Principles of Perceptual Measurement

In this chapter . . .

- You will discover the main controversies that arose in studies to determine the relationship between physical stimuli and the sensations they evoke within us. You will also learn how to describe and give examples of the human ability to estimate sensations.
- You will examine famous classical psychophysicists, such as Gustav Fechner and Ernst Weber, and the experimental methods they designed to study sensory perception. You will become familiar with *psychometric function* and how it can be affected by both sensory and nonsensory parameters.
- You will become familiar with the *difference threshold*, which determines how much extra stimulus is needed in order to *just* notice a change. You will also become familiar with *Weber's law*, which states that the difference threshold does not remain constant as the stimulus increases in intensity; and Fechner's law, which was found to be flawed but transformed the field of sensory science and remains influential to this day.
- You will learn about Stanley S. Stevens, who began the era of modern psychophysics. You will also learn about the method of *magnitude estimation*, which led to the development of the power law.
- You will study the difference between *prothetic* and *metathetic* stimuli and how they are assessed. Finally, you will become familiar with differences in human sensitivity to stimuli and how researchers use techniques to compare those differences in terms of z-scores.

Most of us would be able to correctly identify the colour red or green or blue. But does that mean we are all experiencing an identical psychological event, or could it be that each of us experiences something slightly different? Photo: Trout55/iStockphoto.com

True science investigates and brings to human perception such truths and such knowledge as the people of a given time and society consider most important.

— Leo Tolstoy

We are constantly being bombarded by energy from the physical world, whether it is in the form of visual, auditory, tactile, or chemosensory stimulation. These stimuli are very real and can be measured. The intensity of light reflected by an object, for example, can be exactly determined with a device called a *radiometer*. This device will specify the intensity in a set of units for which it has been calibrated. In general, all physical stimuli that we are capable of perceiving can be specified in real terms that give us a value according to some dimension of its physical reality.

But what about the psychological events that evoke within us an appreciation of that physical **stimulus**? Can the resulting perceptual experience also be measured? That depends on who is doing the measuring. If it happens to be anyone other than the perceiver, the answer of course is *no*. Perception is a very private experience, and since it cannot be exposed to anyone else, it cannot be directly measured by anyone else either. Consider the following. Most of us would be able to correctly identify the colour of a stoplight. But does that mean we are all experiencing an identical psychological event, or could it be that each of us experiences something slightly different but that we have all been taught to call it *red* since childhood? We may never know the answer to this.

If an outsider is not capable of measuring our own perceptions, then are we? Are we capable of determining, say, the psychological intensity of a sound that is experienced in our mind, giving it a value, and comparing its perceived intensity with a different sound or a different type of sensation altogether? Remarkably, the answer is *yes*. And it turns out that we are actually quite good at it even though perceptions do not reside in the very real world of physics (Stevens, 1986). And therein lies a rather thorny problem. Many psychologists have asserted that even making the attempt at measuring a perceptual event is fruitless because it is not a measurable thing and therefore can never be verified (Heidelberger & Klohr, 2004).

To say that this issue has generated some lively debate in the past would be an understatement. This is largely because of the opposite view held by some experimental psychologists that the perceived intensity of sensations can indeed be reliably estimated by the perceiver. Furthermore, the information so obtained is generally consistent across individuals, and therefore the data can be scientifically validated (Gescheider, 1997). We will return to this debate and explore the issues on both sides later in this chapter. But first, it is necessary to learn something about the experimental approaches to studying sensory processes, the kinds of problems to which they can be applied, and the information they reveal about the operation of the brain. What will follow is a set of core concepts that will surface throughout this book as we examine each of the sensory systems in detail.

SideNote 1.1

Although the terms *sensation* and *perception* are often used interchangeably, it is important to establish the distinction between them at the outset. Sensory processes capture information from the physical world and transform them into biological signals that are interpreted by the brain. In so doing, the brain creates a perceptual representation in our mind that allows us to appreciate the physical world. Thus, *perception* represents a single unified awareness of a stimulus that in turn arises from the *sensation* produced by our sensory systems.

A. Scientific Basis of Perceptual Measurement

The most obvious question to begin with is "Why take a scientific approach to this problem?" That is, what do we hope to gain by developing and applying a set of rigorous experimental procedures to the study of perception? The reason most psychologists would first offer is that it satisfies an intellectual curiosity. Perception is such a mysterious and almost magical phenomenon that a first step toward learning anything about it is to establish a quantifiable relationship between the two variables in this process—the physical stimulus and the resulting perceptual impression (SideNote 1.1). Since it is impossible to open up the mind and observe the process of perception, one advantage of knowing this relationship is that it may offer clues about the nature of the brain, the way it processes information, and, ultimately, how the biological operations within it lead to sensation and perception.

Quantitative relationships and their benefits

There are several additional advantages to understanding the mathematical relationship between the physical and perceptual worlds. One is that it provides an estimate of the perceptual quality of a stimulus in numerical terms and thus allows comparisons with other stimuli. Say for example that a new perfume has just been developed and the company wishes to test its aromatic acceptance by the public before spending millions of dollars on its promotion. By applying a set of experimental procedures, which we will soon learn, it is possible to obtain a numerical index of its impact on the sense of smell and then use this to provide a meaningful comparison with the perceptual impression made by other perfumes. Such data can predict the likely social acceptability of the new product and therefore can be used by the company's executives to make important commercial decisions (Lodge, 1981).

Quantitative relationships also have the advantage that they allow comparisons among individuals and even species. The later chapters of this book will cover many details about our limits and capacities in processing information from the physical world, how they vary with age, and, where appropriate, how they compare with other animals. The factors that are used in such comparisons are always mathematical descriptors of the system in question. An extension of this idea is the comparison among the different sensory modalities—a so-called *cross-modal comparison*—to see if any similarities exist among them (Luce, 1990). For example, if we perceive warmth on the skin in some definable way to the temperature of the object, then how does this relationship compare to the way in which we perceive the loudness of sound as a function of its physical intensity? Before we explore such sophisticated issues, we need to address a basic question.

Is there a general relationship between physical stimulus and perception?

This is one of the fundamental questions of perceptual psychology and one to which much effort has been directed over the last 150 years. The early experimentalists who approached this problem were motivated in finding a general formula that could describe all sensory systems. What might such a formula look like—or, rather, what kind of a **function** could relate the physical intensity of a stimulus to its perceived magnitude? We know from everyday experience that this will be an increasing function. That is, as the physical intensity of the stimulus increases, so will our perception of it. But that could happen in a number of ways, as shown in Figure 1.1.

The simplest is a linear function. For any given increase in physical intensity, there is a certain increment in the perceived intensity. The proportion between the two remains constant across the whole range. In other words, the slope remains constant. This is not the case for the other two possibilities shown in Figure 1.1. In an exponential relationship, the perceived sensation intensity changes very slowly at low values of physical intensity. But after a certain point, the function takes off such that even small changes in stimulus intensity produce a dramatic increase in perception. In an exponential function, therefore, the slope itself progressively increases with physical intensity. The opposite is true of a logarithmic function where the slope is very large at the beginning such that perceived intensities can change dramatically with small changes in stimulus intensity. However, this effect diminishes and the function tails off at higher stimulus intensities. A logarithmic function therefore displays a decreasing slope over its entire range. According to this mathematical description, a sensory system would no longer be additionally responsive to further increments in stimulus intensity beyond a certain point.

There are two general approaches to obtaining the precise relationship between physical events and perceptual experience. The first is to simply ask human subjects to rate the perceived intensity of a certain stimulus, say the loudness of a sound, at various physical intensities (Gescheider, 1984). It would then be possible to plot the two sets of values and determine which of the general functions shown in Figure 1.1 best describes the transformation of a physical input—in this case, sound—into a perceptual event. We will look at the information revealed by this kind of approach later

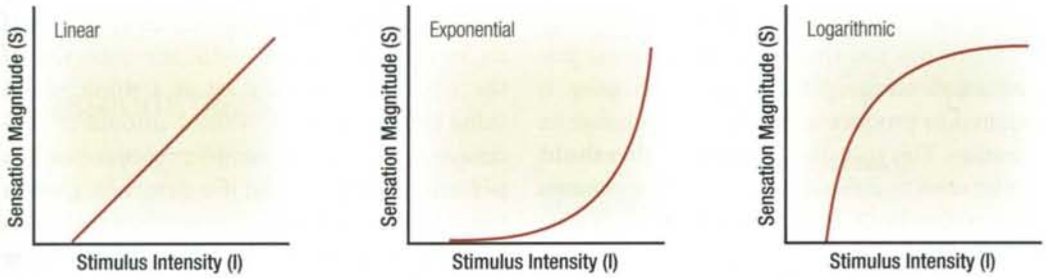


Figure 1.1

Three possible functions that may relate the physical intensity of a stimulus (I) to the perceived intensity of sensation (S).

Gustav Theodor Fechner (1801–1887)

in this chapter. The second approach is a bit more convoluted because it requires a measure of the smallest change in stimulus input that causes a just discriminable change in sensation. To understand how this can reveal anything important, we have to examine the ideas first proposed by the experimental psychologists of the 19th century. They had understood that a mathematical relationship between physical and perceptual qualities could be established by obtaining two basic characteristics or descriptors of that function—the starting point and the slope.

B. Classical Psychophysics

Looking again at Figure 1.1, we see that all three functions do not begin at the origin but are displaced somewhat to the right. This is because we are unable to detect very low levels of stimulus intensity. Although a stimulus is physically present, the biological elements that are involved in capturing the stimulus and transforming it into a sensory experience do not normally function well if the physical intensity is too low (Engen, 1971). Rather, the intensity has to reach a certain minimum level, the so-called **absolute threshold**, before it is registered by the brain as a sensory event. Stimulus intensities below this point are called **subthreshold** and will not produce detectable sensation. So the first item that has to be determined is the absolute threshold, which would then tell us the point from which to begin plotting our function.

We would next want to know what happens beyond this point in the so-called **suprathreshold** region where sensation takes place. For this, we will have to determine how the slope changes as a function of physical intensity. Furthermore, the slope would have to be determined not just for one suprathreshold point but also for several others in order to see how it is changing. One possible way to obtain this information is by knowing just how small a change in stimulus intensity is required to produce a discriminable change in sensation. This so-called **difference threshold** can be used to estimate how the slope changes at suprathreshold levels. And once we know this, we can determine which function best describes the transformation of physical stimuli in the real world into psychological events that we experience as perception.

We have just described the general outline of a scientific approach that had been formulated by the German physicist Gustav Fechner in 1860. Fechner wanted to determine the relationship between mind and body and set out to establish not only a guiding principle but also a set of experimental methods that were to be used in this new field called **psychophysics**. He believed that there existed a general relationship between physical and perceptual qualities, that it was similar for all types of sensations, and that it could be obtained by knowing the stimulus energy at which the output can just be detected or discriminated—that is, the absolute threshold and the difference threshold (Heidelberger & Klohr, 2004). Fechner was not just interested in knowing these thresholds because they would reveal something about the operational sensitivity of sensory systems but because he believed that they represented fundamental parameters in the grand formula of perception.

1. PSYCHOPHYSICAL METHODS

It is possible to apply any one of three general methods that were developed by Fechner to obtain absolute and difference thresholds (Gescheider, 1997). The simplest of these is the **Method of Adjustment** where a human subject is told to simply adjust the physical intensity of a stimulus until it is barely detectable. The initial intensity would be set either above or below threshold, and the subject would accordingly change the value until the stimulus is just perceptible or when the sensation just disappears. Although this procedure is very fast and actively engages the subject in the psychophysical experiment, the **Method of Limits** is preferable if speed is not an issue because this technique provides more reliable estimates. Here, the subject is presented with a stimulus whose intensity is chosen from an ascending or descending series. If an ascending series is used, the intensity of the stimulus is initially set at a subthreshold value and increased by a fixed amount in successive trials until the subject reports that it is perceived. Alternatively, if a descending series is used, a suprathreshold intensity value is gradually reduced until the percept disappears. The transition points from several such ascending and descending series provide a reasonable estimate of the threshold.

Both the Method of Limits and the Method of Adjustment allow the subject to have an idea of what the next stimulus will be like compared to the last one. This predictability in stimulus presentation makes both of these methods less accurate. A more suitable procedure is the **Method of Constant Stimuli** where the intensity values are randomly chosen from a preset range and presented to the subject. Neither the experimenter nor the subject usually knows the value of the next stimulus to be presented. The subject merely replies whether or not a sensation occurred and a frequency chart is established based on the responses collected from many presentations at each intensity.

As an example, let us consider an experiment on the visual system where we will attempt to obtain the absolute threshold for detecting light using the Method of Constant Stimuli. Such experiments are typically conducted with a sophisticated optical setup. However, we will simplify the experiment so that the stimulus will be under computer control and presented on a monitor. The subject will view the stimulus from a fixed distance and after each trial will indicate a response to the computer. This is a typical setup for most modern psychophysical experiments on vision (SideNote 1.2). After each stimulus presentation, the subject hits either a *YES* or a *NO* button to indicate whether a sensation occurred, that is, whether light was detected or not. For any given trial, the stimulus intensity will be randomly chosen by the computer from a predefined set of values. The lowest intensity value must be one that is never detected, whereas the highest value should always be detected. In this way, the threshold intensity will be located somewhere within this range (SideNote 1.3). At the end of the experiment, each intensity will have been presented an equal number of times, and a summary of the frequency of *YES* responses to each stimulus intensity will be provided by the computer.

2. ABSOLUTE THRESHOLD

Before looking at the data that such an experiment might generate, let us consider what the response profile would look like based simply on intuition. One likely possibility is shown in Figure 1.2 where the response curve looks like what is called a **step function**. All intensities below a certain point would be too weak to produce detectable sensation, and so our subject should consistently respond *NO* when asked if something is visible. However, once we reach an intensity that is sufficient to trigger sensation, the subject should then consistently respond *YES*. The transition between these two response levels can then be defined as the absolute threshold. The subject is presumed to behave like an **ideal detector** in such a scenario—that is, all subthreshold intensities fail to produce a detectable sensory event, whereas all suprathreshold ones consistently produce a positive sensation. Furthermore, the subject is absolutely perfect in being able to distinguish between these two conditions.

Humans are not ideal detectors

In reality, however, our responses are quite different. As Figure 1.3 (page 8) shows, the response curve that would emerge from an actual experiment would look more like an S-shaped function or **ogive**. Although we reliably detect very high intensities and always fail to detect very low ones, it appears that the intervening intensity levels cause some uncertainty as to whether or not a sensory event occurred. According to Figure 1.3, it is clear that as the intensity increases, there is a progressive increase in the likelihood that it will be detected. This so-called **psychometric function** provides a typical profile of how our sensory systems respond as a function of physical intensity (Falmagne, 2002). And as such, it is clear that

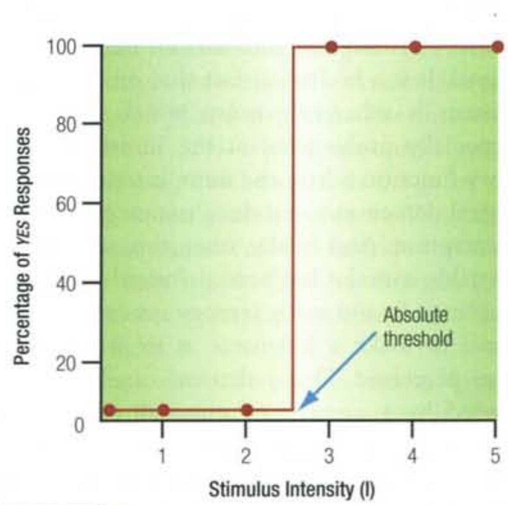
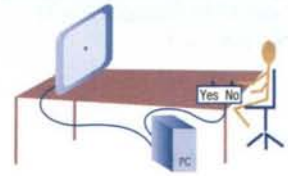


Figure 1.2

The expected response profile in an absolute threshold experiment looks like a step function. All stimulus intensities up to a certain point will fail to produce sensation, whereas all intensities beyond that point will always do so. The absolute threshold is the intensity at which this transition occurs.

SideNote 1.2

A simple psychophysics setup in which a human subject observes computer-generated stimuli on a monitor from a fixed distance. The response is indicated with the press of a button and sent to the computer, which stores this information for later analysis.



SideNote 1.3

One problem in undertaking a threshold experiment with the Method of Constant Stimuli is choosing an appropriate range of stimulus intensities. Optimally, the threshold should be somewhere in the middle of this range. Since this is the parameter being determined experimentally, it becomes difficult to construct a range around an unknown value. One way to get around this is to do a "quick and dirty" Method of Adjustment experiment, which will give an approximate value for the threshold.

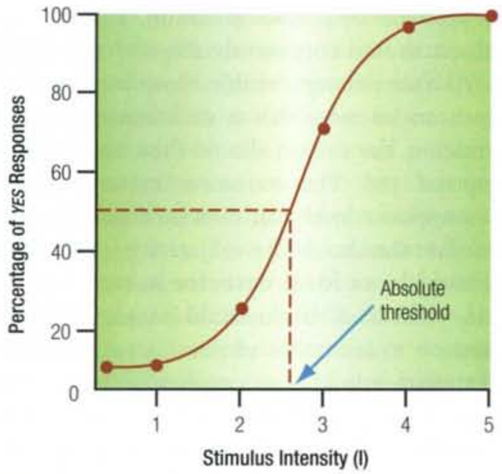


Figure 1.3

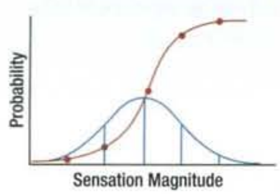
The actual response profile (psychometric function) that is obtained in an absolute threshold experiment. The absolute threshold is usually taken as the intensity at which the stimulus was detected on 50% of the trials.

SideNote 1.4

Cognitive factors can arise from noise in the decision-making process. For example, a subject may actually perceive the stimulus but opt to respond *NO* due to reduced confidence. Alternatively, a subject may not actually have perceived the stimulus but chose to respond *YES* due to eagerness. Cognitive factors are extremely important in psychophysical experiments and will be discussed later in Section C.4.

SideNote 1.5

Let us assume that the sensation produced by a stimulus has a normal probability distribution due to the effects of noise. The detection probability of a signal is given by the cumulative probabilities—that is, the area under the distribution—up to that point. The ogive psychometric function results from the cumulative probabilities determined in this manner at progressively greater values of sensation magnitude. The 0.5 (or 50%) level in the ogive corresponds to the mean of the distribution, which is why it is used to estimate the threshold.



we do not behave as ideal detectors, leading to the natural question of why this is so.

Under most circumstances, our sensory systems have to deal with several sources of uncertainty (Marks, 1974). These factors become especially critical at very low physical intensities where detection thresholds typically arise. One such source is the stimulus itself. There is usually some variability in the intensity of a stimulus simply because no physical device can provide perfect delivery at a specified intensity, especially when it is very low. This stimulus is then captured by a sensory system that adds further noise to the signal. It is a biological fact that our nervous system is inherently noisy, which becomes especially problematic at the limits of sensory function where the noise interferes with signal detection to produce instances of misperception. And finally, once this somewhat variable stimulus has been delivered and then captured by our noisy sensory system, we still have to make a judgment as to whether it was perceived. That judgment can be influenced by a number of physical, emotional, and cognitive factors (SideNote 1.4). While the magnitude of these would certainly vary among different people, these factors can also vary with time within an individual subject. Together, these different sources of variability—from stimulus to subject—make our sensory systems behave quite differently from an ideal detector.

Conventional approaches to threshold estimation

Given that we are not ideal detectors, then which intensity value do we take from Figure 1.3 to represent the absolute threshold? Because there is a gradual increment in stimulus detectability with increasing physical intensity, there actually is no well-defined point that can serve as the threshold. We therefore have to adopt an arbitrary response level that can be used to obtain the threshold (Engen, 1971). By convention, psychophysicists have used the 50% response level for that purpose (SideNote 1.5). Therefore, the physical intensity that produces this response is taken to be the absolute threshold. An experimenter can certainly use a different criterion so long as it is made clear which response level that is. For example, it is possible to use the 60% *YES* value as the definition of threshold sensation. In that case, the stimulus intensity that produces this would be taken as the absolute threshold of detection. What this means is that in reality there is no *all-or-none* condition for stimulus detection. Rather, our thresholds can fluctuate a little, and therefore the notion of a threshold now becomes defined in a more statistical manner.

Since Fechner's time, there has been much effort at determining absolute threshold values for different sensory systems under different conditions (Gescheider, 1997; Stevens, 1986). These results have shown that we are indeed extremely sensitive creatures, and under some conditions, the laws of physics often impose the limits to detection. Here are some examples of how well we do.

Touch—a dimpling of the skin by as little as 10^{-5} cm is sufficient to be detected.

Smell—under optimal conditions, the absorption of only 40 molecules by detectors in the nose is sufficient to produce a detectable smell.

Hearing—detection threshold is so small that it represents movement of the eardrum by only 10^{-10} cm. This is smaller than the diameter of a hydrogen molecule.

Vision—the eye can be exposed to as little as 54–148 photons to produce a detectable sensation of light. If losses in transmission through the eye are considered, it turns out that this represents the absorption of a single photon in about 5 to 14 detector cells of the retina.

These figures attest to the remarkable biological construction of our sensory systems.

3. DIFFERENCE THRESHOLD

As noted before, one of Fechner's central goals was to understand the relationship between the physical and mental worlds—in other words, the way in which stimuli of different physical intensities produce different amounts of sensation, or sensory magnitude. The absolute threshold gives only one point in that profile, that is, the starting point for any of the possible relationships that are shown in Figure 1.1. But this is obviously not enough to determine what the rest of the function would look like. For this, Fechner needed to have an idea of what the slope of the function was at suprathreshold levels and how that slope changed with increasing intensity (Engen, 1971; Manning & Rosenstock, 1967). If the slope remains constant, then the relationship between sensory magnitude and stimulus intensity is described by a linear function. However, if the slope is either increasing or decreasing, then the function becomes either an exponential or a logarithmic one, respectively.

A clue as to which of these possible functions correctly describes the transformation of physical to mental events came to Fechner from a series of experiments on difference thresholds that were carried out by a contemporary German physiologist named Ernst Weber. Weber had been interested in determining the gradations of sensory experience at suprathreshold levels (Weber, 1996). The question now was no longer whether or not a stimulus was perceived but rather how much it needed to change in order to produce a detectable change in sensation. The difference in physical intensity that was required to accomplish this became known as the *difference threshold*. Weber worked mainly with the discrimination of object weights, carrying out a series of careful experiments on the smallest detectable change for a series of different starting weights.

A difference threshold experiment on the visual system

Let us illustrate the principles that Weber developed using discrimination of light intensities as an example. We can set up a psychophysical experiment as before but now ask the subject to examine two stimuli—a reference light, whose intensity is always kept constant, and a target light, whose intensity is either lower or higher than that of the reference. The subject must compare the two and indicate whether the target light is *brighter* or *dimmer*. No other choices are allowed.

We can adopt Fechner's Method of Constant Stimuli again to perform this experiment. A computer will randomly choose the intensity level of the target light from a range and display that stimulus along with the fixed reference stimulus. The subject's task is to compare the two stimuli, make a decision, and hit one of two buttons to register the response. This sequence is repeated many times until a sufficient number of trials (say 50) have been accumulated for each intensity point. We can then calculate the proportion (or percentage) of trials in which the subject judged the target light to be brighter. Of course, we could just as well examine the proportion judged to be dimmer. Either way, the idea is to look at the data and see how much of a change in physical intensity was required for a detectable change in sensation. Since we gave the subject an equal number of brighter and dimmer intensities, one possibility is that all truly *dimmer* intensities were judged correctly as were all truly *brighter* intensities. In this case, the subjects theoretically behaved like an ideal detector because they never failed in distinguishing true differences in stimulus intensities.

However, similar to what we saw earlier for detection judgments, it turns out that we do not behave as ideal detectors when it comes to difference judgments either. The psychometric function in Figure 1.4 (page 10) shows a plot of percentage *brighter* responses against target light intensity. Again, as in Figure 1.3, performance data displays an ogive rather than a step function, indicating that certain intensities generated mixed responses. The intensity that produced 50% *brighter* responses (point a on the x-axis) can be taken as the point of perceptual equivalence. In other words, at this intensity our subject could not decide whether the target light was brighter or dimmer, and it was therefore perceptually equivalent to the reference light.

Our task now is to use this data to determine the difference threshold—that is, that extra bit of physical intensity that needs to be added to or subtracted from the target light intensity at this perceptual equivalence point in order for there to be a **just noticeable difference (JND)** in sensation. This amount will in turn depend on exactly what level of noticeable difference we want as our criterion. By convention, most psychophysicists use

Ernst Heinrich Weber (1795–1878)

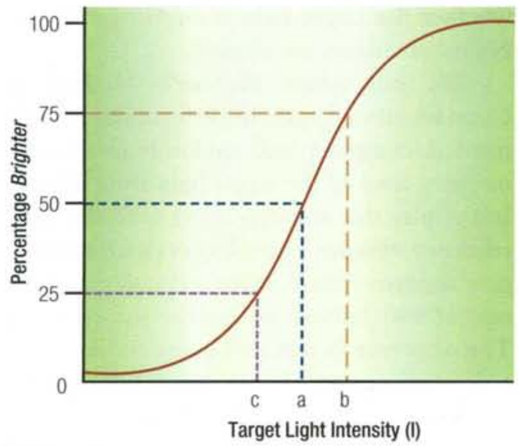


Figure 1.4

A typical psychometric function that is obtained in a difference threshold experiment where the subject has to judge two stimuli and determine whether the target was brighter or dimmer than the reference. The 25% and 75% *brighter* response levels are generally used as the points for a just noticeable difference (JND) in sensation decrement and increment, respectively.

the 75% *brighter* response level as the measure for a noticeable increment in the stimulus (Gescheider, 1997). Thus, when the target light intensity is raised to point b in Figure 1.4, we will achieve this result, and the difference between the two intensities (b *minus* a) is taken as the difference threshold (ΔI). In other words, ΔI represents the extra bit of physical intensity that we would need to add in order to make a stimulus just noticeably brighter. Exactly the same logic can be used if we want to determine the difference threshold for a reduction in sensation, except now we use the 25% *brighter* response level (which corresponds to 75% *dimmer* judgments). The target light intensity now needs to be lowered to point c, and the difference between the two intensities (a *minus* c) is also a difference threshold (ΔI). These two measures of difference threshold are usually distinguished by the terms *increment threshold* and *decrement threshold*, respectively, and are often averaged to provide a composite value.

4. WEBER'S LAW

In the last experiment, brightness comparisons were made to a reference light that was fixed at a particular intensity. What happens if we now change the reference light to a higher level and redo the experiment to find a new difference threshold? Does the difference threshold value (ΔI) still remain the same or will it become different? This was precisely the question that Weber addressed in his experiments with weights, and in so doing, he discovered a fundamental relationship that has come to bear his name (Weber, 1996).

Multiple discrimination threshold experiments

Let us return to the difference threshold experiment with lights. Figure 1.5 shows the psychometric functions that we would likely obtain if we conducted this experiment three times by setting the reference light at progressively higher intensities each time. The psychometric functions are correspondingly displaced to the right and become somewhat flatter. For each psychometric function, we can now determine the difference threshold. To keep it simple, we will restrict this analysis to just the increment threshold.

As before, we would first determine the target light intensities that are perceptually equivalent in brightness to the reference light for all three cases (a_1, a_2, a_3) and then find the intensities producing 75% *brighter* responses (b_1, b_2, b_3). Looking closely at Figure 1.5, we can see that the increment threshold for the first psychometric function (b_1 *minus* a_1) will be less than that of the second function, which in turn will be less than that of the third. In other words, the greater the intensity level at which we have to make a JND judgment, the greater the difference threshold (ΔI) needed to attain that JND. The difference threshold is therefore not constant but actually increases in a linear fashion with stimulus intensity. This is what Weber discovered, and the equation describing this relationship is known as **Weber's law**:

$$\Delta I = k \cdot I$$

Implications of Weber's law

We know from everyday experience that if a small number of items is incremented by just one, it is more likely that we will notice that difference than if the same addition is made to a much larger set. Weber noticed that if one lit candle was added to 60 others, then that addition would be sufficient to cause a JND in brightness perception. However, if there were 120 burning candles, then adding just one more was no longer sufficient to cause a detectable change in sensation. Thus, the requirement for a JND is that the incremental (or decremental) amount be scaled to the stimulus intensity.

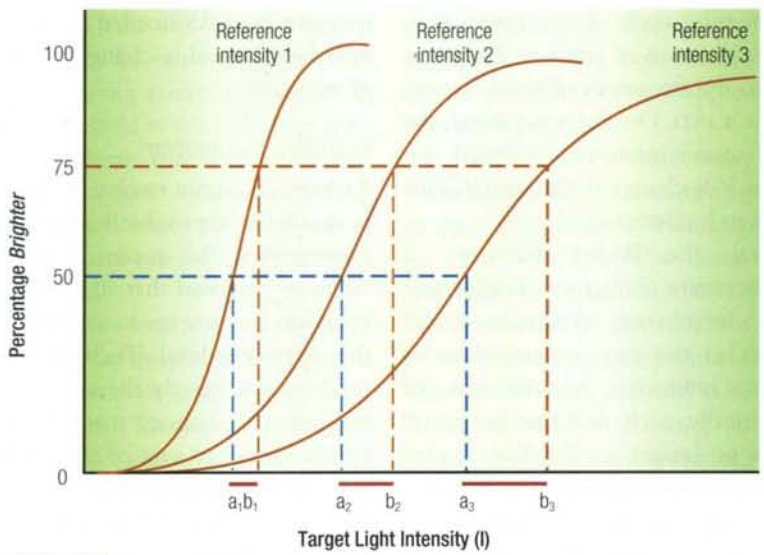


Figure 1.5

Psychometric functions from difference threshold experiments in which the reference light is set at progressively higher intensities. The lowest reference intensity (left curve) produces a small difference threshold, whereas the highest reference intensity (right curve) produces a much larger threshold. The bar lengths below the x-axis show the relative size of the difference thresholds for the three psychometric functions.

The difference threshold (ΔI) is therefore not a constant value but some proportion (k) of the stimulus intensity (I). This proportion (k) is also known as **Weber's fraction**.

Once the Weber fraction is known, the difference threshold can be easily calculated from Weber's law for any given intensity value. But what is the value of k? This must be experimentally determined. The preferred way to do so is to determine the difference threshold at a number of different intensities, as we did in the experiment above. The difference thresholds can then be plotted against the different values of intensity to reveal a straight line (SideNote 1.6). The slope of this linear function is the Weber fraction (k). For the brightness experiment we just performed, we would have found the value of k from the slope to be about 0.08. Thus, an 8% increase (or decrease) in light intensity is sufficient to produce a JND and allow us to detect that change in perceived brightness.

Weber fractions for different sensory systems

We could have conducted a similar difference threshold experiment in any of the other sensory systems, such as taste, touch, hearing, etc., to determine their respective Weber fractions. This has indeed been done by psychophysicists since Weber's time, and some of the results are shown in Table 1.1. Notice that there is no universal Weber fraction that applies to all sensory systems. Rather, there is considerable variation such that certain sensory processes are very sensitive to change, whereas others are

Table 1.1

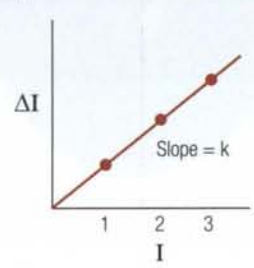
Weber Fractions for Different Sensory Systems

Sensory Dimension	Weber Fraction (k)
Touch (heaviness)	0.02
Touch (vibration)	0.04
Taste	0.2
Smell	0.07
Loudness	0.3
Pitch	0.003
Brightness	0.08

Note. Small values of k imply greater sensitivity in detecting changes of intensity. Adapted from "Psychophysics: I. Discrimination and Detection," by J. Engen, 1971, in *Woodworth & Schlossberg's Experimental Psychology*, Eds. J. W. Kling and L. A. Riggs, New York, NY: Holt, Rinehart & Winston; "On the Exponents in Stevens' Power Law and the Constant in Ekman's Law," by R. Teghtsoonian, 1971, *Psychological Review, 78*, pp. 71–80; "Differential Sensitivity for Smell," by W. S. Cain, 1977, *Science, 195*, pp. 796–798; "Psychological Dimensions and Perceptual Analysis of Taste," by D. H. McBurney, 1978, in *Handbook of Perception*, Eds. E. C. Carterette and M. P. Friedman, New York, NY: Academic Press.

SideNote 1.6

A straight line is produced if we make a plot of the difference threshold (ΔI) that was obtained at each of the three intensity (I) levels. This is the graphical form of Weber's law and has been found to hold true for all sensory systems within a broad range of intensities. The Weber fraction (k) is taken from the slope of this line.



not. Among the most acute of our sensory parameters is the detection of pitch where just a 0.3% change in the frequency of sound is sufficient to cause a JND. On the other hand, the perception of sound intensity (loudness) can require up to a 30% change in the stimulus for that difference to be detected.

In general, the Weber fractions in Table 1.1 are accurate predictors of difference thresholds for a broad range of stimulus intensities. However, at the extreme situations of very high or low intensities, the value of k can change dramatically, such that the generality of Weber's law no longer applies (Gescheider, 1984). This is true of all sensory dimensions. Although the applicability of Weber's law is limited to a certain range of intensities, it nevertheless remains one of most useful equations in perceptual psychology.

5. FECHNER'S LAW

We remarked earlier that one of Fechner's central goals was to obtain the relationship between sensory magnitude and stimulus intensity. We are now ready to complete that story. Fechner knew that to uncover the relationship between those two parameters, it was necessary to know the way in which that function changed at progressively greater suprathreshold values (Fechner & Lowrie, 2008). As we have already seen, Weber's law asserts that higher levels of suprathreshold intensity require a correspondingly greater change in intensity (ΔI) to produce a change in sensation (ΔS) that is just distinguishable (JND). But Fechner knew nothing about the actual magnitude of ΔS needed to produce a JND or whether that value changed at different levels of sensation.

Fechner's assumption

Fechner could not resolve this problem because it is simply impossible to measure sensations. Nevertheless, he made a bold assumption. Fechner proposed that all JNDs were produced by equal increments in sensation regardless of the operating level (Fechner, 1860/1966). In other words, exactly the same value of ΔS was needed at all sensory magnitudes because the JND is a standard unit of change that represents a psychological constant. Fechner was also well aware of Weber's results and the implications they had for his quest to determine the relationship that he sought. Figure 1.6 (left side) shows how Fechner's assumption can be integrated with Weber's law. As shown, higher intensity levels require a greater change in the physical stimulus (ΔI) to produce identical changes in sensation (ΔS). In all of these cases, a JND event is presumed to occur through identical changes in sensation (Fechner's assumption) that are brought about by progressively greater changes in stimulus intensity (Weber's law).

Deriving the stimulus–sensation relationship

Only one of the three possible functions that we explored in Figure 1.1, relating intensity and sensation, can account for this. Figure 1.6 (right side) shows that the stimulus–sensation relationship must necessarily follow a logarithmic function. The intensity values from the difference threshold experiment in Figure 1.5 are shown here on the x-axis. The progressively

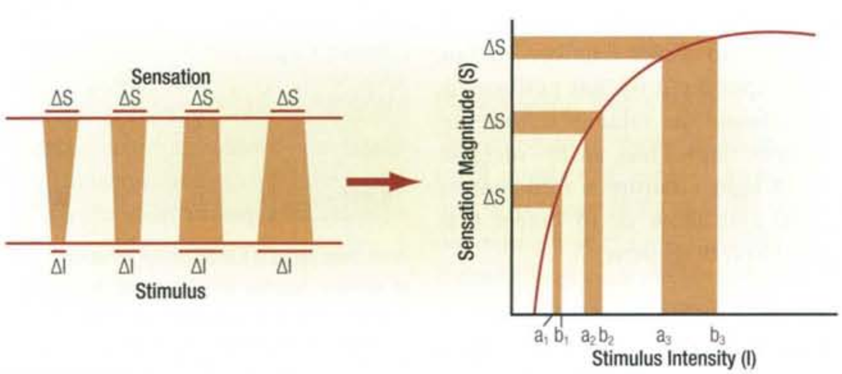


Figure 1.6

The integration of Weber's law and Fechner's assumption implies that with increasing stimulus intensities, the difference threshold (ΔI) progressively increases but continues to be mapped onto a constant change in sensation (ΔS) to produce JNDs (left). Only the logarithmic function allows this condition to hold true (right). Fechner therefore concluded that the relationship between stimulus intensity and sensation is a logarithmic function.

greater change in ΔI that was revealed in that experiment can now be related to Fechner's assumption of ΔS being constant at all levels for a JND. Fechner could reach only one conclusion—the logarithmic function is the only one that will allow for ΔI to increase according to Weber's law but still retain the same values of ΔS. Neither the linear nor exponential functions will permit this.

What we have just seen is a tour de force of experimentation and insight. In the absence of any direct means to study sensation, Fechner was still able to derive a fundamental relationship between sensation magnitude and stimulus intensity. As a tribute to his work, that relationship is now called **Fechner's law** and is formally specified as

$$S = k \cdot \log (I)$$

where the constant k is related to, but not identical to, the constant in Weber's law. Fechner's law asserts that at low intensity levels, the magnitude of our sensations can change quite rapidly with small changes in stimulus intensity, whereas we become much less sensitive at higher intensities. Indeed, at the very highest intensities, our perception of a stimulus should not change appreciably, regardless of how much intensity is added.

These results were soon generalized across the entire domain of perception such that the relationship between all physical events and conscious experience was taken to be largely logarithmic in nature. This eventually turned out to be a flawed conjecture, and indeed the logarithmic function itself later became replaced by somewhat different functions as descriptors of the stimulus–sensation relationship. Nevertheless, the psychophysicists of the 19th century continued to have a profound influence on perceptual psychology, even to this day, in both theory and practice (SideNote 1.7).

C. Modern Psychophysics

The field of psychophysics flourished during Fechner and Weber's time. On the one hand, there was the sheer elegance by which the logarithmic relationship was established, and on the other, there was the persuasive simplicity of Fechner's assumption that JNDs represent fundamental and immutable units of sensory change. Fechner's law thus became the cornerstone of perceptual psychology, and many psychophysicists simply became preoccupied with the logarithmic function as the master descriptor of mental processes. Nothing else was acceptable.

And yet, there were many opponents as well, some of who became quite influential in their criticism of Fechnerian psychophysics (SideNote 1.8). The main objection was not against the logarithmic relationship *per se* but against the very notion that sensations can be described by mathematical functions at all. One of the most scornful critics was William James, who believed that it was simply futile to put numbers on sensations (Richardson, 2007). Nothing about the empirical process, he argued, can allow any quantitative estimate of such private experiences as sensation, and therefore any psychophysical law is fundamentally meaningless. In a classic rebuke, James wrote how terrible it would be if Fechner should "saddle our Science forever with his patient whimsies, and, in a world so full of more nutritious objects of attention, compel all future students to plough through the difficulties, not only of his own works, but of the still drier ones written in his refutation."

Fechner's supporters believed that the stimulus–sensation problem had been solved, whereas his critics believed that the problem could never be solved. Both intransigent attitudes in their own way produced a general decline of interest in the measurement of sensation that lasted until the 1930s, when a Harvard psychologist named Stanley S. Stevens began his psychophysical work. Stevens boldly rejected the assertion that sensation cannot be measured. However, his approach was completely different from the German psychophysicists of the 19th century. Rather than determine psychophysical laws through indirect procedures, Stevens proposed a set of direct methods for studying sensation. And thus began the era of *modern psychophysics*—an entirely new approach that would galvanize the field and produce dramatic insights into sensory processing by the 1950s, revealing psychophysical relationships that in some cases did not even slightly resemble logarithmic functions.

1. MAGNITUDE ESTIMATION AND THE POWER LAW

Whereas Fechner believed that sensations could only be measured indirectly through difference thresholds, Stevens believed that an

SideNote 1.7

Fechner's theory relating stimulus intensity to sensory experience marked the beginning of experimental psychophysics. He is therefore widely regarded as the father of psychophysics. Fechner himself was an eccentric character. The fact that he recorded the date of his psychophysical insight (22 October 1850) has resulted in Fechner Day celebrations on this day in some psychology quarters throughout the world.

SideNote 1.8

Some of the criticisms of Fechnerian psychophysics even began to emerge from his contemporaries:

> How much stronger or weaker one sensation is than another, we are never able to say. Whether the sun is a hundred or a thousand times brighter than the moon, a cannon a hundred or a thousand times louder than a pistol, is beyond our power to estimate.
>
> Wilhelm Wundt, 1890

Stanley Smith Stevens (1906–1973)
Harvard University Archives. Call # HUP Stevens, Stanley S. (3)

exact relationship between stimulus and sensation could be directly obtained (Krueger, 1989). Stevens was instrumental in establishing a set of procedures that are collectively known as **scaling**. Rather than taking the Fechnerian approach of comparing stimuli and judging their differences, Stevens simply asked his subjects to provide a direct rating of the sensation that they experienced. This technique came to be known as **magnitude estimation**.

SideNote 1.9

A typical instruction given to a subject in a magnitude estimation method might be the following: "You will be presented with a series of stimuli in irregular order. Your task is to tell how intense they seem by assigning numbers to them. Call the first stimulus any number that seems appropriate to you. Then assign successive numbers in such a way that they reflect your subjective impression" (Stevens, 1957).

Experimental design and outcomes

The subject is first presented with a standard stimulus, which is known as the *modulus*, and told that it represents a certain value, say 10. If for example the experiment required loudness estimation, the subject would first experience the modulus and then provide a relative numerical rating for other tones of varying intensity that are randomly presented (Stevens, 1966). The numerical estimate represents the subject's judgment of the sensation triggered by that particular stimulus. In one variation of this method, first suggested to Stevens by his wife, Geraldine, subjects are not presented with a modulus to constrain their judgments. Rather, they are free to develop their own modulus and assign numbers in proportion to the sensation magnitude that they experience (SideNote 1.9).

Table **1.2**

Power Law Exponents for Different Sensory Systems

Sensory Dimension	Power Law Exponent
Touch	
Steady pressure (palm)	1.1
Vibration (250 Hz)	0.6
Temperature (cold)	1.0
Temperature (warmth)	1.6
Electric shock (fingers)	3.5
Taste	
Sweet	1.3
Salt	1.4
Bitter	0.8
Smell	
Coffee	0.55
Hearing	
Loudness	0.67
Vision	
Brightness (extended target)	0.33
Brightness (point source)	0.5
Estimated length (line)	1.0
Estimated area (square)	0.7

Note. The exponent values can be different for different aspects of sensation within a particular system. Adapted from "On the Psychophysical Law," by S. S. Stevens, 1957, *Psychological Review, 64*, pp. 153–181.

A remarkable outcome of these experiments was the consistency with which subjects produced their ratings and the similarity in the trends observed among different individuals. The actual numbers obtained were different across subjects because they were free to choose their own scale. But when the numbers were equated by taking into account subject variability, it turned out that there was considerable agreement among different people with regard to their sensory ratings for any given type of stimulus.

The magnitude estimation experiments were a direct challenge to William James' doctrine that sensations simply cannot be measured. Stevens showed that they indeed can and that the data fit very nicely into mathematical functions that were consistent with a **power law**. The general form of the power law is the following:

$$S = k \cdot I^b$$

where S is the sensation experienced by the subject, I is the physical intensity of the stimulus, k is a so-called *scaling constant* that takes into account the units used to represent the stimulus intensity, and b is the exponent (or power) value. According to this relationship, sensation is related to intensity raised to a certain power. But what is the value of that power or exponent? It turned out that there was no one general exponent value that served all of the senses. Rather, different sensory experiences are related to stimulus intensity by a particular exponent (Stevens, 1957). Table 1.2 provides some examples of power law exponents that were derived from experiments on the various senses. As this table shows, there is no uniformity in the exponent values. Furthermore, for any given sense (taste is a good example), the actual exponent value depends on the particular aspect of that sensory dimension, for example, taste sensations generated by salt, bitter, etc.

Power law exponents

Although sensation magnitude is related to stimulus intensity by the power law, the precise nature of that relationship is very much governed by the exponent. Table 1.2 shows that for some sensory dimensions, the exponent is less than 1.0, whereas for others it is greater. Figure 1.7 shows a graph of the two extreme cases from Table 1.2—brightness for extended targets (0.33) and electric shock (3.5). The brightness curve shows what is generally described as a negatively accelerating function. Brightness perception grows rapidly at first with increasing light intensity, though further increments will gradually reduce the rate at which perceived brightness increases. In a similar manner, loudness perception is related to sound intensity by a negatively accelerating function. But its exponent value of 0.67 (see Table 1.2) means that this relationship would show a somewhat steeper rise with intensity (Stevens, 1966). Nevertheless, the power law relationship for loudness perception is such that perception does not keep up with intensity. Indeed, to double loudness requires nearly a threefold increase in sound intensity, whereas for brightness it requires nearly an eightfold increase in light intensity.

The power law relationship predicts quite different perceptual increments for certain sensory parameters where the exponent is greater than 1.0. For example, as seen in Figure 1.7, the sensation of electric shock rises slowly at first but then takes off dramatically with further increases in electric current. Certain other touch parameters, along with a few taste sensations, also display a similar exponential relationship. But what about the case where the exponent value is equal to 1.0, as with the visual impression of line length? This is shown by the dashed line in Figure 1.7. In such cases, there is an exact perceptual relationship with intensity such that our mental impression changes exactly in step with changes in the stimulus.

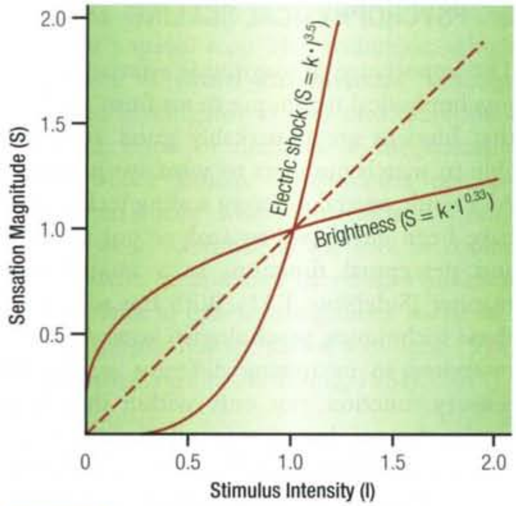


Figure 1.7

Power law functions for two extreme cases of perception. Brightness perception has an exponent value of 0.33 and appears as a negatively accelerating function. The perception of electric shock, with an exponent value of 3.5, rises dramatically with small increments of intensity.

Implications of the power law

Neuroscientists and perceptual psychologists have postulated the origins of the power function and the reasons why there can be such large differences in the exponent value. Stevens suggested that the power law reflects the operation of sensory systems at their lowest levels—that is, at the interface where the physical stimulus becomes converted into a biological signal (Stevens, 1962). According to this idea, the neural output of sensory systems must follow a power law relationship with the incoming stimulus. The exponent in this case is determined by the nature of the transformation at this site.

While there has been general support for this notion from biological experiments (SideNote 1.10), there has also been a fair amount of criticism levelled at this so-called **sensory transducer theory**. British psychologist E. Christopher Poulton suggested that psychophysical magnitude functions are not only related to low-level transformation processes but also to those at the highest levels of the mind where judgments are made on mental impressions (Poulton, 1968). According to Poulton, differences in the power law exponent may be caused by variability in a number of different experimental situations that in turn affect human judgment. Although this issue is still not completely resolved, there has been much discussion on the implications of the power law and the factors that affect the exponent value. Scaling experiments, which became an integral part of modern psychophysics, not only changed our understanding of how stimuli from the physical world map onto our inner world of perception but also introduced new ways of thinking about sensory processes.

SideNote 1.10

In one remarkable experiment by Borg, Diamant, Ström, and Zotterman in 1967, physiological recordings were made from the nerve that carries taste information to the brain in a patient having ear surgery under local anesthesia. The patient was asked to make magnitude estimations on several substances that were applied to the tongue at different concentrations. The results showed that neural signals in the taste nerve and the subjective judgments of the patient were both related to concentration (intensity) by a power function with a similar exponent.

2. PSYCHOPHYSICAL SCALING

The importance of magnitude estimation as a psychophysical technique stems from the fact that humans are remarkably good at being able to match numbers to what we perceive. As a result, several different scaling techniques have been developed to analyze our sensory and perceptual functions in a quantitative manner (SideNote 1.11). With the advent of these techniques, psychologists soon became interested in measuring different aspects of sensory function, not only within that particular domain but also in relation to other sensory dimensions (Baird & Noma, 1978). The technique of **intramodal matching**, for example, produced new insights into how sensitive a particular sensory system is to diverse kinds of stimulation. As we will see in later chapters, much of that effort was applied in vision and hearing to examine how perceived brightness was affected by different colours of lights or how perceived loudness changed for different tones.

SideNote 1.11

Psychophysical scaling procedures can be classified into three general types. In *confusion scaling*, subjects determine whether one sensation is greater or less than another. Fechner used this kind of indirect discriminative judgment in his experiments. The technique of *partition scaling* requires subjects to make direct judgments of differences in sensory magnitude by placing the stimuli into a limited number of categories. Only the *ratio scaling* procedures, such as magnitude estimation, produce measurements that can be placed on a numerical scale.

Cross-modal experiments

Stevens developed a rather unusual procedure called **cross-modality matching** where subjects were asked to compare stimuli from one sensory modality to those of another (e.g., loudness vs. brightness, electric shock vs. vibration, etc.) (Stevens, 1966). What makes this procedure unusual is that comparisons are required not within a single sensory dimension, where the task is easier, but rather with two entirely different sensory experiences, where the task is to make a judgment of equal sensory magnitude. However, it turns out that we are also quite good at these kinds of comparisons (Luce, 1990).

Figure 1.8 shows the collective results of 10 different experiments where subjects were asked to adjust sound level until it matched the perceived intensity of a stimulus from another sensory domain. The resulting *equal sensation functions* show different slopes depending upon the power function for the sensory parameter that was being compared. In fact, the actual slope of these functions turned out to be very close to the predicted slope based on the power law exponents for loudness and the particular sensory parameter to which it was being matched. Thus, electric shock (which has a large exponent value) shows a steep relationship for cross-modal matching with loudness, implying that small changes in electric current require large changes in sound setting for a judgment of equality. The opposite is true for cross-modal matches with brightness (which has a small exponent value). These results not only validated the power law but also showed the utility of psychophysical scaling procedures in comparing sensory function across different systems.

Prothetic and metathetic sensations

The sensory experiences that allow scaling such as those described above have a direct underlying relationship to the physical intensity of the stimulus. Perceptual qualities such

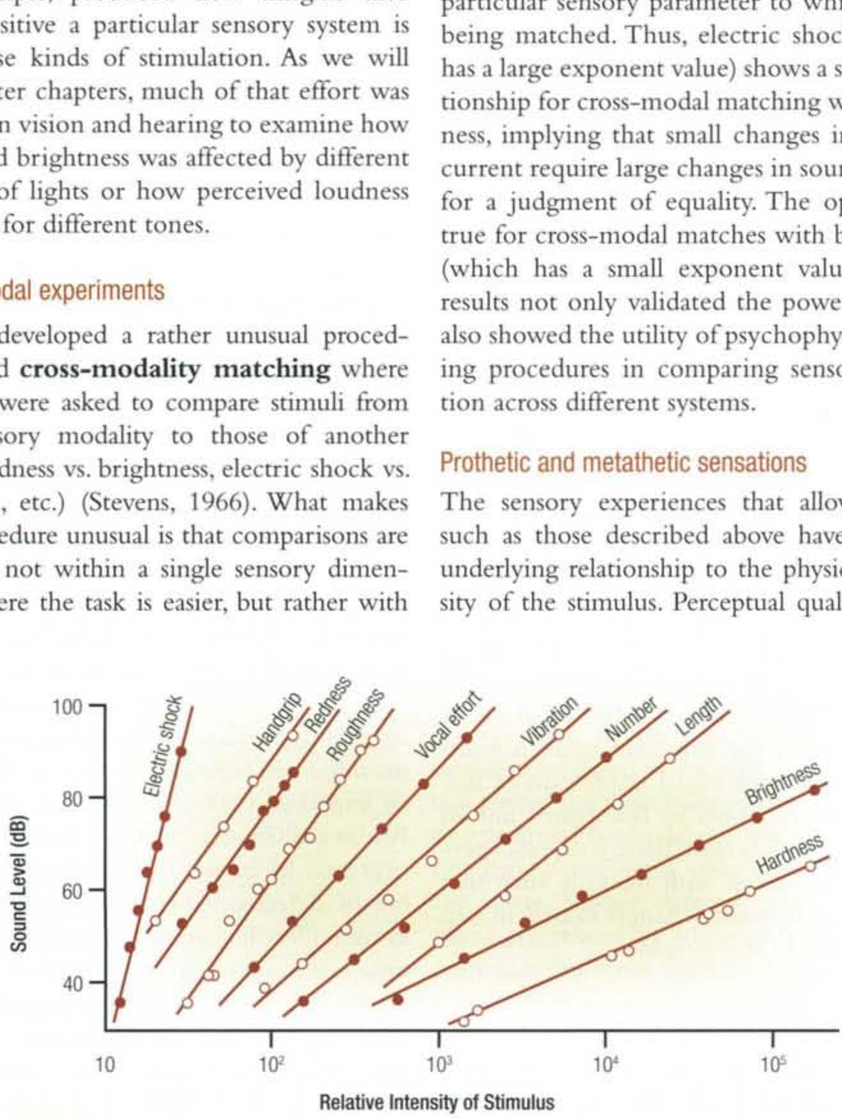


Figure 1.8

Cross-modal matching between loudness and 10 other sensory stimuli. The slope of each *equal sensation function* is determined by comparing exponent values from the power functions of loudness and the particular stimulus. Adapted from "Matching Functions between Loudness and Ten Other Continua," by S. S. Stevens, 1966, *Perception and Psychophysics, 1*, pp. 5–8.

as brightness or loudness, for example, can be associated with a numerical value of physical intensity. Sensory experiences where subjects can make a judgment of "how much" are termed **prothetic**. However, there exists a different class of sensory experience that cannot be directly linked to stimulus intensity. Colour perception is a good example, where there is no quantitative difference between, say, the hues of red or green. They produce two entirely different kinds of perception, which though linked to the wavelength of light, cannot be scaled to wavelength in a meaningful way. Increasing the wavelength of light does not add to the magnitude of the sensory experience but rather changes it entirely. Such perceptual qualities are called **metathetic**.

It turns out that prothetic processes generally obey the power law, but metathetic processes do not (Gescheider, 1997). The reason for this is likely due to the way the two kinds of sensory dimensions are processed by the brain. Prothetic perceptions are believed to rely on additive processes such that changes in stimulus intensity produce either an increase or decrease in the activity of the associated sensory neurons. The collective behaviour of this system is such that it follows the power law. Metathetic perceptions, on the other hand, show a change in quality, and this in turn is associated with the substitution of one kind of neural excitation by another. Therefore, in the absence of an additive process, there is little scope for relating metathetic experiences with the stimulus in a quantitative manner because there is no exact relationship between sensory impression and variation in the stimulus (Manning, 1979).

Multi-dimensional scaling

Psychologists have had to devise some clever techniques to analyze metathetic percepts. In general, these techniques rely on the notion of similarity or dissimilarity (Borg & Groenen, 2005). Consider colour perception as an example. Subjects can be presented with three colours at a time and asked to judge which pair is the most similar—a procedure called the *method of triads*. After enough data has been collected with a sufficient number of colours, it is possible to represent the information by way of a similarity map where those colours that are perceived to be similar occupy nearby positions, and those that are dissimilar are placed farther apart. Thus, psychological similarity is now represented by physical distance in a spatial map. This technique, which is known as **multi-dimensional scaling**, allows an investigator to peer into the underlying attributes or qualities of the stimulus that produce similar or dissimilar perceptual experiences. Multi-dimensional scaling is now well established as the tool of choice for pairwise evaluations of entities in such diverse fields as genetics, linguistics, social sciences, and psychology (Baird & Noma, 1978; Schiffman, Reynolds, & Young, 1981).

3. SCALING OF NONSENSORY VARIABLES

Our keen judgmental abilities are not just restricted to the primary senses but extend to some rather complex aspects of human perception. The general principles of intramodal and cross-modality matching may also be applied to nonsensory variables within the fields of sociology, political science, and esthetics. The same procedures that were used to scale loudness and brightness, for example, can also be applied to questions such as the value of art, the importance of certain occupations, the seriousness of crimes, etc. In other words, a set of scaling methods can be employed in what some have called *social psychophysics* to establish measures of subjective magnitude in the areas of esthetic preference or social/political opinion (Lodge, 1981).

Discrimination scaling versus ratio scaling

The original work in this area actually began with Fechner and was later refined by Louis Thurstone in the 1920s (SideNote 1.12). The basic logic of Fechner's sensory psychophysics was used by Thurstone to study social issues such as preferences for nationalities and the seriousness of crimes (SideNote 1.13). Thurstone made the assumption that dispersions in judgment represented a standard distance in subjective impression (Thurstone, 1959). His use of a nonsensory JND-like parameter produced functions that retained the same mathematical quality as those seen in classical sensory psychophysics. Both Thurstone and Fechner thus made a fundamental assumption that each increment in discrimination, measured as a JND, produces equivalent increases in subjective impression—in other words, the variability in psychological units is constant along a linear psychological continuum. This kind

SideNote 1.12

Fechner himself worked for some time on problems of esthetics and how to apply techniques from sensory psychophysics to matters of social opinion. In one experiment, he obtained esthetic judgments for two versions of Hans Holbein's *Madonna*. There was quite a bit of controversy at the time as to which had actually been painted by Holbein.

SideNote 1.13

"Instead of asking students to decide which of two weights seemed to be the heavier, it was more interesting to ask, for example, which of two nationalities they would generally prefer to associate with, or which they would prefer to have their sister marry, or which of two offenses seemed to them to be the more serious" (Thurstone, 1959).

of psychophysics became generally known as **discrimination scaling** or *confusion scaling* (Torgerson, 1958).

The alternative view that had led to psychophysical power functions was based on the notion that equal units of discrimination along the stimulus continuum did not represent equal distances but rather equal ratios along the subjective continuum. The so-called **ratio scaling** procedures that were developed as a result, including Stevens' magnitude estimation technique, soon found their way into studies of social consensus as well (Ekman & Sjöbert, 1965). Among the more colourful examples in this category are studies on the political importance of Swedish monarchs, the prestige of certain occupations, the factors contributing to social status, the esthetic value of art and music, the perceptions of national power, and the judged seriousness of certain crimes (Chang & Chiou, 2007; Ekman, 1962; Vrij, 2000).

The above examples show how ratio scaling can be used to assess nonsensory variables. In a classic study, Thorsten Sellin and Marvin E. Wolfgang showed that there is a general consensus across society on the perceived seriousness of a variety of criminal offences (Sellin & Wolfgang, 1978). Using magnitude estimation procedures, they showed that the theft of progressively greater sums of money was accompanied by growth in the judged seriousness. While this is hardly surprising, it turned out that the power function for judged seriousness grew with the amount stolen by an exponent value of only 0.17. Thus, approximately 60 times as much money needs to be stolen in order to be perceived as being twice as serious by most people. Similarly, Sellin and Wolfgang found that the judged seriousness of crime is related to jail time prescribed by the Pennsylvania Penal Code by a power function with an exponent value of 0.7. These examples illustrate how important societal issues can be addressed by psychophysical scaling techniques that were originally developed to study sensory processes.

SideNote 1.14

If Fechner had changed his view and adopted Brentano's suggestion that the JND was related to sensation level in a manner similar to Weber's law, then Fechner would actually have been the first to derive the power law function in sensory science, which is now widely accepted.

Ekman's law

As with sensory stimuli, discrimination scaling of nonsensory parameters produced logarithmic functions, whereas ratio scaling procedures consistently yielded power functions. Göesta Ekman at the University of Stockholm provided a theoretical account for this difference (Ekman & Sjöbert, 1965). Ekman proposed that detectable changes in sensation (JND), rather than being constant at all levels as proposed by Fechner, were actually related to sensation in a linear manner. In other words, the relationship between changes in sensation that are just detectable at a particular sensation level (or magnitude) is exactly analogous to Weber's law and can be stated as follows:

$$\Delta S = k \cdot S$$

This relationship was actually proposed as early as 1874 by Franz Brentano. By that time, however, the Fechnerian way of thinking so dominated perceptual psychology that Brentano's idea was largely ignored and remained without influence until Ekman restored the validity of this principle in the 1950s. As a result, the relationship is now known as **Ekman's law**.

Fechner's missed opportunity

The implications of Ekman's law are quite profound. The notion that the JND is not constant at all levels of sensation marks a dramatic departure from the Fechnerian way of thinking. If we strictly adhere to Fechner's postulate that the JND remains constant along the sensory continuum, then, as we saw earlier, logarithmic functions relating stimulus to sensation are the natural consequence, given the existence of Weber's law. If, however, Fechner had applied the idea behind Weber's law to the sensory continuum as well and adopted the view that the JND was not constant but rather a constant ratio of the sensory level, then he would have derived the psychophysical power function. In other words, if both Weber's law and Ekman's law are applied, then the mathematical outcome necessarily becomes Stevens' power law (SideNote 1.14).

But is Ekman's law valid? It has been argued that since the proportionality rule is generally true for the physical sciences and since it also applies in perceptual science by way of Weber's law, it is reasonable to assume that a similar relationship would hold true for the sensory continuum. Several empirical studies have provided support for this view. For example, Robert Teghtsoonian showed that the proportionality rule appeared to be the same for several different sensory experiences (Teghtsoonian, 1971). In other words, the value of k in Ekman's law, which was found to be 0.03, does not change with the nature of the sensory experience. This means that for all types of sensation, the size of the JND expressed in subjective units is approximately 3% of the actual sensation magnitude at any level.

4. SIGNAL DETECTION THEORY

To close this chapter, we return to the idea that the threshold represents a fundamental boundary between stimulus intensities that do not evoke sensation and those that do. We discussed earlier in Section B.2 that there is no such entity as a clear-cut, all-or-none absolute threshold. Rather, there is always some variability due to internal and external **noise** so that the threshold in turn depends on the likelihood that the **signal** exceeds this noise to produce a detectable sensory event. This means that the same stimulus may be detected on some occasions and not on others. The idea that emerged from classical psychophysics is that the threshold itself can vary over time. Modern psychophysicists have sought to identify the sources of this variability and develop new theoretical foundations that take into account nonsensory factors that can affect signal detection. As we will later discover, these developments have revised our thinking about the threshold concept itself.

A major advance in this field was made in the 1950s by Wilson P. Tanner and John A. Swets who proposed the use of statistical decision theory to understand how humans behave in a detection situation (Green & Swets, 1989). This new model, called **signal detection theory (SDT)**, uses statistical concepts that take into account cognitive factors that may influence a subject's decision-making process. Thus, there is not only a signal to be detected, which in turn relies on the inherent sensitivity of the sensory system, but also the decision by the subject as to whether a signal worthy of a positive response indeed existed.

Basic foundations of signal detection theory

In SDT, sensation magnitudes evoked by noise (N) and signal + noise (S + N) are represented as separate distributions. A major source of noise is the baseline firing of nerve cells that produces spontaneous activity in sensory pathways. Because of the random nature of this activity, a probability plot of sensation magnitudes evoked by internal noise alone will appear in the form of a normal distribution, as shown in Figure 1.9. This random fluctuation implies that sensory events triggered by noise alone will vary with time. In an absolute threshold experiment, the subject is asked to detect a weak stimulus against this random background activity. Since the stimulus must be detected by the same *noisy* nervous system, a probability plot of sensation magnitude evoked by the stimulus will also show a normal distribution because the signal must be added to the noise distribution. Because of this additivity, the combined signal + noise distribution must always lie to the right of the noise distribution alone, as shown in Figure 1.9.

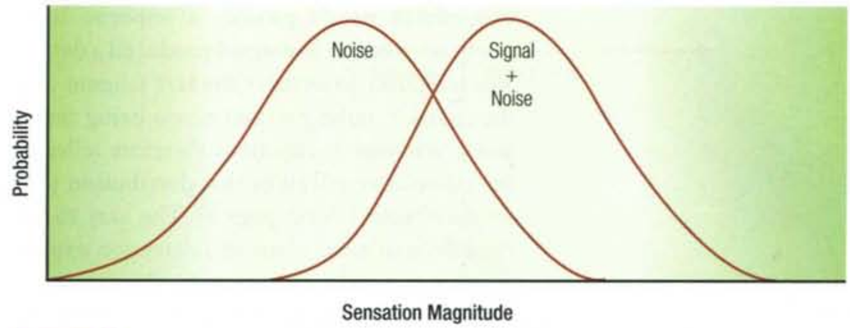


Figure 1.9

Background noise varies randomly over time and therefore appears in the form of a normal distribution. When a weak stimulus is present, the sensory magnitudes produced by it are added to noise and therefore result in a distribution that is shifted to the right.

The random variation in background noise poses an interesting problem. When the stimulus to be detected is quite weak, the two distributions will have considerable overlap, as is the case in Figure 1.9. Therefore, there may be some instances where the noise itself may be so high that it could be mistaken for the signal, whereas in others the noise may be so weak that the signal is mistaken for noise (Swets, 1996). On each trial, the subject must therefore make a decision whether the evoked sensation was due to a signal added to the noise or to the noise alone. Clearly there are two different processes at work here, and the subject must make a distinction between the effects of one versus the other. But how can we parse the effects of noise versus signal + noise at the behavioural level in a detection situation? In other words, how can we measure the relative effects of signal and noise through psychophysical methods?

Measuring the effects of signal and noise

In early psychophysics experiments, a stimulus of some intensity, however weak, was always present in each trial. The assumption was that the subject would provide a response based solely on whether the signal produced a detectable sensation. In terms of the SDT scheme, only the signal + noise parameter was being tested, and psychometric functions therefore reflected the cumulative effects of that distribution (e.g., see SideNote 1.5 on page 8). The way to test the effects of noise alone in a detection experiment is to randomly give the subject a number of trials in which no stimulus is present. All instances of a *YES* response in such trials can then be assumed to be the effects of noise alone because no signal was present. In other words, some internal process within the subject either produced a sensation that coincided with the trial and therefore led to a positive response or, alternatively, an erroneous judgment was made in the belief that a sensory event had occurred. Either way, "no stimulus" trials allow researchers to get a handle on the pervasive effects of noise, regardless of its source, in that particular detection experiment.

The possible outcomes in such a study are shown in Table 1.3. If a trial did not contain a stimulus, then the two possible responses of the subject can be categorized as follows. A *NO* response is termed as a **correct rejection** and implies that at that moment in time, the noise level was not intense enough for the subject to judge that a detectable sensory event had occurred. A *YES* response on the other hand implies just the opposite and is termed a **false alarm**. The subject indicated that a signal was present when in fact the sensation was only produced by noise. If however a signal was actually present in the trial, then the effects of signal + noise in that event may be sufficient for the subject to respond *YES*, which is termed a **hit**. The alternative possibility is that the subject responds *NO*, in which case it is termed a **miss** because the subject failed to detect the signal. Thus, there are only four possible outcomes in an SDT experiment with two being attributed to the effects of the noise component and the other two to the effects of signal + noise (Wickens, 2001).

Table **1.3**

Parameters Involved in the Design and Execution of an SDT Experiment

Signal	Distribution	Response: *NO*	Response: *YES*
Absent	Noise	Correct rejection	False alarm
Present	Signal + Noise	Miss	Hit

Note. In an SDT experiment, the subject must answer either *YES* or *NO* as to whether a detectable or discriminable stimulus was perceived in a given trial. However, the trial may or may not contain a stimulus. If the stimulus is absent, then the relative effects of noise are being assessed, and the two possible answers are termed *false alarm* and *correct rejection*. If a stimulus is present in the trial, then the effects of the signal + noise distribution are being assessed, and the two possible answers are termed *hit* and *miss*.

Criterion effects—general properties

If false alarms are the product of noise, and hits are the result of the combined effects of signal and noise, then which point along the x-axis in Figure 1.9 can these effects be attributed to? In other words, how much sensation must take place before the relative effects of noise and signal + noise yield a false alarm or a hit, respectively? One of the basic assumptions of SDT is that each subject establishes a set point or **criterion (β)** in a given detection experiment. That is, a certain value of sensory magnitude is chosen as a cut-off point that in turn governs the response. If on a particular trial the evoked sensation is greater than this value, the response will be *YES*. If it fails to reach that level, the subject will respond *NO*. The mental process that underlies either decision can in turn be triggered by noise or signal + noise. That is, on each trial the evoked sensation can be attributed to either of the two distributions, and the subject must make a judgment as to which one is correct (Green & Swets, 1966).

The way that the criterion interacts with the noise and signal + noise distributions is shown in Figure 1.10. For clarity, the two distributions are vertically offset in this figure. Let us assume that the subject has adopted a certain criterion value, as shown by the vertical line in this figure. If the sensory magnitude exceeds the criterion, then the subject will always respond *YES*. However, this decision may be either a hit (stimulus was actually present) or a false alarm (stimulus was absent). The area under the noise distribution to the right of the criterion stipulates the probability of false alarms that will be seen in this experiment from noise trials alone (SideNote 1.15). Similarly, the area under the signal + noise

SideNote **1.15**

The likelihood that a *YES* response will be determined by noise alone is given by the cumulative probabilities of all the points on the noise distribution that lie to the right of the criterion. In mathematical terms, this amounts to determining the area under this portion of the noise distribution.

distribution to the right of the criterion gives the probability of hits that will be observed in trials that contained the stimulus. As we can see in Figure 1.10, the number of hits will be far greater than false alarms in this particular situation, given the nature of the two distributions and the criterion value that was adopted by the subject.

Criterion effects—expectation

Is it possible for the subject to adopt a different criterion value? Let us consider what would happen if we conducted two experiments, one in which we told the subject that a stimulus will only be present on 30% of the trials and a second experiment in which we told the subject that the stimulus will be present on 70% of the trials. In the first experiment, the subject will not expect a stimulus on the majority of trials and therefore will likely adopt a conservative criterion. In other words, the criterion value will shift to the right of the one shown in Figure 1.10, implying that the subject will only choose to respond *YES* when the evoked sensory magnitude is quite large. In the second experiment, a more liberal criterion will be adopted, reflecting the higher probability of stimulus appearance. The criterion will now move to the left of the one shown in Figure 1.10. Compared to the first experiment, much lower sensory magnitudes will now be sufficient to elicit a *YES* response because the subject will expect more trials to contain a stimulus. Thus, depending on an inherent expectation of stimulus appearance, the subject will be either more or perhaps less inclined to give a positive answer on each trial, even though none of the other parameters in the experiment have changed.

Both situations will affect the hit and false alarm rates. As we shift the criterion more and more to the right (i.e., reduced expectation), there will be fewer instances of false alarms as well as hits. This is shown by the data in Table 1.4 where a stimulus appearance probability of 30%, and the accompanying rightward (conservative) criterion shift, results in rates of 0.09 and 0.36 for false alarms and hits, respectively (SideNote 1.16). When the subject is notified that stimulus appearance probability will be set at 70%, the accompanying leftward (liberal) criterion shift results in higher rates of false alarms and hits—0.64 and 0.91, respectively. The bottom line is that the criterion level adopted by the subject is changeable and simply defines the sensory magnitude that will be required under the circumstances for a *YES* response. For any given pair of noise and signal + noise distributions, the criterion value will in turn specify the rates of hits and false alarms (Wickens, 2001).

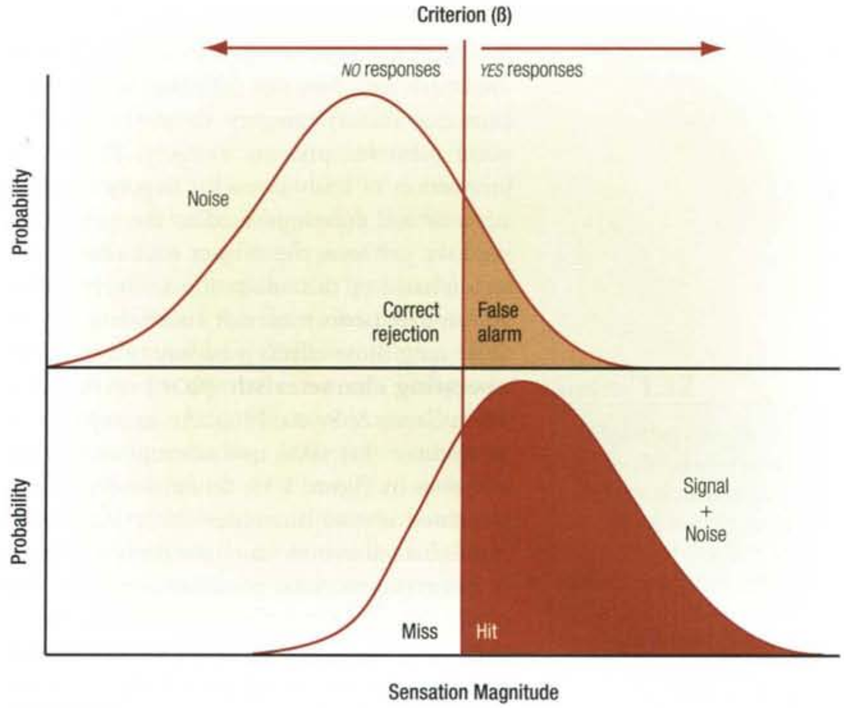


Figure 1.10

The criterion level (β) established by each subject determines the sensation magnitude that must occur for a *YES* response. The interaction of ß with the two distributions determines the relative proportion of each of the four possible outcomes in an SDT experiment. The noise and signal + noise distributions are shown at different vertical levels for clarity.

Table 1.4

The Effects of Expectation on Detection Performance in an SDT Experiment

Stimulus Likelihood	False Alarm	Hit
30%	0.09	0.36
70%	0.64	0.91

Note. If the subject is aware that the likelihood of stimulus appearance is low, she will adopt a conservative criterion that will in turn produce low hit and false alarm rates. The opposite happens if the subject has a high expectation of stimulus appearance because she will then adopt a liberal criterion.

SideNote 1.16

We need not show the rates for correct rejection since it is simply 1 *minus* the false alarm rate. Similarly, the miss rate need not be shown since it is always 1 *minus* the hit rate.

The ROC curve

In a typical detection experiment, several hundred trials are given that fall either in the noise (stimulus absent) category or in the signal + noise (stimulus present) category. The actual proportion of trials in each category is set in advance and communicated to the subject. As we have just seen, the subject establishes a criterion based on this information, which in turn will impact performance. A convenient way of illustrating those effects is by way of a **receiver operating characteristic (ROC)** curve (Egan, 1975; Green & Swets, 1966). An example of an ROC curve that takes into account our results is shown in Figure 1.11. So far, we have been interested in two outcomes—false alarms and hits—that tell us how much the noise and signal + noise distributions contribute to detection performance. An ROC curve plots the probabilities of these two factors with false alarms represented on the x-axis and hits on the y-axis. Each point on an ROC curve is therefore specified by the subject's criterion since that determines the relative values of hits and false alarms in an experiment.

The two experimental situations discussed on the previous page produced different criterion levels because of different stimulus expectations. The resulting hit and false alarm rates from Table 1.4 are shown in the ROC curve of Figure 1.11. The experiment with the higher stimulus appearance probability (70%) produced a liberal criterion, which on an ROC plot appears as a point toward the upper end of the curve. Had the stimulus appearance probability been set even higher, then this point too would have edged farther up the ROC curve in response to the adoption of an even more liberal criterion. In contrast, the experiment with the lower stimulus appearance probability (30%) produced a more conservative criterion, which on the ROC curve shows up as a point toward the lower end. If we had chosen an even lower stimulus appearance probability, then this point would have edged farther down the ROC curve. All intermediate values of stimulus appearance would have produced hit and false alarm rates that map onto the ROC curve between the two that have been outlined. The important feature of an ROC curve is that it illustrates the effects of different criterion levels in a detection experiment. As the criterion shifts from low to high, the probabilities of hits and false alarms will change and when plotted in relation to each other will produce the ROC curve.

Criterion effects—motivation

In addition to stimulus expectation, there are other factors that can affect a subject's criterion and therefore also influence the detection of weak stimuli. An especially powerful factor is motivation (Swets, 1996). Consider a situation where a subject is paid to participate in a stimulus detection experiment in which there are neither penalties for wrong answers (i.e., false alarms) nor rewards for correct ones (i.e., hits). The experimenter is entirely at the mercy of the subject, hoping that the subject will give a conscientious effort despite being guaranteed a certain amount of money for merely participating. Let us make this experiment a little more interesting. As in all SDT experiments, we give a certain number of trials that will contain a very weak stimulus (i.e., signal + noise trials) and others that will not (i.e., noise-only trials). But now we will tell the subject that payment is contingent upon performance in both sets of trials. That is, every time there is a correct response to a signal + noise trial (hit), the subject will be rewarded. However, there will be a penalty if an incorrect response is given in a noise trial (false alarm). This way we will ensure that the subject will not arbitrarily respond

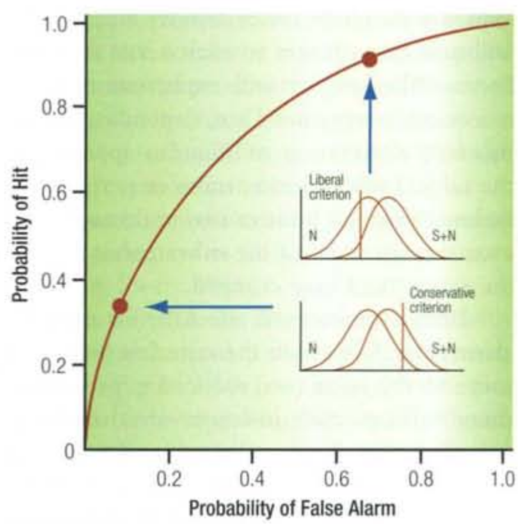


Figure 1.11

The receiver operating characteristic (ROC) curve plots the relative effects of hits vs. false alarms for a signal of fixed intensity. Changes in criterion produce hit and false alarm rates that fall on different points of the ROC curve. A liberal criterion appears toward the left end of the noise and signal + noise distributions (see inset), which in turn produces relatively high hit and false alarm rates. A conservative criterion produces the opposite result and maps onto the bottom end of the ROC curve.

YES throughout the experiment because of the false alarm penalty or similarly respond NO throughout because then rewards will not accumulate. In short, we will now have a highly motivated subject who will try very hard to distinguish the signal from noise trials (Lu & Dosher, 2008).

It turns out that the way we set up the rewards and penalties will influence the subject's criterion in the same way that we found for stimulus expectancies. Table 1.5 shows two possible payoff conditions that may be used. If the subject is told in advance that each hit will be worth 50¢ and each false alarm will incur a penalty of 10¢, then we will create a greater tendency for *YES* votes because the disparity in reward vs. penalty will assure a greater payoff in the long run. In other words, the subject will adopt a liberal criterion. If however we reverse the payment conditions and impose a penalty for false alarms that is much greater than the reward for hits, then the subject will tend to be very cautious and take fewer risks. The subject now adopts a conservative criterion. If we take the hit and false alarm rates from these two situations and plot them on an ROC curve, we will find a situation analogous to that seen in Figure 1.11. The first payoff condition will place the criterion value more toward the left side of the noise/signal + noise distributions and therefore will produce hit and false alarm rates that will plot toward the upper end of the ROC curve. The second payoff condition will produce a criterion more toward the right side of the two distributions, and this will yield a point on the lower end of the ROC curve. If we employed other payoff conditions, then the reward/penalty ratio would produce appropriate points elsewhere on the ROC curve. In effect, we find that motivational states induced by different payoff conditions produce criterion shifts that are similar to those we saw on the previous page for stimulus expectancies.

The problem with thresholds

The two factors that we have considered thus far—stimulus expectancy and motivation—have nothing to do with the signal itself (SideNote 1.17). In the experiments considered above, the signal strength was kept constant throughout, and the only parameter that changed was the nonsensory factors. And yet, we have shown that these factors can produce considerable **response bias** that in turn affects the probability of signal detection. These results call into question the very existence of thresholds that supposedly demarcate the onset of detectable sensations because clearly such boundaries are susceptible to the effects of nonsensory variables (King-Smith, 2005).

In classical psychophysics, the physical intensity of a stimulus that produced *YES* responses 50% of the time was taken as the absolute threshold of detection. Given what we now know about the hit rate being susceptible to criterion effects, the actual intensity value producing 50% *YES* responses should therefore also vary. In other words, the psychometric functions themselves should change with the subject's criterion, and therefore no single all-encompassing threshold value can be derived (SideNote 1.18). Given that detection performance relies so heavily on the effects of nonsensory factors, the very concept of an immutable absolute threshold has become meaningless.

Signal intensity and detection sensitivity

According to SDT, there is a certain inherent sensitivity that applies to the operation of sensory systems. Human performance in detection experiments is governed by that sensitivity as well as various nonsensory factors. If the detectability of sensory events is

Table 1.5

Payoff Conditions for Two Different SDT Experiments

Signal	Payment Conditions for a *YES* Response	
	Experiment 1	Experiment 2
Absent (false alarm)	−10¢	−50¢
Present (hit)	50¢	10¢
	Liberal criterion	Conservative criterion

Note. In the first experiment, hits are rewarded at a far greater level than the penalty for false alarms, leading to the adoption of a liberal criterion. In the second experiment, the penalty for false alarms is far greater than the reward for hits, leading to the adoption of a conservative criterion.

SideNote 1.17

An often-used example can serve to distinguish the relative effects of expectancy and motivation. A person who is in charge of observing a radarscope to detect enemy aircraft is highly motivated to ensure that a true signal does not go undetected because the cost for that failure is too high. Thus, we have an individual who will likely adopt a liberal criterion based on this factor alone. However, the likelihood of a signal actually appearing is quite small since enemy aircraft usually do not pop up too often. Therefore the criterion will tend to shift toward more conservative levels that will reduce the likelihood of a hit. Nevertheless, given the importance of signal detection (and the penalty for a miss), the probability for a hit is kept high and must be accompanied by a relatively high false alarm rate as well.

SideNote 1.18

Early psychophysicists were aware that biasing factors were present in their absolute and difference threshold experiments and that these factors could influence their data. One way to reduce bias was to use highly trained subjects who could be relied upon to make accurate detection judgments. Another technique was the use of so-called *catch trials*, in which no stimulus was present. The false alarm rate taken from these trials was then used to scale the data from stimulus-containing trials.

susceptible to higher-level mental functions that influence our judgments, then how is it possible to gather insight into detection sensitivity that is uncontaminated by such factors? To answer this, we have to take a closer look at the noise and the signal + noise distributions in relation to each other.

Thus far we have said very little about the stimulus itself and have vaguely referred to it as a weak signal that is added to noise and whose detectability is assessed by way of a simple "*YES–NO*" experiment. The signal + noise distribution that we have become familiar with is actually a reflection of two different parameters—signal intensity and detection sensitivity. To understand this, let us consider three different stimuli, each one being of a progressively greater intensity. The signal + noise distribution of each stimulus progressively shifts farther away from the noise distribution, which does not change because the underlying effects (e.g., random noise in the nervous system) are not disturbed. This is shown in Figure 1.12 where the separation between the two distributions is quite small in the top panel (weak stimulus) and very large in the bottom one (strong stimulus). A measure of the separation between the two distributions is taken at their peaks and is denoted as **d'** (pronounced *d-prime*) (Swets, 1996).

The three pairs of distributions in Figure 1.12 can be interpreted another way. Let us assume that the signal is now kept constant and instead three different individuals are being tested, each one having a different inherent sensitivity to the stimulus. The more sensitive a person is to this particular stimulus, the greater the sensation evoked by that stimulus. Since the signal + noise distribution is a probability plot of sensory magnitudes, a highly sensitive individual will have a distribution shifted farther to the right and away from the noise distribution, as shown in the bottom panel of Figure 1.12. In other words, the same stimulus will generate greater sensory magnitudes in a more sensitive person and therefore produce a more rightward shifted signal + noise distribution. In this context, a large d' value is taken to represent an individual with a high detection sensitivity. The less sensitive the subject is to

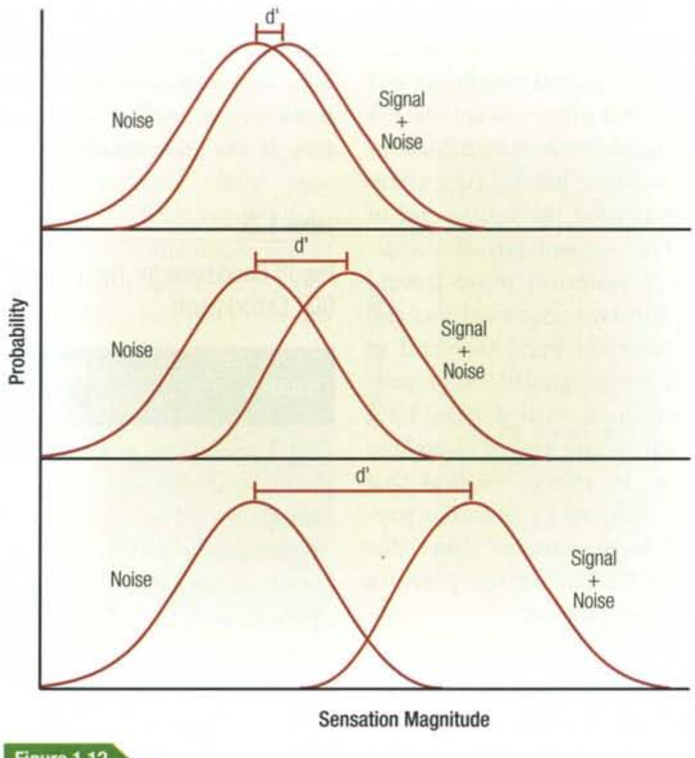


Figure 1.12

The relative positions of the noise and signal + noise distributions are determined by signal intensity and detection sensitivity. The signal + noise distribution is progressively shifted to the right and away from the noise distribution as signal strength increases. A similar effect is seen if the signal is kept constant but the detector becomes more sensitive. The relative separation of the two distributions is taken at their peaks and denoted as d'.

INVESTIGATION

Cognitive Factors That Influence Perception

We see cognitive factors at play all the time in our ability to perceive stimuli. In fact, two people can be in the same place experiencing the same stimuli yet perceive different things. For example, say you are driving with a friend and a dog runs out in the middle of the road. You as the driver are more likely to see the dog first and react accordingly. Why? (See SideNote 1.17 for some hints.)

the stimulus, the closer the two distributions will be with respect to each other, and accordingly d' will be smaller (Wickens, 2001).

Sensitivity and d'

The importance of d' is that it provides a numerical estimate of a person's sensitivity and therefore allows comparisons among different individuals. Unlike threshold values that can change with criterion levels, it has been shown that d' remains relatively robust and is unaffected by nonsensory factors. In other words, d' as a measure of sensitivity simply stipulates the relative separation of the noise and the signal + noise distributions. The different criterion levels can operate independently upon these distributions to produce different experimental outcomes of hit and false alarm rates. This idea is illustrated in Figure 1.13 where four different pairs of noise/signal + noise distributions are shown, each with a different d' value ranging from 0.5 to 3.0 (SideNote 1.19). The accompanying ROC curves show the expected detection performance if we apply a continuously variable criterion to each of these sets of distributions.

As an example, let us consider the two extreme cases. If d' = 3.0, then the large separation of noise and signal + noise distributions will ensure that the hit rate far exceeds the

SideNote 1.19

By convention, d' is expressed as standard deviation units of the noise distribution. Thus, d' values of 0.5, 1.0, 3.0, etc., represent respective factors of standard deviation (or z-score).

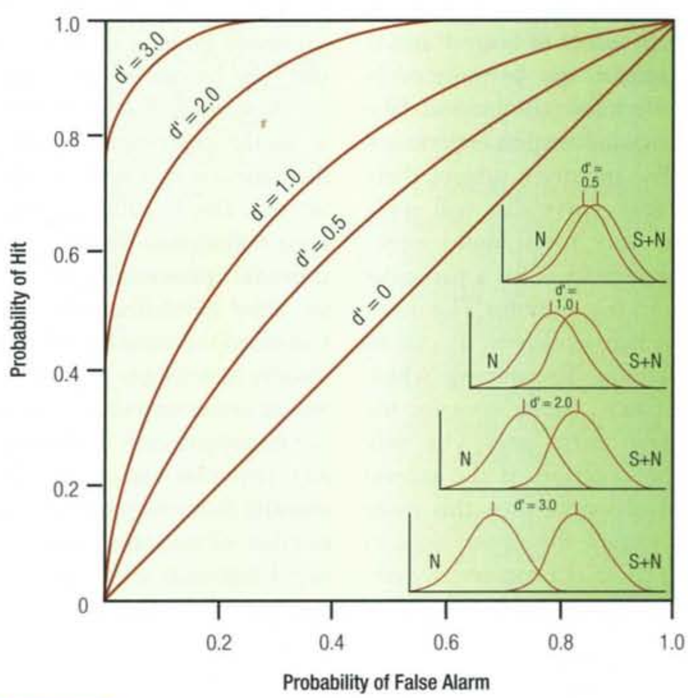


Figure 1.13

A family of ROC curves that are generated by different values of d'. The greater the sensitivity to a particular stimulus, the greater the separation of the noise and the signal + noise distributions. A large d' value produces an ROC curve that is bowed toward the upper left. As the two distributions get closer (smaller d' values), and eventually overlap, the ROC curve flattens out and becomes a straight line.

false alarm rate for moderate to liberal criterion levels (i.e., rightward criterion placement). The ROC curve will bow upward to reflect a far greater proportion of hits in comparison to false alarms. If however the two distributions are very close together (e.g., d' = 0.5), then there will be a greater similarity in hit and false alarm rates because of the closeness of the two distributions. This situation will produce a weakly bowed ROC curve. Thus, as the noise/signal + noise distributions approach each other, the ROC curves will progressively flatten out. The limit is reached when the two distributions overlap each other (i.e., d' = 0) and produce a straight line. In this case, either there is no signal or the subject is simply incapable of detecting the stimulus. In either event, detection performance will be random, and there will be equal probabilities of hits and false alarms regardless of the criterion.

Procedural aspects

SDT has become highly popular among perceptual psychologists because it provides both an estimate of the relative sensitivities of different individuals to a particular stimulus and a measure of how nonsensory factors may influence the judgments of various subjects in its detection. The purpose in any SDT experiment therefore is to obtain values of both d' and ß. Both of these parameters can be quite easily determined once we know the hit and false alarm rates from a signal detection experiment (McNicol, 2004). For any given subject, there will be only one ROC curve that will apply in that experiment since the stimulus intensity is fixed and the individual has a particular inherent sensitivity to that stimulus. The numerical descriptor of that sensitivity, d', can be obtained by graphically determining which one of a family of ROC curves contains the subject's hit and false alarm rates. The only variable now is the criterion. If the subject employed a liberal criterion, then this point would be located toward the upper right of that particular ROC curve. If a conservative criterion was employed, then this point would be toward the lower left. We can obtain a measure of the criterion used by the subject because all possible points will map onto a single ROC curve that in turn will be governed by that person's detection sensitivity.

SDT provides insight not only into the intrinsic sensitivity of the sensory system but also into the motives, expectancies, and other human psychological factors that influence the decision-making process (Macmillan & Creelman, 2004). However, there may be situations where a sensitivity measure is required without the influence of such nonsensory factors. In such cases, the use of forced choice procedures allows rapid estimation of only the sensitivity parameter. In the **two-alternative forced choice (2AFC)** procedure, two presentations are made on each trial. The subject is told that one of the presentations will contain the signal and the other will not. The task is to indicate which presentation contained the signal. The impact of criterion effects is minimized because the subject knows that one of the two presentations will definitely contain a stimulus. The only experimental outcome to consider then is the hit rate, which can fluctuate between 0.5 (random guessing) to 1.0 (perfect performance). The proportion of correct responses can then be used as a measure of sensitivity because nonsensory factors do not affect the hit rate in this situation.

A valuable feature of the 2AFC procedure is that the experimenter knows whether or not the subject is responding correctly in a particular trial. This has allowed more elaborate versions of this procedure to be developed. In the **staircase procedure**, the stimulus level can be varied in relation to the subject's responses. For example, stimulus intensity may be continually increased as long as the subject is making incorrect responses. Similarly, the intensity can be progressively decreased when only correct responses are given. This alternation in stimulus intensity is continued until a specified number of response reversals take place. The signal intensity at this point can be used as a measure of sensitivity.

Summary

1. There is a rich history of scientific research on sensory perception, beginning with the German psychophysicists of the 19th century. Their goal was to arrive at a quantitative relationship between stimulus intensities and sensation magnitudes. Knowing the quantitative relationship has several advantages, though it is difficult to obtain directly because of our inability to measure sensation. The approach taken by the German scientists was to first obtain two parameters—the starting point and the slope of the function. This information could then be used to reveal the nature of the mathematical relationship between stimulus and sensation.

2. Fechner developed several psychophysical techniques to determine the absolute threshold (which represents the starting point of the stimulus–sensation relationship) and the difference threshold (which provides insight into how the slope of the stimulus–sensation function changes at suprathreshold levels). The Method of Constant Stimuli provides the most accurate data, whereas the Method of Adjustment is the easiest to conduct and produces the fastest results. Psychophysical experiments with these techniques have shown that humans do not behave as ideal detectors but instead show a gradual progression of responsiveness when increasing some physical parameter related to the stimulus.

3. Weber was interested in the gradation of sensory experience by studying how the difference threshold itself varied with the stimulus level. He found that the difference threshold is not constant but actually increases linearly with stimulus intensity (known as *Weber's law*). To derive the stimulus–sensation relationship, Fechner made the assumption that a detectable change in sensation (ΔS) caused by the difference threshold (ΔI) remained constant at all levels of sensory magnitude. This insight, in conjunction with Weber's law, led Fechner to postulate that sensation magnitude is related to stimulus intensity by way of a logarithmic function (known as *Fechner's law*).

4. The era of modern psychophysics began with Stevens who believed that sensory magnitudes could be directly determined through quantitative methods. His technique of magnitude estimation led him to establish the *power law*, which states that sensory magnitude is related to stimulus intensity raised to an exponent value that is generally less than 1.0, though some sensory experiences (e.g., electric shock) have an exponent greater than 1.0.

5. Psychophysical techniques can be used to determine quantitative relationships within the same sensory system (intramodal matching) or across sensory systems (cross-modality matching). Whereas techniques such as magnitude estimation can be used to assess sensations that have a direct relationship to the stimulus (prothetic sensations), a different set of techniques such as *multi-dimensional scaling* must be used to assess those sensations that are entirely altered when a stimulus parameter is changed (metathetic sensations).

6. The same psychophysical principles and techniques used to understand sensory perception can also be used to assess various nonsensory questions in the domains of economics, marketing, sociology, and politics. A power law function is derived in all cases where the exponent value provides insight into the underlying relationship between the variables being probed.

7. Signal detection theory (SDT) is based on statistical concepts that examine the possible relationships between the stimulus (signal) and the underlying noise. The probability distributions of the signal and signal + noise profiles provide the basis for estimating the behaviour of individuals in terms of their criterion level, expectation, and motivation in a psychophysical setting. The way in which noise and signal + noise can affect detection performance is given by the *receiver operating characteristic* (ROC) curve. SDT experiments have shown that there is no exact threshold value for any sensory parameter but rather the threshold is something that is affected by other nonsensory parameters. Consequently, a more reliable parameter is d', which provides a more robust numerical estimate of a person's sensitivity that is unaffected by nonsensory factors.

Key Terms

absolute threshold, 6
correct rejection, 20
criterion (β), 20
cross-modality matching, 16
d' (d–prime), 24
difference threshold, 6
discrimination scaling, 18
Ekman's law, 18
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two-alternative forced choice (2AFC), 26
Weber's fraction (k), 11
Weber's law, 10

Recall Questions

1. What are the three principal advantages of obtaining a mathematical relationship between stimulus intensity and the resulting sensation magnitude?
2. What are the parameters that prevent human subjects from behaving as ideal detectors?
3. What is the difference between the *absolute threshold* and the *difference threshold*? Why did Weber have to undertake multiple experiments on the difference threshold to derive the law that bears his name?
4. What was the fundamental problem in Fechner's assumption on the constancy of the JND at all sensory magnitudes? Could Fechner have derived his law without this assumption?
5. How did modern psychophysics depart from classical psychophysics in terms of both its methodology and its core underlying principle?
6. What is the fundamental difference between a prothetic and a metathetic sensation? Provide some examples other than the ones discussed in this chapter.
7. What would Weber's law have to look like for the stimulus–sensation function to have an exponential profile?
8. How does Ekman's law differ from the assumption of JND constancy made by Fechner? Is it possible to verify Ekman's law with absolute certainty?
9. What are the key departures in the *signal detection theory* model from the concept of an all-or-none threshold? What are the different variables that can affect the threshold? What is the advantage of using d' as a measure of sensitivity?

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