greater than the distance between the sensations produced between stimuli C and D, also on this continuum. Among the method-specific equisection scales, there is bisection. In such a case, the observer is required to select a stimulus whose intensity is located halfway between the intensities of two other stimuli.

As for the ratio scales, there are the estimation tasks and the production tasks. A procedure often used is called “magnitude estimation.” When this procedure is used, an observer is exposed to a standard stimulus, also called *modulus*, which is assigned a numerical value. Then, at each presentation of a stimulus, the observer must assign to this stimulus a numerical value relative to the standard. The observer sets his own scale around the value of the modulus, taking care of never choosing zero. If a stimulus appears to be twice as intense (greater) than a modulus of 50, the observer will assign it a value of 100. Thus, it becomes possible to establish a correspondence between the different assigned values (psychological magnitude on the y-axis) and the magnitude of the physical stimuli (on the x-axis).

The ratio production (or fractionation) is among the various types of other ratio scales. For example, an observer may be required to produce the intensity of a stimulus such that it corresponds to a percentage (e.g., half or one-third) of another stimulus.

1.4.2 Stevens’s Law

Thus, another fundamental question in psychophysics is related to identification and quantification of the relationship between the magnitude of sensation and the physical magnitude of a stimulus. This relationship is sometimes referred to as *psychophysical law*.

Of course, it is reasonable to expect that the relationship between the magnitude of sensation and the physical magnitude of a stimulus will be monotonic, that is to say, that the psychological magnitude increases continuously with the increase of the physical magnitude. The question remains concerning the exact nature of this increase: is it fast at the beginning, for stimuli with low amplitude, and slower when the stimuli are of greater magnitude?

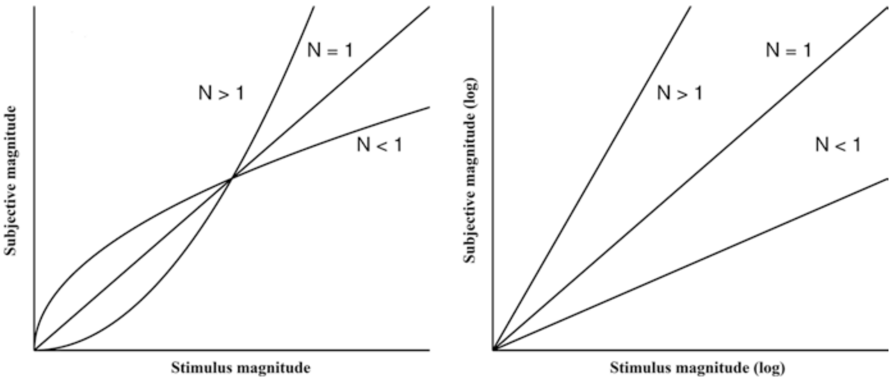

Fig. 1.4 Three types of relationship, exponential ($N > 1$), linear ($N = 1$), and logarithmic ($N < 1$), between sensation and the physical magnitude of a stimulus. *Left panel*: $S = K\phi^N$. *Right panel* shows the same function in log-log coordinates: $\log(S) = N\log\phi + \log K$

In fact, this increase depends on the nature of the stimulus under study. Essentially, as shown in Fig. 1.4 and as reported by Stevens following a very large number of empirical studies, there are three types of growth: exponential, linear, and logarithmic. Thus, Stevens established that the best description of the relationship between the magnitude of perceived sensation and intensity of a stimulus is expressed using a power function:

$$S = K\phi^N$$

where S is the sensation, K is a constant whose value depends on the measurement units used, and N is the exponent specific to a given sensory dimension. This law is called the power law, Stevens's law, and sometimes Stevens's power law.

The exponent N is the main feature of this equation, the signature of a sensory continuum. Its value is 1 if the relationship is linear, is smaller than 1 if the relationship is logarithmic, and is greater than 1 if the relationship is exponential. The N values reported by Stevens (1961) are, for example, 0.55 for smell, 0.60 for loudness, 1.00 for temperature, and 3.50 for electric shocks. These values however are likely to fluctuate from one experience to another. For example, Stevens (1961) reports a N value of 1.0 for the duration, but after a lengthy review of the literature on the issue, Eisler (1976) came to the conclusion that 0.90 is probably a better approximation (see Grondin & Laflamme, 2015).

1.4.3 Other Contributions from Stevens

Stevens (1975) makes a fundamental distinction between two types of sensory experiences. These experiences are part of one of two sensory continua, called *prothetic* and *metathetic*. In the case of a prothetic continuum, the sensory experiences are based on an additive physiological process, i.e., a process in which the increase in the physical intensity of a stimulus leads to an increase of the frequency of action potentials by neurons responsible for receiving these stimuli. In contrast, a metathetic continuum is not based on the idea of addition, but rather on that of substitution.

Thus, with a prothetic continuum, it is logical to try to answer a question based on the idea of "how much?" whereas with the second type, the metathetic continuum, the question rather consists of knowing "of what kind?" the sensation is. For example, in the visual modality, a brightness change will be additive; a light source will be more or less intense than another. Therefore, we will be dealing with a prothetic continuum. If we are dealing with a change in the wavelength of light, the change will be a substitution, that is to say that what will be observed will not depend on a quantitative sensory difference, but on a simple qualitative change in appearance, namely, a change of color (hue).

As mentioned above, Stevens is also responsible for identifying the various measurement scales. He had identified four: the nominal scale, which only serves to identify an object; the ordinal scale, which indicates the rank or order of scores; the interval scale, which includes the notion of distance between the scores; and the ratio scale, which includes, in addition to the notion of distance, an absolute zero.

That said, it is not possible to use the same scale for all the sensory qualities. Some of these qualities can be quantified (prothetic continuum), others not (metathetic continuum). In the first case, the scores can be distributed on an ordinal or even interval scale, but with a metathetic continuum, the nominal scale is appropriate.