Chapter 43

Psychophysical Methods

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Introduction

When Fechner (1860/1966) introduced the new transdisciplinary research program of "*Psychophysik*", his goal was to present a scientific method of studying the relations between body and mind, or, to put it more precisely, between the physical and phenomenal worlds. The key idea underlying Fechner's psychophysics was that body and mind are just different reflections of the same reality. From an external, objective viewpoint we speak of processes in the brain (i.e., of bodily processes). Considering the same processes from an internalized, subjective viewpoint, we can speak of processes of the mind. In suggesting that processes of the brain are directly reflected in processes of the mind, Fechner anticipated one of the main goals of modern neuroscience, which is to establish correlations between neuronal (objective) and perceptual (subjective) events.

The goal of this chapter is to present Fechner's techniques and those extensions and modifications of psychophysical methods that may be helpful to the modern neuroscientist with the time-honored objective of discovering the properties of mind and their relation to the brain.

Inner and Outer Psychophysics

In Fechner's time there were no physiological methods that enabled the objective recording and study of sensory or neuronal functions. Sensory physiology at that time was essentially "subjective" in that it had to rely on subjective phenomena, that is, on percepts rather than on receptor potentials or neuronal activity. Nonetheless, Fechner referred to neuronal functions in his concept of *inner psychophysics*, or the relation of sensations to the neural activity underlying them (Scheerer 1992). This he distinguished from *outer psychophysics*, which deals with the relation between sensations and the corresponding physical properties and variations of the stimulus itself (see Fig. 1).

For much of the century following Fechner's publication of *Psychophysik* in 1860, inner psychophysics remained a theoretical concept, whereas the notion of outer psychophysics provided the basis for methods to study sensory and brain processes. The study of subjective phenomena with psychophysical techniques has shaped not only the development of experimental psychology, but also of sensory physiology. Psychophysical methods were used by pioneers in the field of sensory research, such as Aubert, Exner, Helmholtz, Hering, von Kries, Mach, Purkinje and Weber, and provided the basis for

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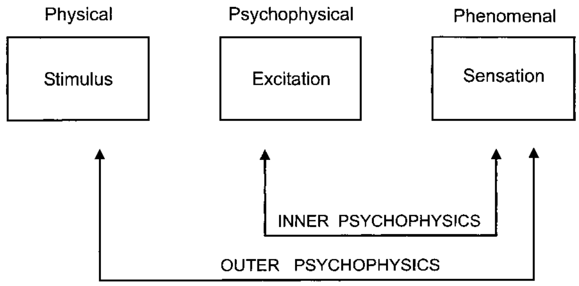

Fig. 1. Fechner's conception of psychophysics. Whereas outer psychophysics was assumed to be based on the methods of physics to describe and control the stimulus, inner psychophysics was a theoretical concept and relied on the methods of outer psychophysics to infer the rules of sensory and neuronal stimulus processing and transformation.

many fundamental insights into and understanding of sensory mechanisms. This psychophysical approach to sensory physiology has come to be referred to as *subjective sensory physiology* (see Jung 1984).

Correlational Research

With the development of various objective methods, such as electrophysiology (e.g., electroencephalography: EEG, Chapter 35 ; visually evoked potentials: VEP, Chapter 36; and single-unit recordings, Chapter 5), magnetoencephalography (MEG, Chapter 37), positron emission tomography (PET, Chapter 39) and functional magnetic resonance imaging (fMRI, Chapter 38), it has become possible to study sensory and brain processes and their locations directly. The relative ease of use and non-invasiveness of most of these techniques has made possible a new interplay between classic psychophysics and modern neuroscience (see Fig. 2). Psychophysical methods have, however, maintained their importance and are used in conjunction with the various objective methods to confirm and complement neurophysiological findings. The complementary research approach that concerns itself with subjective and objective correlates of sensory and neural processes has come to be called *correlational research* (Jung 1961a 1972). This approach, which compares psychophysical and neuronal data on a quantitative, descriptive level (neutral with respect to the question of a material or causal relationship between mental and brain processes), was first established in the study of vision by Jung and colleagues (Jung 1961b, Jung & Kornhuber 1961; Jung & Spillmann 1970; Grüsser and Grüsser-Cornehls 1973). The correlational research approach was soon followed in other sensory areas (see, e.g., Keidel and Spreng 1965; Werner and Mountcastle 1965; Ehrenberger et al. 1966; Borg et al. 1967; Hensel 1976) and has by now become an established venue of research in modern neuroscience (e.g., Spillmann and Werner 1990; Gazzaniga 1995; Spillmann and Ehrenstein 1996;).

As indicated in Fig. 2, the goals of inner psychophysics can be achieved now that the means to directly correlate phenomenal, subjective findings with objective evidence of

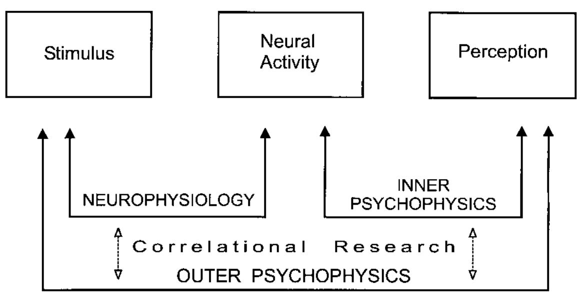

Fig. 2. Modern conception of psychophysics. Because of advanced neurophysiological methods, neural activity can be measured objectively, thus allowing for quantitative correlations between psychophysical and neural correlates of perception

sensory and neuronal activity are available. Thus, Fechner's conception of inner psychophysics is no longer dependent on the methodology of outer psychophysics alone. With further progress in correlational research, greater steps in inferring subjective events and perceptual performance by objective techniques are sure to come. For example, perceptual performance losses due to a brain lesion of a given size and location can be examined in great detail with psychophysical tasks. Moreover, in the context of the immensely increased knowledge of sensory and brain functions, inner psychophysics can be addressed much more specifically by choosing stimuli to selectively tap a given mechanism at a certain location. In turn, the hypothesized perceptual (behavioral) significance of a given mechanism or brain area can be determined by means of psychophysical testing (e.g., Wist et al. 1998).

How to Measure Perceptual Experience

Psychophysics starts out with a seeming paradox: It requires the objectification of subjective experience. No apparatus is necessary to obtain percepts; they are immediately present and available to each of us. Thus, the problem is not how to obtain perceptual experience, but how to describe and investigate individual percepts so that they can be communicated and shared by others.

Psychophysics tries to solve this problem by closely linking perceptual experience to physical stimuli. The basic principle is to use the physical stimuli as a reference system. Stimulus characteristics are carefully and systematically manipulated and observers are asked to report their perception of the stimuli. The art of psychophysics is to formulate a question that is precise and simple enough to obtain a convincing answer. An investigation might begin with a simple question such as, "Can you hear the tone?" That is, the task may be one of *detection*.

Sometimes we are not only interested in whether detection has occurred, but in determining which characteristics of the stimulus the observer can identify, e.g., sound characteristics or spatial location. Thus, the problem of sensing something, that of detection, may be followed by that of *identification*.

Detection and identification problems are solved quickly and almost simultaneously when they concern stimuli which are strong and clear. However, under conditions of weak and noisy signals we often experience a stage at which we first detect only that something is there, but fail to identify exactly what or where it is. In such a situation we try to filter out the consistent signal attributes, for instance, the sound of an approaching car, from inconsistent background noise. In such a case, the task is one of *discrimination* of the stimulus, or signal, from a noisy background, and the task is performed under uncertainty. As the car approaches and its sound becomes stronger, the probability of correct discrimination between signal and noise is enhanced. Even if we clearly perceive and identify an object, we may still be faced with the further problem of perceptual judgment, such as, "Is this car dangerously close?" or "Is the rattle under the hood louder than normal?" Questions such as these, concerning "How much x is there?", are part of another fundamental perceptual problem, that of *scaling*, or interpreting, the magnitude of the stimulus on a psychophysical scale.

Outline

In the following sections we will describe the principles of psychophysical methods and give three examples to illustrate their application. First, we present methods that are based on *threshold psychophysics*, starting with the classical procedures along with modern modifications of the classical procedures that allow for adaptive testing. Techniques for control of observer criteria and strategies are also discussed. Second, we describe the methods of *suprathreshold psychophysics*, including the use of reaction time, category scaling, magnitude estimation and cross-modality matching. A third section deals with *comparative psychophysics*, that is, with the special conditions and methods of psychophysical testing in animals.

The description of methods is followed by three specific *examples of psychophysical research*. These examples illustrate how to: (1) study basic mechanisms of adaptation in auditory motion perception, (2) assess impairment of visual function in neurological patients, and (3) measure perceptive fields in monkey and man.

Methods and Procedures

In the following, we will describe the psychophysical tasks and methods that have proven to be most useful in sensory research. Most of the principles are classic, with some having already been worked out by Fechner. The methods of stimulus presentation, response recording and data analysis, however, have been modernized, especially with regard to currently available computer-assisted procedures (see also Chapter 45).

Methods Based on Threshold Measurements

The most basic function of any sensory system is to detect energy or changes of energy in the environment. This energy can consist of chemical (as in taste or smell), electromagnetic (in vision), mechanical (in audition, proprioception and touch) or thermal stimulation. In order to be noticed, the stimulus has to contain a certain level of energy. This minimal or liminal amount of energy is called the *absolute threshold,* and is the stimulus intensity that, according to Fechner, "lifts its sensation over the threshold of consciousness." The absolute threshold is thus the intensity that an observer can just barely detect. Another threshold, known as the *difference threshold,* is based on stimulus intensities above the absolute threshold. It refers to the minimum intensity by which a variable *comparison* stimulus must deviate from a constant *standard* stimulus to produce a noticeable perceptual difference.

Method of Adjustment

The simplest and quickest way to determine absolute and difference thresholds is to let a subject adjust the stimulus intensity until it is just noticed or until it becomes just unnoticeable (in the case of measurements of the absolute threshold) or appears to be just noticeably different from, or to just match, some other standard stimulus (to measure a difference threshold). The observer is typically provided with a control of some sort that can be used to adjust the intensity, say of a sound, until it just becomes audible (or louder than a standard sound), and then the stimulus intensity is recorded to provide an estimate of the observer's threshold. Alternatively, the observer can adjust the sound from clearly audible to just barely inaudible (or to match the standard sound), providing another estimate of the threshold. Typically, the two kinds of measurement, that is, series in which the signal strength is increased (ascending series) and series of decreasing signal strengths (descending series) are alternated several times and the results are averaged to obtain the threshold estimate. For example, if a 500-Hz tone is first *heard* at 5 dB on one ascending trial and at 5.5 dB on another, and the tone is first *not* heard at 4 dB on one descending trial and at 4.5 dB on another, the resulting threshold estimate is 4.75 dB.

The following methods of threshold determination differ from the adjustment method in that they do not allow the observer to control the stimulus intensity directly. As they rely on the experimenter's rather than on the subject's control, they provide a more standardized method of measurement.

Method of Limits

In the method of limits, a single stimulus, say a single light, is changed in intensity in successive, discrete steps and the observer's response to each stimulus presentation is recorded. As in the previous method, the stimulus should initially be too weak to be detected, so that the answer is "not seen"; intensity is then increased in steps until the stimulus becomes visible (ascending series), or it is changed from a clearly visible intensity until it becomes invisible (descending series). The average of the intensity of the last "seen" and the first "not seen" stimuli in the ascending trials, or vice versa in the descending trials, is recorded as an estimate of the absolute threshold (for an example, see Table 1). Ascending and descending series often yield slight but systematic differences in thresholds. Therefore, the two types of series are usually used in alternation and the results are averaged to obtain the threshold estimate.

The determination of the difference threshold requires stimuli, such as two flashes of light, which may be presented simultaneously, one next to the other, or successively, one after the other. While the intensity of the standard stimulus is kept constant, the intensity of the comparison stimulus is changed in a series of steps. The comparison stimulus is either initially weaker (ascending series) or initially stronger (descending series) than the standard. A series terminates when the observer's response changes from "weaker" to "stronger" or vice versa. The difference threshold is then the intensity difference between the stimuli of the first trial on which the response differs from the previous one. As before, ascending and descending series are alternated and the results averaged to obtain the threshold estimate.

Method of Constant Stimuli

In the method of constant stimuli the experimenter chooses a number of stimulus values (usually from five to nine) which, on the basis of previous exploration (e.g., using the Method of Adjustment) are likely to encompass the threshold value. This fixed set of

Table 1. Method of Limits. Determination of Absolute Threshold.
Response (Stimulus Perceived): yes (Y), no (N).

Stimulus Intensity	Alternating Ascending and Descending Series					
0	N		N		N	
1	N		N		N	
2	N		N	N	N	
3	N	N	N	Y	N	N
4	N	Y	N	Y	N	Y
5	N	Y	Y	Y	Y	Y
6	Y	Y		Y		Y
7		Y		Y		Y
Transition Points	5.5	3.5	4.5	2.5	4.5	3.5

Threshold = Average Transition Points = (5.5.+3.5+4.5+2.5+4.5+3.5)/6 = 24/6 = 4

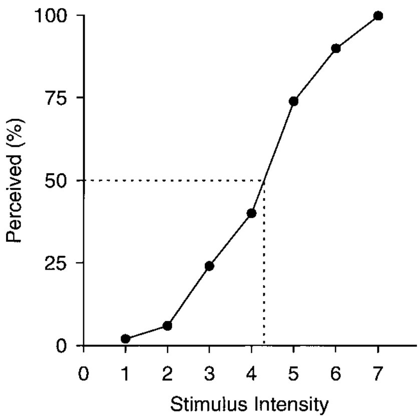

Fig. 3. Psychometric function which shows the relationship between the percentage of times that a stimulus is perceived and the corresponding stimulus intensity. The threshold is defined as the intensity at which the stimulus is detected 50 percent of the time.

Table 2. Method of Constant Stimuli (50 Presentations for each Stimulus Intensity)

Stimulus Intensity (arbitrary units)	1	2	3	4	5	6	7
Frequency of Perceived Stimuli	1	3	12	20	37	45	50
Percentage of Perceived Stimuli	2	6	24	40	74	90	100

stimuli is presented multiple times in a quasi-random order that ensures each will occur equally often. After each stimulus presentation, the observer reports whether or not the stimulus was detected (for the absolute threshold) or whether its intensity was stronger or weaker than that of a standard (for computing a difference threshold). Once each stimulus intensity has been presented multiple times (usually not less than 20), the proportion of "detected" and "not detected" (or, "stronger" and "weaker") responses is calculated for each stimulus level (for an example, see Table 2). The data are then plotted with stimulus intensity along the abscissa and percentage of perceived stimuli along the ordinate. The resulting graph represents the so-called *psychometric function* (see Fig. 3).

If there were a fixed threshold for detection, the psychometric function should show an abrupt transition from "not perceived" to "perceived." However, psychometric functions seldom conform to this all-or-none rule. What we usually obtain is a sigmoid (S-shaped) curve that reflects that lower stimulus intensities are detected occasionally and higher values more often, with intensities in the intermediate region being detected on some trials but not on others. There are various reasons why the psychometric function obeys an S-shaped rather than a sharp step function. A major source of variability are the continual fluctuations in sensitivity that are present in any biological sensory system (due to spontaneous activity or internal noise). Those inherent fluctuations mean that an observer must detect activity elicited by external stimulation against a background level of activity.

In any case, the threshold thus occurs with a certain *probability* and its intensity value must be defined statistically. By convention, the absolute threshold measured with the method of constant stimuli is defined as the intensity value that elicits "perceived" responses on 50% of the trials. Notice that in the example shown in Table 2 and Fig. 3, no stimulus level was detected on exactly 50% of the trials. However, level 4 was detected 40% of the time and level 5, 74% of the time. Consequently, the threshold value of 50% lies between these two points. If we assume that the percentage of trials in which the stimulus is detected increases linearly between these intensities (which is justified given that sigmoid functions are approximately linear in the middle range), we can determine the threshold intensity by linear interpolation as follows:

$$T = a + (b - a) \cdot \frac{50 - p_a}{p_b - p_a}$$

where T is the threshold, a and b are the intensity levels of the stimuli that bracket 50% detection (with a being the lower intensity stimulus), and p_a and p_b the respective percentages of detection. For the present case we obtain the following result:

$$T = 4 + (5 - 4) \cdot \frac{50 - 40}{74 - 40} = 4 + \frac{10}{34} = 4.29$$

Although the method of constant stimuli is assumed to provide the most reliable threshold estimates, its major drawback is that it is rather time-consuming and requires a patient, attentive observer because of the many trials required.

Adaptive Testing

Adaptive testing procedures are used to keep the test stimuli close to the threshold by adapting the sequence of stimulus presentations according to the observer's response. Since a smaller range of stimuli need be presented, adaptive methods are relatively efficient. An example of such an adaptive procedure is the *staircase method* first introduced by von Békésy (1947), who applied it to audiometry.

Staircase Method

The staircase method is a modification of the Method of Limits. A typical application of this method is shown in Fig. 4, where the stimulus series starts with a descending set of stimuli. Each time the observer says "yes" (I can detect the stimulus), the stimulus intensity is decreased by one step. This continues until the stimulus becomes too weak to be detected. At this point we do not, as in the method of limits, end the series, but rather reverse its direction by increasing the stimulus intensity by one step. This procedure continues with increasing the intensity if the observer's response is "no" and decreasing the intensity if it is "yes." In this way, the stimulus intensity flips back and forth around the threshold value. Usually six to nine such reversals in intensity are taken to estimate the threshold, which is defined as the average of all the stimulus intensities at which the observer's responses changed, i.e., the transition points as defined in the Methods of Limits (see Table 1).

In the staircase method, most of the stimulus values are concentrated in the threshold region, making it a more efficient method than the method of limits. A problem with this *simple staircase* procedure is that an observer may easily become aware of the

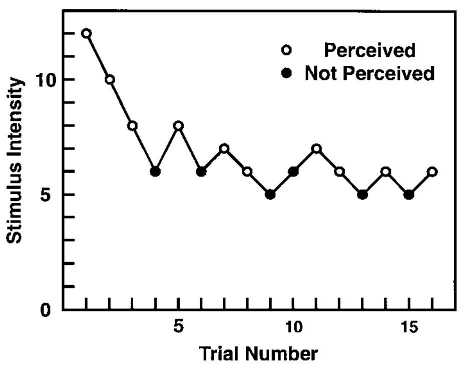

Fig. 4. Adaptive testing technique using a single staircase procedure. This example shows a descending staircase for which stimulus intensity is decreased when the stimulus is perceived and increased when it is not perceived.