Introduction

Welcome to Our World

YOU'VE TAKEN THE PLUNGE TO READ AT LEAST PART OF A TEXTBOOK on "sensation and perception." You may be majoring in psychology or studying an allied field, such as neuroscience or biology, or you may be simply curious. No matter what interests you most, your understanding will be informed by sensation and perception.

This first chapter provides an introduction to the sorts of questions that captivate the authors of this book and the sorts of methods that researchers have developed to answer those questions. These are only examples and we could have picked many others. The rest of the book will introduce you to a panorama of questions that have occupied and continue to occupy the attention of thousands of scientists.

Sensation and Perception

What does your smartphone feel as you run your finger down its touch screen (**Figure 1.1**)? What does it hear as you whisper into its receiver? We assume that these are silly questions, though it would not be silly to ask about the lightest touch that the screen could sense or the faintest vibration in the air that the microphone could sense. What does your cat feel as you run your finger down its back? That seems a more reasonable question, though you have no access to the private experience of the cat. You don't even have access to the private sensations of a person whose back you might stroke. Your own sensory experience is directly accessible only to you.

This book is titled *Sensation & Perception*. The ability to detect the pressure of a finger and, perhaps, to turn that detection into a private experience is an example of **sensation**. **Perception** can be thought of as the act of giving meaning and/or purpose to those detected sensations. How do you *understand* the finger that runs down your back? Is it a gesture of affection? Is it an officer at an airport security checkpoint looking for weapons? This book will trace the path from stimuli in the world, through your sense organs, to the understanding of the world that you perceive.

Everything we feel, think, and do depends on sensations and perceptions. For this reason, philosophers have thought, talked, and written about the topic in profound and systematic ways for over two millennia. (See **Web Essay 1.1: Senses of Reality through the Ages**.) The idea that sensation and perception are central to mental life has deep roots. The eighteenth-century French philosopher Étienne Bonnot de Condillac (1715–1780) (**Figure 1.2**) famously asked his readers to imagine the mental life of a statue with no senses, and he concluded that the statue would have no mental life. Then Condillac imagined opening the statue's nose and giving it a whiff of the scent of a rose. Then, he

sensation The ability to detect a stimulus and, perhaps, to turn that detection into a private experience.

perception The act of giving meaning to a detected sensation.

FIGURE 1.1 Would it make sense to ask what a cell phone feels when you stroke its screen?

thought, the entire mental life of the statue would consist of that smell. With more senses and more experience, Condillac imagined, a real mental life would develop. If our mental life relies on information from our senses, then it follows that the place for the study of the senses is within the science of human behavior and human mental life—that is, within psychology. Of course, this placement is not absolute. Researchers studying topics in sensation and perception can be found in biology, computer science, medicine, neuroscience, and many other fields. Critically, however, we approach the study of sensation and perception as a scientific pursuit. As such, it needs scientific methods. That's why the next sections of this chapter are devoted to the variety of methods used in the study of the senses.

METHOD 1: THRESHOLDS What is the faintest sound you can hear? How would you know? What is the loudest sound you can hear? This last question is not as stupid as it may sound, though it could be rephrased like this: What is the loudest sound you can hear *safely*? If you listened to sounds above that limit, perhaps by blasting your music too enthusiastically, you would change the answer to the first question. You would damage your auditory system. Then you would be unable to hear the faintest sound that you used to be able to hear. Your threshold would have changed (for the worse) How would you measure that? As we'll learn in this chapter, a variety of methods are available for measuring sensory thresholds of this sort.

qualia (sing. *quale*) In philosophy, private conscious experiences of sensation or perception.

METHOD 2: SCALING—MEASURING PRIVATE EXPERIENCE When you say that you "hear" or "taste" something, are those experiences—what the philosophers call **qualia** (singular *quale*)—the same as the experiences of the person you're talking to? We can't really answer the question of whether your qualitative experience of "red" is like my qualitative experience of "green" or, for that matter, "middle C." We still have no direct way to experience someone else's experiences. However, we can demonstrate that different people do, in some cases, inhabit different sensory worlds. Our discussion in this chapter will show how scaling methods can be used to perform this act of mind reading. Further discussion of qualia can be found in Chapter 5.

METHOD 3: SIGNAL DETECTION THEORY—MEASURING DIFFICULT DECISIONS A radiologist looks at a mammogram, the X-ray test used to screen for breast cancer. There's something on the X-ray that might be a sign of cancer, but it is not perfectly clear. What should the radiologist do? Suppose she decides to call it benign, not cancerous, and suppose she is wrong. Her patient might die. Suppose she decides to treat it as a sign of malignancy. Her patient will need more tests, perhaps involving surgery. The patient and her family will be terribly worried. If the radiologist is wrong and the spot on the mammogram is, in fact, benign, the consequences may be less dire than those of missing a cancer, but there will be consequences. This is a perceptual decision, made by an expert, that has real consequences. Our discussion of signal detection theory will show how decisions of this sort can be studied scientifically.

FIGURE 1.2 Étienne Bonnot de Condillac imagined how a statue could develop a mental life.

METHOD 4: SENSORY NEUROSCIENCE Grilled peppers appear on your table as an appetizer. They have an appealing, smoky smell. When you bite into one, it has a complex flavor that includes some of that smokiness. Fairly quickly you also experience a burning sensation. There is no actual change in the temperature in your mouth, and your tongue is no warmer than it was, but the "burn" is unmistakable. How does the pepper fool your nervous system into thinking that your tongue is on fire? This chapter's exploration of sensory neuroscience will introduce the ways in which sensory receptors and nerves undergird your perceptual experience.

METHOD 5: NEUROIMAGING—AN IMAGE OF THE MIND Suppose you arrange to view completely different images with each of your two eyes. We might present a picture of a house to one eye and a face to the other (Tong et al., 1998). The result would be an interesting effect known as "binocular rivalry" (see Chapter 6). The two images would compete to dominate your perception: sometimes you would see a house, and sometimes you would see a face. You would not see the two together. One reason binocular rivalry is interesting is that it represents a dissociation of the stimuli, presented to the eyes, and your private perceptual experience. Even if we cannot share the experience, modern brain-imaging techniques enable us to see traces of that experience as it takes place in the brain. Methods of neuroimaging will be our final topic in this chapter.

Thresholds and the Dawn of Psychophysics

The study of the senses was always a mix of experimental science and philosophy. It is very interesting to look for precursors of the modern, scientific study of sensation and perception. We will start with the very interesting and versatile nineteenth-century German scientist-philosopher **Gustav Fechner** (1801–1887) (**Figure 1.3**). Fechner is sometimes considered to be the true founder of experimental psychology (Boring, 1950), even if that title is usually given to **Wilhelm Wundt** (1832–1920), who began his work sometime later.

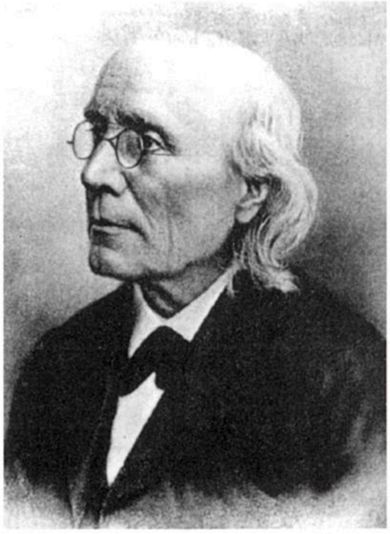

FIGURE 1.3 Gustav Fechner invented psychophysics and is thought by some to be the true founder of experimental psychology. Fechner is best known for his pioneering work relating changes in the physical world to changes in our psychological experiences.

Before making his first contributions to psychology, Fechner had an eventful personal history. Young Fechner earned his degree in medicine, but his interests turned from biological science to physics and mathematics. Though this might seem an unlikely way to get to psychology, events proved otherwise. Fechner was a very hardworking young scientist. He worked himself to exhaustion. In addition to being overworked, he suffered severe eye damage from gazing too much at the sun while performing vision experiments (a not uncommon problem for curious vision researchers in the days before reliable, bright, artificial light sources). As a consequence, Fechner fell into deep depression. Not only did he resign from his position at the university, he also withdrew from almost all his friends and colleagues. For 3 years he spent almost all of his time alone with his thoughts.

Then Fechner experienced what he believed to be a miracle when his vision began to recover quickly. His spiritual convictions deepened, and he became absorbed with the relationship between mind and matter. This pursuit placed him in the middle of a classic philosophical debate between adherents of **dualism** and **materialism**. Dualists hold that the mind has an existence separate from the material world of the body. Materialists hold that the mind is not separate. A modern materialist position, probably the majority view in scientific psychology, is that the mind is what the brain does. Fechner proposed to effectively split the difference by imagining that the mind, or consciousness, is present in all of nature. This **panpsychism**—the idea that the mind exists as a property of all matter—extended not only to animals, but to inanimate things as well. Fechner described his philosophy of panpsychism in a provocative book entitled *Nanna, or Concerning the Mental Life of Plants*. This title alone gives a pretty good idea of what Fechner had in mind.

Inspired by what we might consider to be somewhat unconventional ideas, Fechner took on the job of explaining the relation between the spiritual and material worlds: mind and body. From his experience as a physicist, Fechner

dualism The idea that the mind has an existence separate from the material world of the body.

materialism The idea that the only thing that exists is matter, and that all things, including the mind and consciousness, are the results of interaction between bits of matter.

panpsychism The idea that the mind exists as a property of all matter—that is, that all matter has consciousness.

FIGURE 1.4 Ernst Weber discovered that the smallest detectable change in a stimulus, such as the weight of an object, is a constant proportion of the stimulus level. This relationship later became known as "Weber's law."

thought it should be possible to describe the relation between mind and body using mathematics. His goal was to formally describe the relationship between sensation (mind) and the energy (matter) that gave rise to that sensation. He called both his methods and his theory **psychophysics** (*psycho* for mind, and *physics* for matter).

In his effort, Fechner was inspired by the findings of one of his Leipzig colleagues, **Ernst Weber** (1795–1878) (Figure 1.4), an anatomist and physiologist who was interested in touch. Weber tested the accuracy of our sense of touch by using a device much like the compass one might use when learning geometry. He used this device to measure the smallest distance between two points that was required for a person to feel touch on two points instead of one. Later, Fechner would call the distance between the points the **two-point touch threshold**. We will discuss two-point touch thresholds, and touch in general, in Chapter 13.

For Fechner, Weber's most important findings involved judgments of lifted weights. Weber would ask people to lift one standard weight (a weight that stayed the same over a series of experimental trials) and one comparison weight that differed from the standard. Weber increased the comparison weight in incremental amounts over the series of trials. He found that the ability of a subject to detect the difference between the standard and comparison weights depended greatly on the weight of the standard. When the standard was relatively light, people were much better at detecting a small difference when they lifted a comparison weight. When the standard was heavier, people needed a bigger difference before they could detect a change. He called the difference required for detecting a change in weight the **just noticeable difference**, or **JND**. Another term for JND, the smallest change in a stimulus that can be detected, is the **difference threshold**.

Weber noticed that JNDs changed in a systematic way. The smallest change in weight that could be detected was always close to one-fortieth of the standard weight. Thus, a 1-gram change could be detected when the standard weighed 40 grams, but a 10-gram change was required when the standard weighed 400 grams. Weber went on to test JNDs for a few other kinds of stimuli, such as the lengths of two lines, for which the detectable change ratio was 1:100. For virtually every measure—whether brightness, pitch, or time—a constant ratio between the change and what was being changed could describe the threshold of detectable change quite well. This ratio rule holds true except when intensities, size, and so on are very small or very large, nearing the minimum and maximum of our senses. In recognition of Weber's discovery, Fechner called these ratios **Weber fractions**. He also gave Weber's observation a mathematical formula. Fechner named the general rule—that the size of the detectable difference (ΔI) is a constant proportion (K) of the level of the stimulus (I)—**Weber's law**.

In Weber's observations, Fechner found what he was looking for: a way to describe the relationship between mind and matter. Fechner assumed that the smallest detectable change in a stimulus (ΔI) could be considered a unit of the mind because this is the smallest bit of change that is perceived. He then mathematically extended Weber's law to create what became known as **Fechner's law** (Figure 1.5):

$$S = k \log R$$

psychophysics The science of defining quantitative relationships between physical and psychological (subjective) events.

two-point touch threshold The minimum distance at which two stimuli (e.g., two simultaneous touches) are just perceptible as separate.

just noticeable difference (JND) or **difference threshold** The smallest detectable difference between two stimuli, or the minimum change in a stimulus that enables it to be correctly judged as different from a reference stimulus.

Weber fraction The constant of proportionality in Weber's law.

Weber's law The principle describing the relationship between stimulus and resulting sensation that says the just noticeable difference (JND) is a constant fraction of the comparison stimulus.

Fechner's law A principle describing the relationship between stimulus and resulting sensation that says the magnitude of subjective sensation increases proportionally to the logarithm of the stimulus intensity.

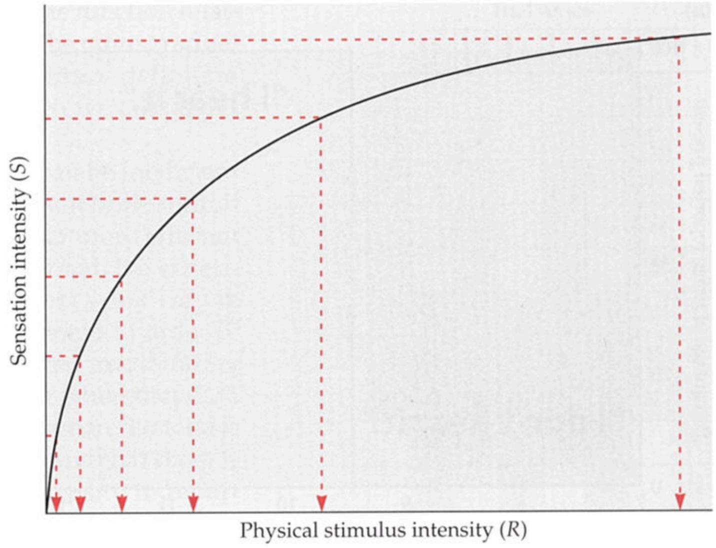

FIGURE 1.5 This illustration of Fechner's law shows that as stimulus intensity grows larger, larger changes are required for the changes to be detected by a perceiver.

where S is the psychological sensation, which is equal to the logarithm of the physical stimulus level ($\log R$) multiplied by a constant, k. This equation describes the fact that our psychological experience of the intensity of light, sound, smell, taste, or touch increases less quickly than the actual physical stimulus increases. With this equation, Fechner provided a mathematical expression that formally demonstrated a relationship between psyche and physics (psychophysics).

Consider the similarity between Fechner's law and Albert Einstein's famous equation:

$$E = mc^2$$

Like mind and body, energy (E) and mass (m) had, before Einstein, been thought of as distinct things. (The letter c corresponds to the speed of light, almost a billion feet per second.) Just as Einstein showed how to equate energy and mass, Fechner provided us with at least one way to think about mind and matter as equivalent. As you learn about the senses when reading this book, you will find that we typically make a distinction between units of physical entities (light, sound) and measures of people's perception. For example (as we'll learn in Chapter 9), we measure the physical intensity of a sound (sound pressure level) in decibels, but we refer to our sensation as "loudness."

absolute threshold The minimum amount of stimulation necessary for a person to detect a stimulus 50% of the time.

Fechner invented new ways to measure what people see, hear, and feel. All of his methods are still in use today. In explaining these methods here, we will use absolute threshold as an example because it is simpler to understand, but we would use the same methods to determine difference thresholds such as ΔI. An **absolute threshold** is the minimum intensity of a stimulus that can be detected (**Table 1.1**). This returns us to the question we raised earlier: What is the faintest sound you can hear? Of course, we could ask the same question about the faintest light, the lightest touch, and so forth. (See **Web Activity 1.1: Psychophysics**.)

TABLE 1.1
Some commonsense absolute thresholds

Sense	Threshold
Vision	Stars at night, or a candle flame 30 miles away on a dark, clear night
Hearing	A ticking watch 20 feet away, with no other noises
Vestibular	A tilt of less than half a minute on a clock face
Taste	A teaspoon of sugar in 2 gallons of water
Smell	A drop of perfume in three rooms
Touch	The wing of a fly falling on your cheek from a height of 3 inches

Source: From Galanter, 1962.

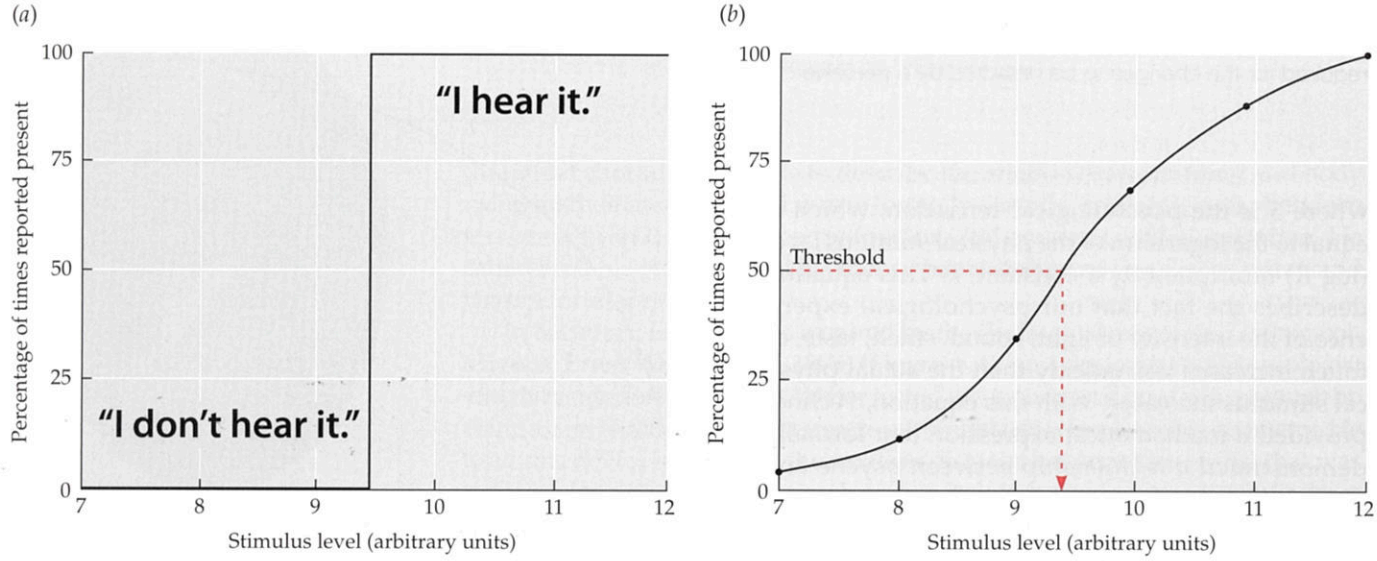

FIGURE 1.6 The method of constant stimuli. (*a*) We might expect the threshold to be a sharp change in detection from never reported to always reported, as depicted here, but this is not so. (*b*) In reality, experiments measuring absolute threshold produce shallower functions relating stimulus to response. A somewhat arbitrary point on the curve, often 50% detection, is designated as the threshold.

Psychophysical Methods

How can we measure an absolute threshold in a valid and reliable manner? One method is known as the **method of constant stimuli**. This method requires creating many stimuli with different intensities in order to find the tiniest intensity that can be detected (**Figure 1.6**). If you've had a hearing test, you may recall having to report when you could and could not hear a tone that the audiologist played to you over headphones. In this test, intensities of all of the tones would be relatively low, not too far above or below the intensity where your threshold was expected to be. The tones, varying in intensity, would be presented randomly, and tones would be presented multiple times at each intensity. The "multiple times" piece is important. Subtle perceptual judgments (e.g., threshold judgments) are variable. The stimulus varies for physical reasons. The observer varies. Attention waivers and sensory systems fluctuate for all sorts of reasons. As a consequence, one measure is almost never enough. You need to repeat the measure over and over and then average responses or otherwise describe the pattern of results. Some experiments require thousands of repetitions (thousands of "trials") to establish a sufficiently reliable data point. Returning to our auditory example, as the listener you would report whether you heard a tone or not. You would always report hearing a tone that was relatively far above threshold, and almost never report hearing a tone that was well below threshold. In between, however, you would be more likely to hear some tone intensities than not hear them, and you would hear other, lower intensities on only a few presentations. In general, the intensity at which a stimulus would be detected 50% of the time would be chosen as your threshold.

method of constant stimuli A psychophysical method in which many stimuli, ranging from rarely to almost always perceivable (or rarely to almost always perceivably different from a reference stimulus), are presented one at a time. Participants respond to each presentation: "yes/no," "same/different," and so on.

That 50% definition of absolute threshold is rather interesting. Weren't we looking for a way to measure the weakest detectable stimulus? Using the hearing example, shouldn't that be a value below which we just can't hear anything (see Figure 1.6*a*)? It turns out that no such hard boundary exists. Because of variability in the nervous system, stimuli near threshold will be detected sometimes and missed at other times. As a result, the function relating the probability of detection with the stimulus level will be more gradual (see Figure 1.6*b*), and we must settle for a somewhat arbitrary definition of an absolute threshold. (We will return to this issue when we talk about signal detection theory.)

The method of constant stimuli is simple to use, but it can be inefficient in an experiment because much of the subject's time is spent with stimuli that are clearly well above or below threshold. A somewhat more efficient approach is the **method of limits** (Figure 1.7). With this method, the experimenter begins with the same set of stimuli—in this case, tones that vary in intensity. Instead of random presentations, tones are presented in order of increasing or decreasing intensity. When tones are presented in ascending order, from faintest to loudest, listeners are asked to report when they first hear the tone. With descending order, the task is to report when the tone is no longer audible. Data from an experiment such as this show that there is some "overshoot" in judgments. It usually takes more intensity to report hearing the tone when intensity is increasing, and it takes more decreases in intensity before a listener reports that the tone cannot be heard. We take the average of these crossover points—when listeners shift from reporting hearing the tone to not hearing the tone, and vice versa—to be the threshold.

The third and final of these classic measures of thresholds is the **method of adjustment**. This method is just like the method of limits, except the subject is the one who steadily increases or decreases the intensity of the stimulus. The method of adjustment may be the easiest method to understand because it is much like day-to-day activities such as adjusting the volume dial on a stereo or the dimmer switch for a light. Even though it's the easiest to understand, the method of adjustment is not usually used to measure thresholds. The method would be perfect if threshold data looked like those plotted in Figure 1.6*a*. But, real data look more like Figure 1.6*b*. The same person will adjust a dial to different places on different trials, and measurements get even messier when we try to combine the data from multiple persons.

Trial series

Intensity (arbitrary units)	↓1	↑2	↓3	↑4	↓5	↑6	↓7	↑8
20	Y						Y	
19	Y		Y		Y		Y	
18	Y		Y		Y		Y	
17	Y		Y		Y		Y	
16	Y		Y		Y		Y	Y
15	Y	Y	Y	Y	Y	Y	Y	Y
14	Y	N	Y	N	Y	N	Y	Y
13	N	N	Y	N	Y	N	N	Y
12		N	N	N	N	N		N
11		N		N		N		N
10		N		N		N		N
	13.5	14.5	12.5	14.5	12.5	14.5	13.5	12.5

Crossover values (average = 13.5)

FIGURE 1.7 The method of limits. Here the subject attends to multiple series of trials. For each series, the intensity of the stimulus is gradually increased or decreased until the subject detects (Y) or fails to detect (N), respectively, the stimulus. For each series, an estimate of the threshold (red dashed line) is taken to be the average of the stimulus level just before and after the change in perception.

Scaling Methods

Moving beyond absolute thresholds and difference thresholds, suppose we wanted to know about the magnitude of your experiences. For example, we might give you a light and ask how much additional light you would need to make another light that looks twice as bright? Though that might seem like an odd question, it turns out to be answerable. We could give you a knob to adjust so that you could set the second light to appear twice as bright as the first, and you could do it.

We don't need to give the observers a light to adjust. A surprisingly straightforward way to address the question of the strength or size of a sensation is to simply ask observers to rate the experience. For example, we could give observers a series of sugar solutions and ask them to assign numbers to each sample. We would just tell our observers that sweeter solutions should get bigger numbers, and if solution A seems twice as sweet as solution B, the number assigned to A should be twice the number assigned to B. This method is called **magnitude estimation**. This approach actually works well, even when observers are free to choose their own range of numbers. More typically, we might begin the experiment by presenting one solution at an intermediate level and telling the taster to label this level as a specific value—10, for instance. All of the responses should then be scaled sensibly above or below this standard of 10. If you do this for sugar solutions, you will get data that look like the blue "sweetness" line in Figure 1.8.

method of limits A psychophysical method in which the particular dimension of a stimulus, or the difference between two stimuli, is varied incrementally until the participant responds differently.

method of adjustment A method of limits in which the subject controls the change in the stimulus.

magnitude estimation A psychophysical method in which the participant assigns values according to perceived magnitudes of the stimuli.

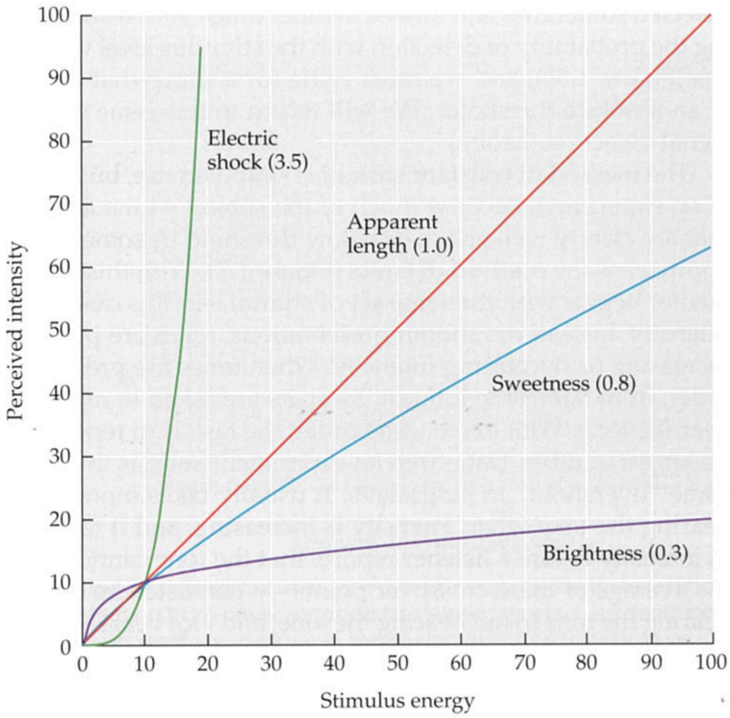

FIGURE 1.8 Magnitude estimation. The lines on this graph represent data from magnitude estimation experiments using electric shocks of different currents, lines of different lengths, solutions of different sweetness levels, and lights of different brightnesses. The exponents that describe these lines are 3.5, 1.0, 0.8, and 0.3, respectively. For exponents greater than 1, such as for electric shock, Fechner's law does not hold, and Stevens' power law must be used instead.

Stevens' power law A principle describing the relationship between stimulus and resulting sensation that says the magnitude of subjective sensation is proportional to the stimulus magnitude raised to an exponent.

Harvard psychologist S. S. Stevens (1962, 1975) invented magnitude estimation. He, his students, and successors measured functions like the one in Figure 1.8 for many different sensations. Even though observers were asked to assign numbers to private experience, the results were orderly and lawful. However, they were not the same for every type of sensation. That relationship between stimulus intensity and sensation is described by what is now known as **Stevens' power law**:

$$S = aI^b$$

which states that the sensation (S) is related to the stimulus intensity (I) by an exponent (b). So, for example, experienced sensation might rise with intensity squared ($I \times I$). That would be an exponent of 2.0. If the exponent is less than 1, this means that the sensation grows less rapidly than the stimulus. This is what Fechner's law and Weber's law would predict.

Suppose you have some lit candles and you light 10 more. If you started with 1 candle, the change from 1 to 11 candles must be quite dramatic. If we add 10 to 100, the change will be modest. Adding 10 to 10,000 won't even be noticeable. In fact, the exponent for brightness is about 0.3. The exponent for sweetness is about 0.8 (Bartoshuk, 1979). Properties like length have exponents near 1, so, reasonably enough, a 12-inch-long stick looks twice as long as a 6-inch-long stick (S. S. Stevens and Galanter, 1957). Note that this relationship is true over only a moderate range of sizes. An inch added to the size of a spider changes your sensory experience much more than an inch added to the height of a giraffe. Some stimuli have exponents greater than 1. In the painful case of electric shock, the pain grows with $I^{3.5}$ (Stevens, Carton, and Shickman, 1958), so a 4-fold increase in the electrical current is experienced as a 128-fold increase in pain!

At this point in our discussion of psychophysics, it is worth taking a moment to compare the three laws that have been presented: Weber's, Fechner's, and Stevens'.

- *Weber's law* involves a clear objective measurement. We know how much we varied the stimulus, and either the observers can tell that the stimulus changed or they cannot.
- *Fechner's law* begins with the same sort of objective measurements as Weber's, but the law is actually a calculation based on some assumptions about how sensation works. In particular, Fechner's law assumes that all JNDs are perceptually equivalent. In fact, this assumption turns out to be incorrect and leads to some places where the "law" is violated, such as in the electric shock example just given.
- *Stevens' power law* describes rating data quite well, but notice that rating data are qualitatively different from the data that supported Weber's law. We can record the subjects' ratings and we can check whether those ratings are reasonable and consistent, but there is no way to know whether they are objectively right or wrong.

A useful variant of the scaling method can show us that different individuals can live in different sensory worlds, even if they are exposed to the same stimuli. The method is **cross-modality matching** (J. C. Stevens, 1959). In cross-modality matching, an observer adjusts a stimulus of one sort to match the perceived magnitude of a stimulus of a completely different sort. For example, we might ask a listener to adjust the brightness of a light until it matches the loudness of a particular tone. Again, though the task might sound odd, people can do this, and for the most part, everyone with "normal" vision and hearing will produce the same pattern of matches of a sound to a light. We still can't examine someone else's private experience, but at least the relationship of visual experience and auditory experience appears to be similar across individuals.

Not so when it comes to the sense of taste. There is a molecule called propylthiouracil (PROP) that some people experience as very bitter, while others experience it as almost tasteless. Still others fall in between. This relationship can be examined formally with cross-modality matching (Marks et al., 1988). If observers are asked to match the bitterness of PROP to other sensations completely unrelated to taste, we do not find the sort of agreement that is found when observers match sounds and lights (Figure 1.9). Some people—we'll call them nontasters—match the taste of PROP to very weak sensations like the sound of a watch or a whisper. A group of **supertasters** assert that the bitterness of PROP is similar in intensity to the brightness of the sun or the most intense pain ever experienced. Medium tasters match PROP to weaker stimuli, such as the smell of frying bacon or the pain of a mild headache (Bartoshuk, Fast, and Snyder, 2005). As we will see in Chapter 15, there is a genetic basis for this variation, and it has wide implications for our food preferences and, consequently, for health. For the present discussion, this example shows that we can use scaling methods to quantify what appear to be real differences in individuals' taste experiences.

cross-modality matching The ability to match the intensities of sensations that come from different sensory modalities. This ability allows insight into sensory differences. For example, a listener might adjust the brightness of a light until it matches the loudness of a tone.

supertaster Supertasters are those individuals who experience the most intense taste sensations; for some stimuli, they are dramatically more intense than for medium tasters or nontasters. Supertasters also tend to experience more intense oral burn and oral touch sensations.

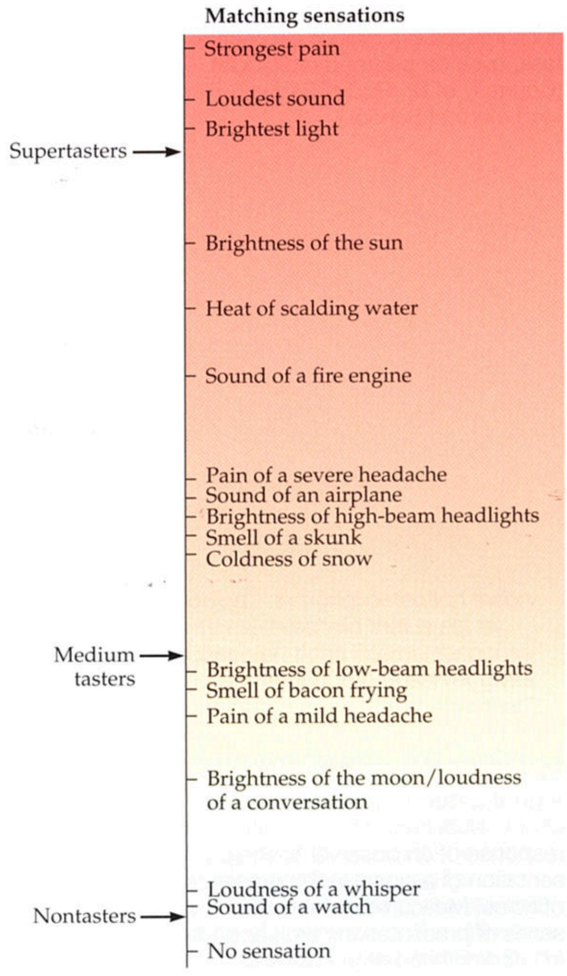

FIGURE 1.9 Cross-modality matching. The levels of bitterness of concentrated PROP perceived by nontasters, medium tasters, and supertasters of PROP are shown on the left. The perceived intensities of a variety of everyday sensations are shown on the right. The arrow from each taster type indicates the level of sensation to which those tasters matched the taste of PROP. (Data from Fast, 2004.)

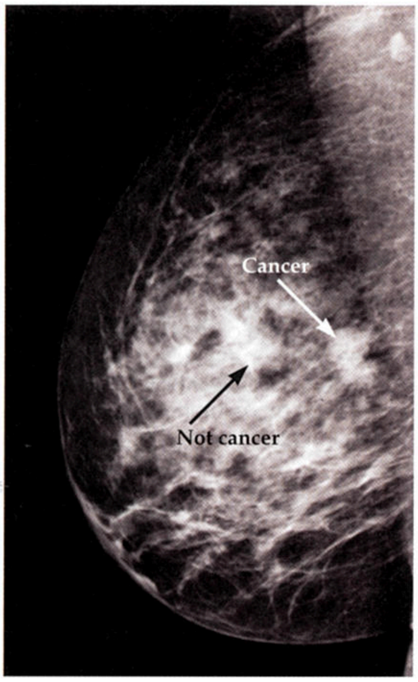

FIGURE 1.10 Mammograms, X-rays of the breast, are used to screen women for breast cancer. Reading such images is a difficult perceptual task, even for a trained radiologist. (Courtesy of Dr. Robyn Birdwell, Harvard Medical School.)

Signal Detection Theory

Let's return to thresholds—particularly to the fact that they are not absolute. An important way to think about this fact and to deal with it experimentally is known as **signal detection theory** (D. M. Green and Swets, 1966). Signal detection theory holds that the stimulus you're trying to detect (the "signal") is always being detected in the presence of "noise." If you sit in the quietest place you can find and you wear your best noise-canceling headphones, you will find that you can still hear *something*. Similarly, if you close your eyes in a dark room, you still see something—a mottled pattern of gray with occasional brighter flashes. This is internal noise, the static in your nervous system. When you're trying to detect a faint sound or flash of light, you must be able to detect it in the presence of that internal noise. Down near threshold, it will be hard to tell a real stimulus from a particularly vigorous surge of internal noise.

There is external noise too. Consider that radiologist, introduced earlier, reading a mammogram looking for signs of breast cancer. In **Figure 1.10**, it is the marked fuzzy white region that is the danger sign. As you can see, however, the mammogram contains lots of other similar regions. We can think of the cancer as the signal. By the time it is presented to the radiologist in an X-ray, there is a signal plus noise. Elsewhere in the image, and in other images, are stimuli that are just noise. The radiologist is a visual expert, trained to find these particular signals, but sometimes the signal will be lost in the noise and missed, and sometimes some noise will look enough like cancer to generate a false alarm (Nodine et al., 2002).

Of course, sometimes neither internal nor external noise is much of a problem. When you see this dot, •, you are seeing it in the presence of internal noise, but the magnitude of that noise is so much smaller than the signal generated by the dot that it has no real impact. Similarly, the dot may not be exactly the same as other dots, but that variation, the external noise, is also too small to have an impact. If asked about the presence of a dot here, •, and its absence here, , you will be correct in your answer essentially every time. Signal detection theory exists to help us understand what's going on when we make decisions under conditions of uncertainty.

Because we are not expert mammographers, let's introduce a different example to illustrate the workings of signal detection theory. You're in the shower. The water is making a noise that we will imaginatively call "*noise*." Sometimes the noise sounds louder to you; sometimes it seems softer. We could plot the distribution of your perception of noise as shown in **Figure 1.11*a***. On the x-axis, we have the magnitude of your sensation from "less" to "more." Imagine that we asked you, over and over again, about your sensation. Or imagine we took many repeated measures of the response in your nervous system to the sound. For some instances, the response would be less. For some, it would be more. On average, it would lie somewhere in between. If we tabulated all of the responses, we would get a bell-shaped (or "normal") distribution of answers, with the peak of that distribution showing the average answer that you gave.

Now the phone rings. That will be our "*signal*." Your perceptual task is to detect the signal in the presence of the noise. What you hear is a combination of the ring and the shower. That is, the signal is added to the noise, so we can imagine that now we have two distributions of responses in your nervous system: a noise-alone distribution and a signal-plus-noise distribution (**Figure 1.11*b***).

For the sake of simplicity, let's suppose that "more" response means that it sounds more like the phone is ringing. So now your job is to decide whether it's time to jump out of the shower and answer what might be the phone. The problem is that you have no way of knowing at any given moment whether

signal detection theory A psychophysical theory that quantifies the response of an observer to the presentation of a signal in the presence of noise. Measures obtained from a series of presentations are sensitivity (d') and criterion of the observer.

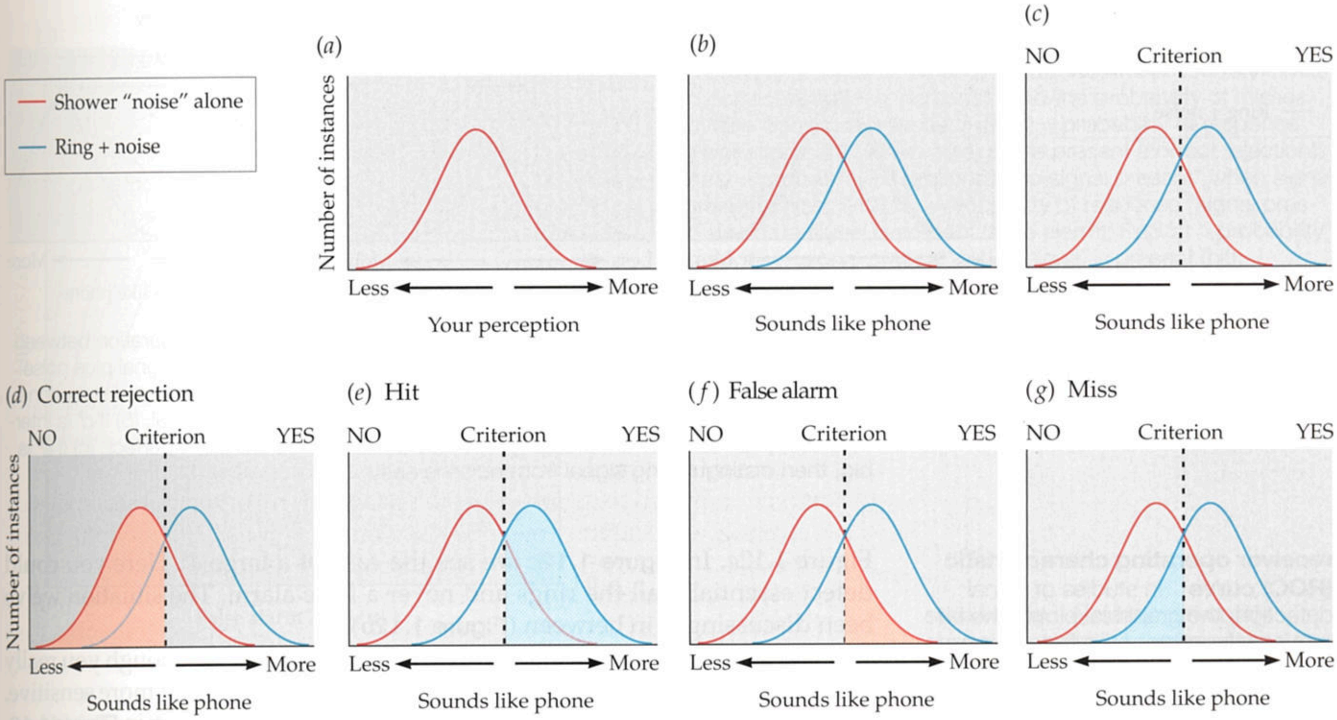

FIGURE 1.11 Detecting a stimulus using signal detection theory (SDT). (*a*) SDT assumes that all perceptual decisions must be made against a background of noise (the red curve) generated in the world or in the nervous system. (*b*) Your job is to distinguish nervous system responses due to noise alone (red) or to signal plus noise (blue). (*c*) The best you can do is establish a criterion (dotted line) and declare that you detect something if the response is above that criterion. SDT includes four classes of responses: (*d*) correct rejections (you say "no" and there is, indeed, no signal); (*e*) hits (you say "yes" and there is a signal); (*f*) false-alarm errors (you say "yes" to no signal); and (*g*) miss errors (you say "no" to a real signal).

you're hearing noise alone or signal plus noise. The best you can do is to decide on a **criterion** level of response (**Figure 1.11c**). If the response in your nervous system exceeds that criterion, you will jump out of the shower and run naked and dripping to find the phone. If the level is below the criterion, you will decide that it is not a ring and stay in the shower. Note that this "decision" is made automatically; it's not that you sit down to make a conscious (soggy) choice. Thus a criterion, in signal detection theory, is a value that is somehow determined by the observer. A response, inside the observer, above criterion will be taken as evidence that a signal is present. A response below that level will be treated as noise.

There are four possible outcomes (**Figure 1.11*d–g***): You might say "no" when there is no ring; that's a correct rejection (Figure 1.11*d*). You might say "yes" when there is a ring; that's known as a hit (Figure 1.11*e*). Then there are the errors. If you jump out of the shower when there's no ring, that's a false alarm (Figure 1.11*f*). If you miss the call, that's a miss (Figure 1.11*g*).

How sensitive are you to the ring? In the graphs of Figure 1.11, the sensitivity is shown as the separation between the noise-alone and signal-plus-noise distributions. If the distributions are on top of each other (**Figure 1.12*a***), you can't tell noise alone from signal plus noise. A false alarm is just as likely as a hit. By knowing the relationship of hits to false alarms, you can calculate a **sensitivity** measure known as d' (*d*-prime), which would be about zero in

criterion In signal detection theory, an internal threshold that is set by the observer. If the internal response is above criterion, the observer gives one response (e.g., "yes, I hear that"). Below criterion, the observer gives another response (e.g., "no, I hear nothing").

sensitivity In signal detection theory, a value that defines the ease with which an observer can tell the difference between the presence and absence of a stimulus or the difference between stimulus 1 and stimulus 2.

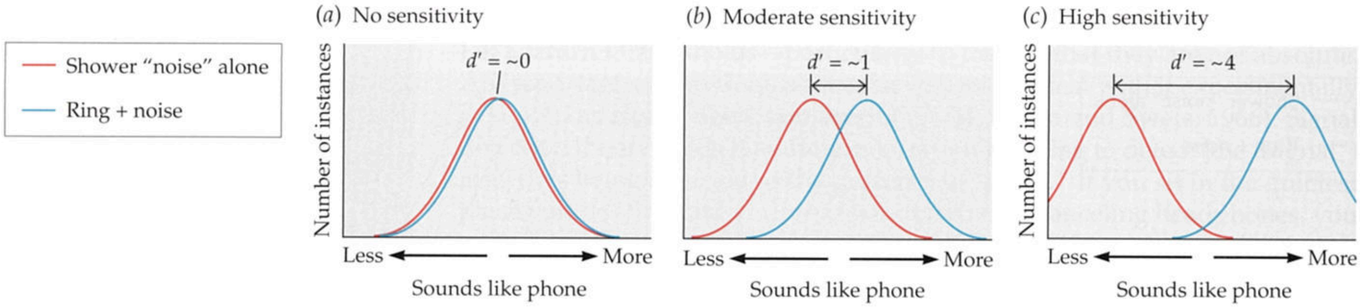

FIGURE 1.12 Your sensitivity to a stimulus is illustrated by the separation between the distributions of your response to noise alone (red curve) and to signal plus noise (blue). This separation is captured by the measure d' (d-prime). (*a*) If the distributions completely overlap, $d' = 0$ and you have no ability to detect the signal. (*b*) If d' is intermediate, you have some sensitivity but your performance will be imperfect. (*c*) If d' is big, then distinguishing signal from noise is easy

receiver operating characteristic (ROC) curve In studies of signal detection, the graphical plot of the hit rate as a function of the false-alarm rate. If these are the same, points fall on the diagonal, indicating that the observer cannot tell the difference between the presence and absence of the signal. As the observer's sensitivity increases, the curve bows upward toward the upper left corner. That point represents a perfect ability to distinguish signal from noise (100% hits, 0% false alarms).

Figure 1.12*a*. In **Figure 1.12*c*** we see the case of a large d'. Here you could detect essentially all the rings and never a false alarm. The situation we've been discussing is in between (**Figure 1.12*b***).

Now suppose you're waiting for an important call. Even though you really don't want to miss the call, you can't magically make yourself more sensitive. All you can do is move the criterion level of response, as shown in **Figure 1.13**: If you shift your criterion to the left, you won't miss many calls, but you will lots of false alarms (Figure 1.13*a*). That's annoying. You're running around naked, dripping on the floor, and traumatizing the cat for no good reason. If you shift your criterion to the right, you won't have those annoying false alarms, but you will miss most of the calls (Figure 1.13*c*). For a fixed value of d', changing the criterion changes the hits and false alarms in predictable ways. If you plot false alarms on the x-axis of a graph against hits on the y-axis for different criterion values, you get a curve known as a **receiver operating characteristic (ROC) curve** (**Figure 1.14**).

Suppose you were guessing (the Figure 1.12*a* situation); then you might guess "yes" on 40% of the occasions when the phone rang, but you would also guess "yes" on 40% of the occasions when the phone did not ring. If you moved your criterion and guessed "yes" on 80% of phone-present occasions, you would also guess "yes" on 80% of phone-absent occasions. Your data

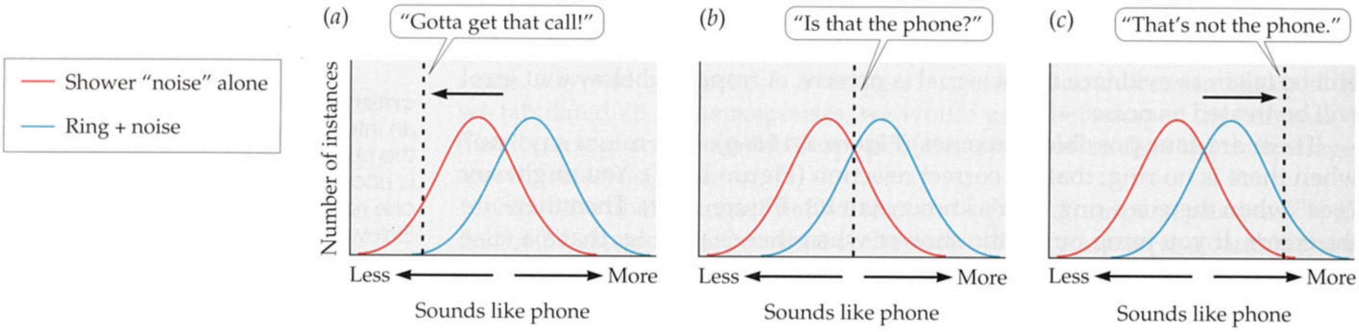

FIGURE 1.13 For a fixed d', all you can do is change the pattern of your errors by shifting the response criterion. If you don't want to miss any signals, you move your criterion to the left (*a*), but then you have more false alarms. If you don't like false alarms, you move the response criterion to the right (*c*), but then you make more miss errors. In all these cases (*a–c*), your sensitivity, d', remains the same.

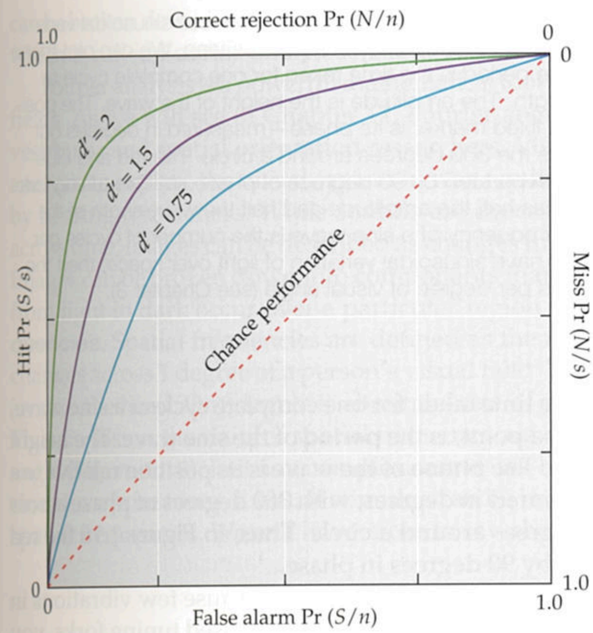

FIGURE 1.14 Theoretical receiver operating characteristic (ROC) curves for different values of d'. Note that $d' = 0$ when performance is at chance. When d' increases, the probability of hits and correct rejections increases, and the probability of misses and false alarms decreases. Pr(*N/n*) = probability of response "no signal present" when no signal is present (correct rejection); Pr(*N/s*) = probability of response "no signal present" when signal is present (miss); Pr(*S/n*) = probability of response "signal present" when no signal is present (false alarm); Pr(*S/s*) = probability of response "signal present" when signal is present (hit).

would fall on that "chance performance" diagonal in Figure 1.14. If you were perfect (the Figure 1.12*c* situation), you would have 100% hits and 0% false alarms and your data point would lie at the upper left corner in Figure 1.14. Situations in between (Figure 1.12*b*) produce curves between guessing and perfection (the green, purple, and blue curves in Figure 1.14). If your data lie below the chance line, you did the experiment wrong!

Let's return to our radiologist. She has an ROC curve whose closeness to perfection reflects her expertise. On that ROC, her criterion can slide up and to the right, in which case she will make more hits but also more false alarms, or down and to the left, in which case she will have fewer false alarms but more misses. Where she places her criterion (consciously or unconsciously) will depend on many factors. Does the patient have factors that make her more or less likely to have cancer? What is the perceived "cost" of a missed cancer? What is the perceived cost of a false alarm? You can see that what started out as a query about the lack of absolute thresholds can become, quite literally, a matter of life and death.

Signal detection theory can become a rather complicated topic in detail. To learn about how to calculate d' and about ROC curves, you can take advantage of many useful websites and several texts (e.g., Macmillan and Creelman, 2005; see Burgess, 2010, if you're interested in the application to radiology).

sine wave A simple, smoothly changing oscillation that repeats across space. Higher frequency sine waves have more oscillations and lower frequencies have fewer oscillations over a given distance. 1. In hearing, a waveform for which variation as a function of time is a sine function. Also called *pure tone*. 2. In vision, a pattern for which variation in a property like brightness or color as a function of space is a sine function.

Fourier Analysis

While we're on the topic of signals, there's just one more tool in the researcher's arsenal that will prove helpful to you as you learn about sensation and perception. French mathematician **Joseph Fourier** (1768–1830) (**Figure 1.15**) developed analyses that permit modern perception scientists to better understand how complex sounds such as music and speech, complex head motions, and complex images such as objects and scenes can be decomposed into a set of simpler signals. To understand Fourier's analytical technique, let's begin with sounds, because they're relatively easy to describe.

FIGURE 1.15 Joseph Fourier showed how very complex signals could be understood more easily as a combination of simple sine wave components.

One of the simplest kinds of sounds is a **sine wave** (in hearing, a *pure tone*). The air pressure in a sine wave changes continuously (sinusoidally) at one

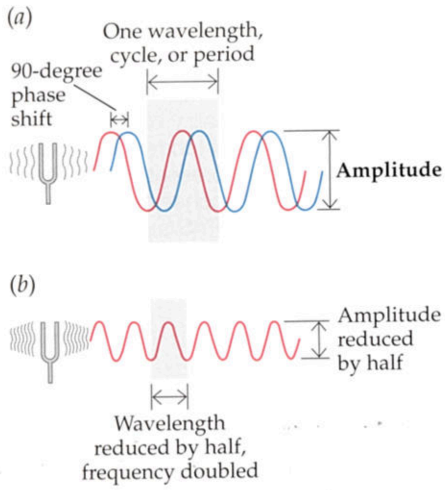

FIGURE 1.16 Sine waves. (*a*) A vibrating tuning fork produces sinusoidal variations in air pressure—variations that are the stimulus for hearing. We can plot those variations as sine waves. The period is the time taken for one complete cycle or the passage of one wavelength. The amplitude is the height of the wave. The position of the wave relative to a fixed marker is its phase—measured in degrees out of a total of 360 degrees, like the 360 degrees around a circle. The red and blue sine waves shown here are separated by 90 degrees of phase. (*b*) This tuning fork produces a sine wave that has half the amplitude and half the wavelength of the waves in (*a*). In hearing, the frequency of a sine wave is the number of cycles per second. In vision, you might have sinusoidal variation of light over space; then the frequency would be in cycles per degree of visual angle (see Chapter 3).

wavelength The distance required for one full cycle of oscillation for a sine wave.

period For hearing, the time required for a full wavelength of an acoustic sine wave to pass by a point in space.

phase A fraction of the cycle of the sine wave described in degrees (0° to 360°) or radians (0π to 2π). In hearing, phase can be used to describe fractions of a period that relate to time.

frequency (**Figure 1.16**). The time taken for one complete cycle of a sine wave, or for a **wavelength** to pass a point, is the **period** of the sine wave. The height of the wave is its amplitude. The **phase** of the wave is its position relative to a fixed marker. Phase is measured in degrees, with 360 degrees of phase across one period, like the 360 degrees around a circle. Thus, in Figure 1.16 the red and blue sine waves differ by 90 degrees in phase.

Sine waves are not common, everyday sounds, because few vibrations in the world are so pure. If you've taken a hearing test or used tuning forks, you may have heard sine waves. Flutes can produce musical notes that are close to pure tones, but other musical instruments, human voices, birds, cars, and almost all other sound sources in the world produce complex sounds.

If pure tones are so uncommon, you may wonder why we're bothering to discuss them. It turns out that all sounds, no matter how complex, can be described as a combination of sine waves (**Figure 1.17**). Fourier proved that even the cacophony of a room full of people talking or the swelling sound of a full orchestra can be broken down into combinations of sine waves at many different frequencies with different amplitudes and phases. Any complex sound

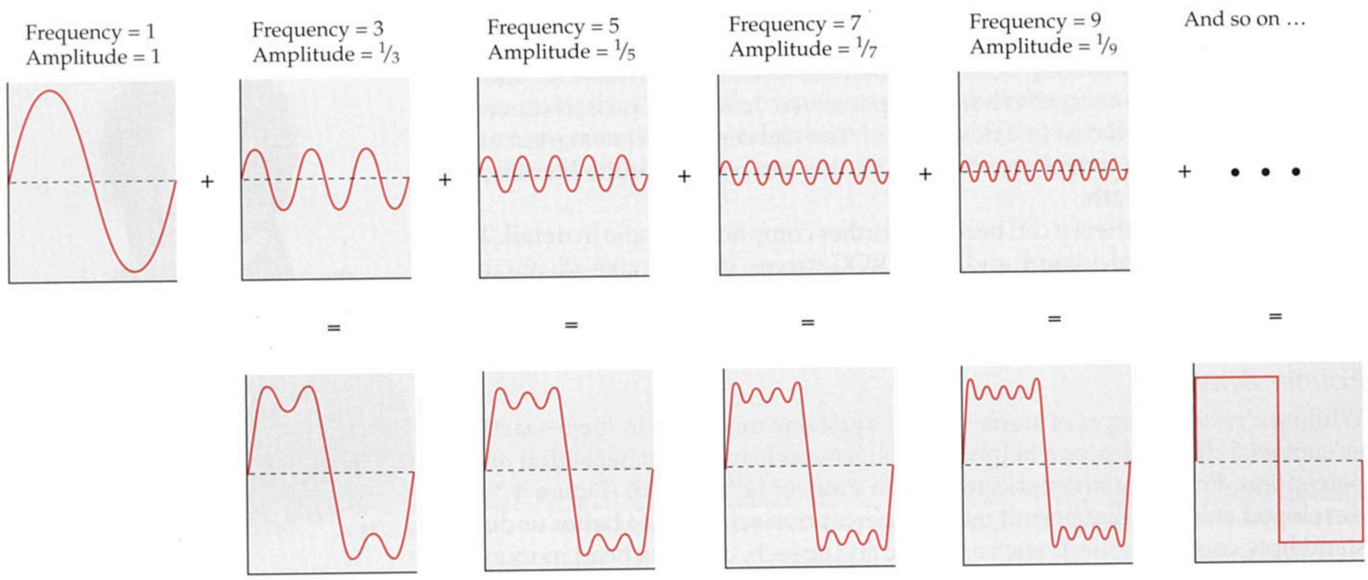

FIGURE 1.17 Every complex sound wave can be analyzed as a combination of sine waves, each with its own frequency, amplitude, and phase. Here, multiple, specific sine waves (top) are added together to form more complex waveforms (bottom). When infinitely more sine waves with even higher frequencies are added, a square wave (bottom right) can be constructed.

can be broken down into individual sine wave components through this process, which is called **Fourier analysis**. (See **Web Activity 1.2: Fourier Analysis**.)

Fourier analysis is a powerful mathematical tool that is used in many research fields. As we will see in Chapter 12, Fourier analysis is used extensively by vestibular and spatial orientation researchers. Vision researchers use Fourier analysis to explore the visual system in ways quite similar to those employed by hearing researchers. While sounds are described as changes in pressure across time, images can be described as changes in light and dark across space. Images can be broken down into components that capture how often changes from light to dark occur over a particular region in space, called **spatial frequencies**. Spatial frequencies are defined as the number of these light/dark changes across 1 degree of a person's visual field. There would be 360 degrees around the head. One degree is about the size of a thumbnail at arm's length. Thus, in vision the units of spatial frequency are **cycles per degree** of visual angle (**Figure 1.18**). Just as a complex sound can be broken down into a set of sine wave pure tones, a visual stimulus can be broken down into component spatial frequencies. We will have more to say about this in Chapter 3.

Fourier analysis A mathematical procedure by which any signal can be separated into component sine waves at different frequencies. Combining these sine waves will reproduce the original signal.

spatial frequency The number of cycles of a grating per unit of visual angle (usually specified in cycles per degree).

cycles per degree The number of pairs of dark and bright bars per degree of visual angle.

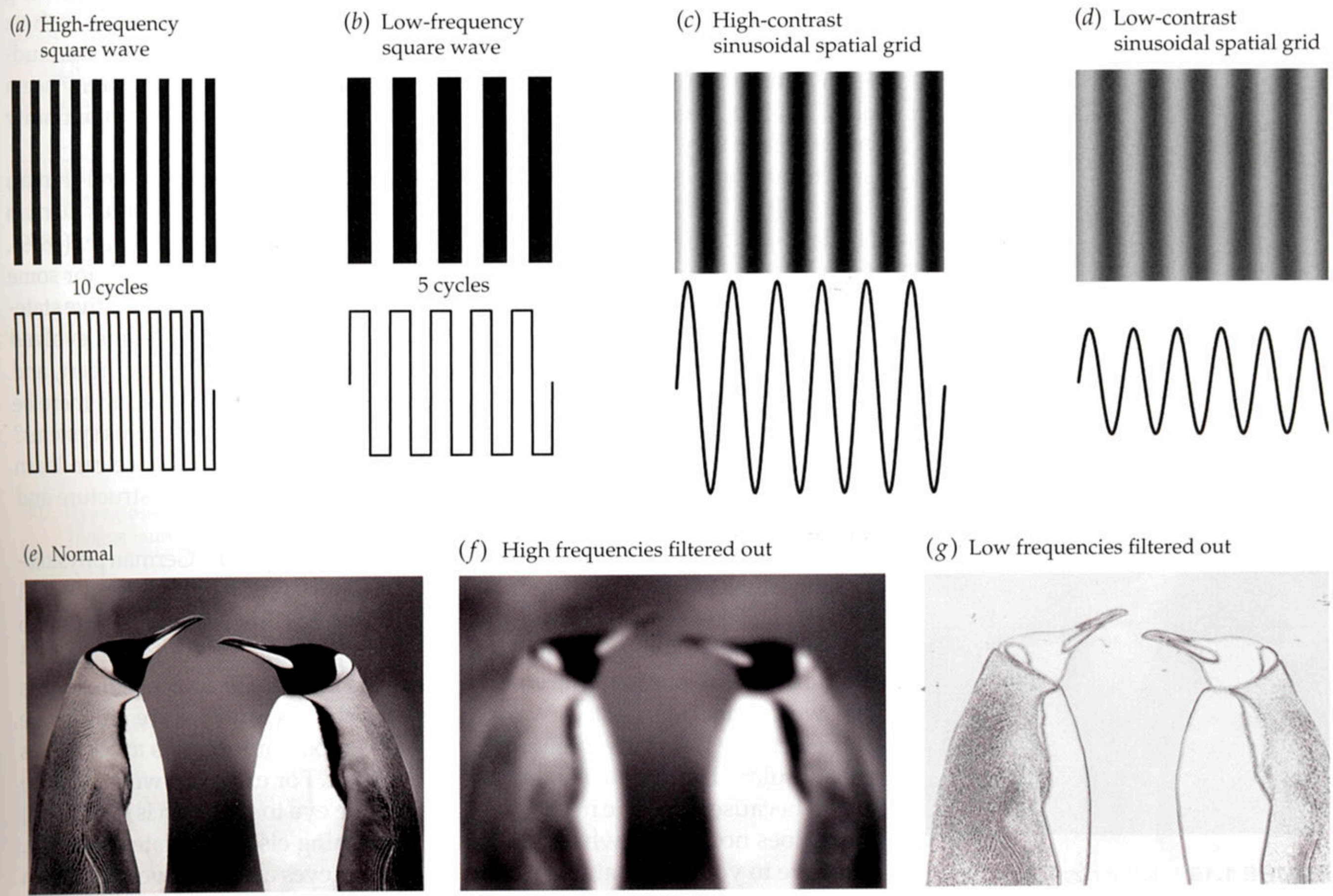

FIGURE 1.18 The spacing between dark and light stripes in (*a*) has a spatial frequency that is twice the spatial frequency of (*b*). When spatial frequency is represented as sinusoids (*c*, *d*), there are greater amplitude differences for high contrast (*c*) than for low contrast (*d*). A photograph of penguins (*e*) illustrates how images appear when high spatial frequencies are taken away (filtered out) (*f*) and when low spatial frequencies are filtered out (*g*). (From Breedlove and Watson, 2013.)

Fourier analysis is more than a mathematical curiosity. To a first approximation, your auditory and visual systems appear to break down real-world sounds and images into sine wave components. When we study how individual neurons respond to sounds and images, we find many neurons that have strong preferences for some frequency components over others, and this is especially true for early stages of auditory and visual processing. Understanding how simpler sounds and images are encoded provides essential insights into how we hear and see real events and objects in our world.

Sensory Neuroscience and the Biology of Perception

doctrine of specific nerve energies A doctrine, formulated by Johannes Müller, stating that the nature of a sensation depends on which sensory fibers are stimulated, not on how fibers are stimulated.

cranial nerves Twelve pairs of nerves (one for each side of the body) that originate in the brain stem and reach sense organs and muscles through openings in the skull.

Most students taking this course will have had an introduction to neuroscience. Our discussion of some of the neuroscience that is relevant to the study of sensation and perception should serve as a reminder of what you have learned elsewhere. If this is your first encounter with neuroscience, you may want to consult a neuroscience text to give yourself a more detailed background than we will provide here.

During the nineteenth century, when Weber and Fechner were initiating the experimental study of perception, physiologists were hard at work learning how the senses and the brain operate. Much of this work involved research on animals. It's worth spending a moment on a key assumption here: that studies of animal senses tell us something about human senses. That may seem obvious, but the assumption requires the belief that there is some continuity between the way animals work and the way humans work.

The most powerful argument for a continuity between humans and animals came from Darwin's theory of evolution. During the 1800s, Charles Darwin (1809–1882) proposed his revolutionary theory in *The Origin of Species* (1859). Although many of the ideas found in that book had been brewing for some time, controversy expanded with vigor following Darwin's provocative statements in *The Descent of Man* (1871), where he argued that humans evolved from apes. If there was continuity in the structure of the bones, heart, and kidneys of cows, dogs, monkeys, and humans, then why wouldn't there be continuity in the structure and function of their sensory and nervous systems? An inescapable implication of the theory of evolution is that we can learn much about human sensation and perception by studying the structure and function of our nonhuman relatives.

FIGURE 1.19 Johannes Müller formulated the doctrine of specific nerve energies, which says that we are aware only of the activity in our nerves, and we cannot be aware of the world itself. For this reason, what is most important is *which* nerves are stimulated, not *how* they are stimulated.

At the same time that Darwin was at work in England, the German physiologist **Johannes Müller** (1801–1858) (**Figure 1.19**) was writing his very influential *Handbook of Physiology* during the early 1830s. In this book, in addition to covering most of what was then known about physiology, Müller formulated the **doctrine of specific nerve energies**. The central idea of this doctrine is that we cannot be directly aware of the world itself, and we are only aware of the activity in our nerves. Further, what is most important is *which* nerves are stimulated, and not *how* they are stimulated. For example, we experience vision because the optic nerve leading from the eye to the brain is stimulated, but it does not matter whether light, or something else, stimulates the nerve. To prove to yourself that this is true, close your eyes and press very gently on the outside corner of one eye through the lid. (This works better in a darkened room.) You will see a spot of light toward the inside of your visual field by your nose. Despite the lack of stimulation by light, your brain interprets the input from your optic nerve as informing you about something visual.

The **cranial nerves** leading into and out of the skull illustrate the doctrine of specific nerve energies (**Figure 1.20**). The pair of optic nerves is one of 12