Chapter 2

Psychophysics: Identity Experiments

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Psychophysics\textsuperscript{1} is the study of quantitative relationships between physical stimuli and perceptions. Alternatively, we can define psychophysics as the science of quantifying the system properties of vision – the answers to Type 1 questions: What and how well do we see?

Somehow, information originating from physical stimuli arrives in our retina, is encoded and recoded in our visual systems, and eventually maps to our perception of those stimuli. These mappings are remarkably regular and lawful – the same stimulus usually brings about the same perception – as they must be if we are to respond properly and consistently to stimuli and objects in the physical world. Our first concern in this chapter is how scientists quantify the relationships between physical and perceptual realms. To that end, we introduce some of the measurement techniques used in psychophysics.

Measurement techniques become more interesting as they are used to discover the system properties of vision. As soon as we introduce a measurement technique, we want to put it right to work. In this chapter, after we discuss psychophysical techniques, we will use them to define a new set of system properties having to do with the effect on our visual perception of variations in the \textit{wavelength and intensity of light}. As you will notice, many of the questions are the same as they

\textsuperscript{1}DT was once trying to define psychophysics for a physicist. He listened attentively for about five minutes, and then said, “Oh, I get it. But why don’t you just call it crazy physics?”!
were for grating acuity, but translated into the realm of wavelength. What wavelengths of light can we see, and at what intensities? Can we tell different wavelengths of light apart?

But first, how do we study the characteristics of human vision? Figure 2.1 shows two examples of subjects being tested in a psychophysics laboratory. In Figure 2.1A, the stimuli are being presented to the subject via a classical optical system. Such optical systems allow the precise specification of light at the retina. They often allow careful control of the wavelength of light and the ability to vary the intensity over many orders of magnitude. There disadvantage is an inability to display a wide range of spatial and temporal patterns. In Figure 2.1B, the stimuli are being presented on a video display system. These systems have relatively limited range of light levels (2 orders of magnitude) and no freedom to vary wavelength. But they have the advantage of almost unlimited freedom in displaying spatial and temporal patterns. In either case, the psychophysicist varies the physical characteristics of the stimuli, and the subject reports what she sees, typically by turning a knob (as in A) or pressing a key (as in B). Now, more specifically, how do we quantify the lawful relationships between the physical stimulus and the subject’s perception?

2.1 Class A vs. Class B experiments

In 1960, in his now-famous chapter on linking hypotheses, Giles Brindley made a distinction between what he called Class A and Class B psychophysical observations. Class A observations are those in which a subject is asked judge whether two perceptions are identical. Three common examples of identity experiments are: detection, discrimination and identity matching. In detection experiments, one judges the presence or absence of a stimulus. In discrimination experiments, one judges whether two stimuli are identical; in identity matching, one typically adjusts one stimulus to be identical with a second stimulus in all perceptual respects. As we will see, these kinds of observations are measurements of what are called detection thresholds, discrimination thresholds or matches, respectively. We suggest the term Identity experiments as a more memorable label than Class A experiments.

In contrast, Class B observations are those in which the subject is asked to judge how some more general aspect of his perceptions varies with the physical properties of the stimulus. Common examples include: matching the brightness of two lights that can vary in color, comparing (rather than matching) two lights in brightness when they differ in color, or naming the color of a light. By Brindley’s definition, any judgment that depends on more than identity is considered Class B. We will focus on a subset of Class B experiments that can be called Appearance experiments. All of the examples of given above depend on the appearance of the percepts internal to an observer and not external feedback. Class B experiments that do not depend on appearance (e.g. categorization of externally-defined categories) are beyond the scope of this book.

In the present chapter we confine our attention to identity experiments (Class A) – primarily detection and discrimination thresholds. Appearance experiments (subset of Class B) will be discussed in Chapter 3.

2.1.1 Detection and discrimination experiments: What is a threshold?

In everyday English, a threshold is a boundary between one thing and another – between the inside and the outside of a house, for example. In psychophysics, a threshold is the boundary between conditions under which a stimulus is seen and conditions under which it is not seen. The term
Figure 2.1: A subject being tested in a psychophysical experiment.
threshold captures the idea that the transition from seeing to not seeing, like the transition from inside to outside a house, is relatively abrupt. But in fact, the precise place at which we should say one enters the house is slightly ambiguous. Is it the porch steps, or the front door, or halfway between? A visual threshold is similar – relatively abrupt, but with a small region of ambiguity that requires further consideration.

Suppose that we arrange our laboratory equipment so that we can provide spots of light of many intensities, covering a range of (say) $10^{10}$, or 10,000,000,000 to 1 (a realistic estimate of the range of intensities that the human eye can handle)\(^2\). As shown in Figure 2.2, as we look at these different stimuli, letting our eyes adjust to changes of intensity as necessary, we will find informally that there is a large range at the low intensity end where we never see the test spot, and a large range at the high intensity end within which we always see it. In between there is a remarkably small region of uncertainty, within which we see the stimulus only some of the time. This region of uncertainty points to the location of the subject’s threshold.

By the way, that this is another example of the departure of perceptual from physical properties. The intensity of the light – a physical variable – is continuous, and there is nothing in the physical stimulus to mark the range over which the subject’s threshold will occur. The threshold is a perceptual variable, and marks a remarkably abrupt perceptual transition along the physical continuum.

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\(^2\)Vision scientists generally plot the intensity of light in logarithmic units. This is because the range of intensities over which the visual system operates is enormous – about $10^{10}$ from the dimmest star to a snowy ski slope when the sun is shining. The use of logarithmic units is a convenient way to compress the range into something that is manageable graphically. It also allows easy comparison between threshold curves and sensitivity curves, as will be discussed later.
2.2 Classical psychophysical methods applied to detection

As psychophysicists, our first goal is to make quantitative estimates of thresholds. How shall we go about it? In the following paragraphs we give examples of three different, rather typical, classical psychophysical methods.

In choosing a psychophysical method, there are at least three interrelated design factors: The stimuli to be used; the task the subject is asked to perform; and the responses the subject is allowed to use. As will be seen, these three factors all vary among the three psychophysical methods we will describe. Many more combinations, of course, are possible and have been used.

2.2.1 The method of adjustment

The first and most intuitively obvious method can be called the method of adjustment. To apply the method of adjustment to light detection, we present the subject with a stimulus such as a spot of light. We give him a knob to turn or a computer key to press, and ask him to adjust the physical intensity\(^3\) of the spot until he can just barely see it. The subject is asked to repeat the adjustment some number of times; say, ten.

Hypothetical results of a method of adjustment experiment are shown in Figure 2.3A. In this figure, the abscissa shows the physical intensity of the spot of light, on an expanded, arbitrary intensity axis. The ordinate shows the frequency with which the subject sets the light to each of the different intensities in a set of ten trials. Subjects do this task quite reliably – the range of intensities might typically span only about a factor of about two or three. The mean or median of the set of intensities is the response measure, and is used to characterize the intensity required for threshold – that is, to specify quantitatively the location of the threshold region along the intensity axis.

The main advantage of the method of adjustment is that it is quick and efficient – each setting might take, say, 10 seconds. Thus, ten settings of a single threshold might take a couple of minutes, and a set of ten thresholds could be measured readily in a 20 minute session. Because of its speed, the method of adjustment is extremely useful in preliminary work, or in cases in which large effects are being measured and/or only rough estimates of thresholds are required.

However, the method of adjustment has two major limitations. First, it leaves the definition of “seeing” up to the subject. That is, a liberal vs. conservative definition of seeing might well cause a difference in the measured threshold. One subject may set the threshold higher than another because the first subject will only say she “sees” the stimulus when it is clearly visible, while the second subject requires it to be only fleetingly so. And second, the subject can turn the intensity of the light up or down at will over any range she chooses. That is, the method of adjustment does not allow the experimenter to control the order of presentation of different stimulus intensities. If the immediate history of stimulation influences the detection threshold – and it does, as will be discussed in Chapter 10 – these variations will increase the variability of the subject’s individual threshold measurements.

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\(^3\)The term intensity has two uses in vision science. In this book, it is always used informally, to refer to variations in either the physical or the quasi-physical quantity of light (see Chapter 3). But it is also used technically, as part of a formal specification system for the physical intensity of light.
Figure 2.3: Illustrative data from three psychophysical methods. A. The method of adjustment. B. The Yes-No method of constant stimuli. C. The forced-choice method of constant stimuli. The arrows show the threshold estimates from each of the three methods.


2.2. CLASSICAL PSYCHOPHYSICAL METHODS APPLIED TO DETECTION

2.2.2 The Yes/No method of constant stimuli

A second kind of approach, which allows the experimenter more control of the order of presentation of stimuli, can be called the method of constant stimuli. In this method, the experimenter pre-selects a set of stimulus intensities near where she thinks the subject’s threshold will be. These stimuli are presented to the subject, one at a time, in random order, many times each. For example, the experimenter might decide to present the five stimuli 40 times each, for a total of 200 trials.

The experimenter’s next decision concerns the choice of response measures and the subject’s task. In what we will call the Yes-No method of constant stimuli, the experimenter asks the subject to use the responses “Yes” and “No”. The subject’s task is to say “Yes” (I saw the stimulus), or “No” (I didn’t see it) on each trial. The use of many trials at each of several different intensities allows the experimenter to plot the percentage of “Yes” responses as a function of the intensity of the stimulus.

A hypothetical example of the kind of data one would obtain is shown in Figure 2.3B. A data set of this kind is called a psychometric function. In this example we have chosen our stimuli well, as the psychometric function spans the range from near zero to near 100% over the chosen stimulus range. By fitting an S-shaped curve to these data, we can estimate quantitatively the intensity at which the subject says “Yes” on, say, 50% of the trials, and define that intensity as the threshold value. As with the method of adjustment, the threshold value defines the location of the psychometric function along the intensity axis.4

The Yes/No method of constant stimuli has the major advantage of giving the experimenter control over the stimuli used. In particular, in case the prior history of stimuli viewed influences the threshold – and it often does – the method of constant stimuli brings this history under control. It is not without its own problems, however. If each trial takes, say, 3 seconds, and 200 trials per threshold are required, measurement of a single threshold will take 10 minutes; and a set of ten thresholds will take two hours, compared to 15 minutes for the method of adjustment.

Moreover, even though the experimenter controls the order of stimuli, the subject is still in charge of deciding how he defines seeing. In fact, by changing the instructions to the subject, and thereby changing the subject’s criterion of what “seeing” is, it is easy to move the psychometric function by small amounts along the intensity axis. If the instruction is “Be liberal – say “Yes” if there’s even just a tiny flicker of something,” the curve will shift toward lower intensities. If the instruction is “Be conservative – say “Yes” only if you see the stimulus very clearly,” the curve will shift toward higher intensities. The experimenter can also shift the curve by providing different incentives or payoffs for saying “Yes”, and in various other ways. In short, the experimenter controls the stimuli, but the experiment still confounds the sensory variable of threshold with the subject’s cognitive criterion for saying “Yes” or “No”.

2.2.3 The forced-choice method of constant stimuli

A third approach can be called the forced-choice method of constant stimuli. In this method, the experimenter again modifies the pattern of stimulus presentation. Rather than presenting only a

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4Psychometric functions actually have four parameters: the threshold (or location along the abscissa), the slope (or steepness), and the upper and lower asymptotes (which are assumed to be 1 and 0 in Figure 2.3B, and 1 and 0.5 in Figure 2.3C). All of these parameters can be estimated if enough trials are run. Mathematically, psychometric functions have traditionally been fitted with a variety of S-shaped functions, including the cumulative normal (probit), logit, or Weibull functions.
single stimulus on each trial, the experimenter presents the stimulus in either of two alternative spatial or temporal positions. For example, the stimulus can be presented either on the left or on the right, or in a first or second time interval. This stimulus format allows us to change the subject’s task: instead of asking him to say whether or not he sees the stimulus, thereby leaving the criterion for seeing up to him, we can require the subject to make a judgment as to whether the stimulus occurred in one place or another, or in one time interval or another. For example, in a spatial forced-choice technique, the subject is asked to respond “Left” if he judges that the stimulus was presented on the left, or “Right” if he judges that the stimulus was presented on the right.

Notice that a critical change of task is being made here. In this case, the task is not, “Did you see it?” – a question about the subject’s perceptions – but rather, “In which location did it occur?” – a question about the state of the physical world. This change of task has two other intertwined and important consequences. First, there is a right and a wrong answer on each trial – the stimulus is always presented in one or the other position (or time interval). And second, since the judgments can be either correct or wrong, trial by trial feedback can be given to the subject. The subject’s overall task is to maximize the percent of trials on which his answer is correct, and providing trial-by-trial feedback allows him to learn, over time, to be correct on the maximum number of trials.

Tasks that involve judging the state of the physical world can be called objective, or externally-referred, or physically-referred tasks. Tasks that involve judging one’s own perceptions can be called subjective, or internally-referred, or perceptually-referred tasks. We will use the terms physically-referred and perceptually-referred in this book.

Hypothetical results of such an experiment are shown in Figure 2.3C. As in Figure 2.3B, psychometric functions are plotted, but this time with the subject’s percent correct plotted on the ordinate. Since the subject can get 50% correct by guessing, the psychometric function spans the range from 50% to 100%. The threshold in such an experiment is typically defined as 75% correct – halfway between chance (50%) and 100%.

Among the three methods discussed here, the forced-choice method of constant stimuli is the most logically elegant, in the sense that it brings the stimuli, the subject’s task and the subject’s criterion under the tightest possible experimental control. However, it is also the least efficient, as many more trials (and therefore more time) must be invested to estimate the location of the psychometric function. For statistical reasons, it takes two to three times as many trials to locate the threshold to a given degree of accuracy when the lower asymptote is at 50% than when it is at zero. So a set of ten thresholds, held to the same criterion of accuracy, would take perhaps six hours, compared to 20 minutes for the method of adjustment and two hours for the Yes/No method of constant stimuli.

A final note on terminology: unfortunately, the term forced-choice is not consistently used in the psychophysics literature. Sometimes the term is used very broadly, to refer to any experiment in which the subject is allowed only two responses (e.g. “Yes” and “No”). With this definition, the Yes/No method of constant stimuli – the second method defined above – is also a forced-choice method. Other sources use “forced-choice” less inclusively, to refer only to experiments in which the response is to specify which of two stimulus were presented: Stimulus A is present on some trials and Stimulus B is present on others (e.g. leftward vs rightward direction of motion). If the stimuli are “symmetrical” such as leftward vs rightward motion, this choice shares with spatial and temporal forced-choice the advantage of minimizing bias. Finally, in the most stringent usage (and
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2.2. CLASSICAL PSYCHOPHYSICAL METHODS APPLIED TO DETECTION

Figure 2.4: A “staircase”. In this graph the abscissa shows the number of the experimental trial, and the ordinate shows the log intensity of the stimulus. The experimenter starts on trial 1 by presenting a stimulus she judges the subject will always be able to see. The subject replies “Yes”, marked by the X over trial #1. The experimenter then presents an 0.5 log unit dimmer stimulus. This pattern continues until trial #5, when the subject says “No”, whereupon the experimenter reverses direction and presents (say) an 0.5 log unit higher intensity stimulus on trial #6. When the subject again says “Yes” on trial #7, the experimenter reduces the step size, and presents (say) an 0.25 log unit dimmer stimulus on trial #8.

particularly in Signal Detection Theory, as discussed below), the term “forced-choice” is reserved for experiments in which, within each trial, the stimulus is presented in either of two spatial positions or temporal intervals and the subject’s task is physically-referred. This usage has the advantage of making it most likely that the specific models used in Signal Detection Theory will apply to the task. In this book we use the most stringent usage. But when an experimenter says that a forced-choice technique was used, the only way to find out what was actually done is to study the Methods section of the paper.

2.2.4 Staircases and other adaptive techniques

There’s one more trick worth knowing. With the method of constant stimuli, we choose the set of stimuli before starting the experiment, and we’re stuck with it. If it turns out not to sample the actual psychometric function well, we will do a poor job of estimating the threshold; we may even have to start over. There is another set of psychophysical methods, in which the trials that have been run before the current one are used to determine the optimal stimulus to use on the current trial. The earliest adaptive methods were called staircase methods, for reasons that become obvious in Figure 2.4.

In this figure, the experimenter is carrying out a Yes/No staircase experiment. The experimenter starts with a high intensity stimulus on the first trial. If the subject says “Yes”, the experimenter decreases the intensity for the second trial. In this example, this pattern was repeated until on trial 5 the subject says “No”. At this point the experimenter increases the intensity for trial 6. Depending on the subject’s responses, the pattern of intensities goes up and down – hence the
name staircase. [Could you use a staircase for a physically-referred forced-choice experiment? Why or why not?]

In more sophisticated versions of *adaptive techniques*, all of the trials up to trial $n-1$ can be collapsed into a psychometric function; the psychometric function can be fitted with a theoretical curve; and statistical rules can be used to select the optimal stimulus – the one whose use would yield the maximal information – to use on trial $n$. These adaptive techniques increase the efficiency of estimating the threshold, in comparison to the corresponding method of constant stimuli.

In sum, the choice of a psychophysical method depends upon one’s needs for balancing speed and accuracy. For a “quick and dirty” estimate, the method of adjustment is the obvious choice; it’s fast but open to serious stimulus artifacts and potential criterion problems. For a more controlled but still criterion-limited method, the Yes-No method of constant stimuli may be the best choice. For minimum influence of the subject’s criterion, choose the forced-choice method of constant stimuli, but expect to spend a lot of time in the laboratory! And, with either of the techniques based on the method of constant stimuli, efficiency can be improved somewhat by the use of adaptive techniques.

### 2.3 Discrimination thresholds

Up until now, we have confined our discussion to detection thresholds. Is a spot of light present? In which of two positions is it located? *Discrimination thresholds* are a closely related concept. To measure discrimination, two stimuli are presented, and the subject is asked to tell them apart. Is one of the spots of light of higher intensity than the other? In which of two locations is the higher intensity spot located?

Each of the methods used for detection experiments (adjustment, Yes/No method of constant stimuli, forced-choice method of constant stimuli, and staircase methods) can also be used for measuring discrimination thresholds. For example, one could use the method of adjustment by setting one of the two stimuli to a fixed value, and having the subject adjust the intensity of the second stimulus until it looks just barely different from the first. [How would you measure a discrimination threshold with the Yes/No method of constant stimuli? With the forced-choice method of constant stimuli? With a staircase?] We will return to both detection and discrimination experiments below.

### 2.4 Explaining thresholds using the Theory of Signal Detection

In 1966, David Green and J. A. Swets proposed a theoretical analysis of detection thresholds, called the *theory of signal detection* (TSD). Their analysis suggests that our previous discussion of the concept of threshold is incomplete, and that a full account of thresholds requires two parameters. The first parameter, which Green and Swets called $d'$ (d-prime), represents the *detectability* of the stimulus – a sensory variable. The second, which Green and Swets called $c$, represents the subject’s *criterion* – a more cognitive variable. Green and Swets argued that a traditional Yes/No experiment, as described above in Figure 2.3B, confounds these two variables. That is, when the subject chooses to be liberal or conservative, his psychometric function shifts. Is this to be considered a change of the sensory threshold, or just a change in the subject’s criterion? How can we tease the two apart?

The essence of the theory of signal detection is shown in Figure 2.5. Green and Swets began
by assuming that the psychophysical subject has access to an internal (perceptual) variable whose strength varies with the intensity of the stimulus. For the sake of concreteness, in the present case we can think of this variable as the perceived brightness of a spot of light. The abscissa of Figure 2.5 represents the possible values of this internal variable, and the ordinate represents the probability of occurrence of each of the possible values.

Now let’s modify our Yes/No method of constant stimuli experiment in two ways. First, instead of presenting five different stimuli interleaved, let’s present just one of these stimuli – say, the middle one of the former five. And second, let’s present the stimulus on only half of the trials (stimulus trials), and not on the other half (no stimulus trials). The subject’s task is to judge whether or not the stimulus was presented on each trial. (Notice that this is a physically-referred, Yes/No task — a different combination of experimental design factors than was used in any of our three examples.)

The fundamental argument made by Green and Swets is that a detection task should be viewed as a signal/noise discrimination. Even on trials on which no stimulus is presented, Green and Swets proposed that the internal perceptual variable will have a non-zero value due to sensory noise. The noise arises from many internal and external sources, and the value of the noise fluctuates randomly over time. The hypothetical distribution of the values that the noise will take is shown by the curve at the left in Figure 2.5, labeled noise alone. On trials on which a stimulus is presented, the value of the perceptual variable will be increased — say, a constant value will be added to the noise. As a result, on these trials, the values that the perceptual variable will take are shown by the right-hand curve in Figure 2.5, labelled signal + noise.

The key assumption is that these two distributions lie on a single perceptual dimension — noise and stimulus both contribute to the value of the same internal variable. Thus, there is no way for the subject to know whether a given value arises from noise alone or from the presentation of the stimulus in the midst of the noise. Nonetheless, the subject’s task is to judge whether or not the stimulus was presented on each trial by saying, “Yes”, the stimulus was presented, or “No”, the stimulus was not presented. TSD suggests that the subject’s only possible strategy is to choose a criterion value, shown by the arrow on the abscissa in Figure 2.5, and to say “Yes” if the value of the internal variable is above the criterion value, and “No” if it is below the criterion value.

The four possible outcomes of each of the trials in a TSD experiment are shown in Table 2.1. On each trial the stimulus is either present or absent, and the subject’s response is either “Yes” or “No”. On trials on which the stimulus was presented, a “Yes” response yields a hit, and a “No” response yields a miss. On trials in which no stimulus was presented, a “Yes” response yields a false alarm, and a “No” response yields a correct rejection. The probabilities of these four outcomes are related to areas under the two curves in Figure 2.5. The subject’s criterion forms the boundary between hits and misses on signal trials, and between false alarms and correct rejections on noise-alone trials. As the criterion is shifted leftward, the subject will say “Yes” on an increasing percentage of the trials, and generate more hits, but of necessity he will also generate more false alarms. By comparing the percentage of hits to the percentage of false alarms, and applying established formulas from TSD, the experimenter can estimate both $d'$, the subject’s sensitivity to the signal, and $c$, the subject’s criterion.

What if we now go back to a more classical method of constant stimuli, and think about stimuli of several different intensities rather than just one? The result is shown in Figure 2.6. The location of the signal-plus-noise distribution will vary along the abscissa with the intensity of the stimulus. As shown in Figure 2.6A, the lowest intensity of our five stimuli will yield a signal distribution that overlaps nearly completely with the noise-alone distribution, so that the percentage of hits
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Figure 2.5: Signal Detection Theory. The abscissa shows the value of a hypothetical perceptual variable having to do with the strength of an internal signal. The ordinate shows the probability of occurrence of each of the possible values of the internal perceptual variable. A near-threshold stimulus is presented on half of the trials, and these trials generate the signal + noise distribution at the right. The other half of the trials contain no stimulus, and these trials generate the noise alone distribution at the left. The subject’s task is to judge whether or not a stimulus occurred on each trial. The subject is free to vary his cutoff point, or criterion c, along the abscissa. The number of Hits (saying “Yes” when the stimulus was present) and the number of False Alarms (saying “Yes” when no stimulus was presented) are tied together, and depend upon two variables: d’, the separation of the maxima of the two distributions, and c, the subject’s criterion.

<table>
<thead>
<tr>
<th>STIMULUS</th>
<th>RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>Hit</td>
</tr>
<tr>
<td></td>
<td>Miss</td>
</tr>
<tr>
<td>Absent</td>
<td>False alarm</td>
</tr>
<tr>
<td></td>
<td>Correct rejection</td>
</tr>
</tbody>
</table>

Table 2.1: Contingency table for outcomes of a trial in a signal detection experiment.
2.5. IDENTITY MATCHING

and the percentage of false alarms will have to be nearly equal no matter what the criterion. But as shown in Figures 2.6B-E, the higher the intensity of the stimulus, the more the signal plus noise distribution will shift to the right, and the more the percentage of hits can exceed the percentage of false alarms. Moreover, the parameter $d'$ corresponds to the distance between the peaks of the noise-alone and signal-plus-noise distributions. The threshold region we first encountered in Figure 2.2 can now be seen to be the range of stimulus values that yield substantial (but not complete) overlap between the noise-alone and signal-plus-noise distributions.

In short, TSD is a useful mathematical model because it provides a theoretical account of several aspects of detection thresholds. It suggests a reason why observed psychometric functions are gradual rather than completely abrupt – because of the presence of noise, and the fluctuating value of the noise from trial to trial. It also allows us to separate the sensory variable $d'$ from the cognitive variable $c$, and provides us with an honorable way of arguing that the subject’s adoption of a liberal vs. conservative criterion does not change the incoming sensory signal.

Since Green and Swets first applied TSD to psychophysics in 1966, it has provided the basic conceptual foundation for our understanding of detection and discrimination thresholds. Many quantitative accounts of phenomena we will see later have been formulated in terms of signal/noise models, with the noise arising from sources both outside and within the subject’s visual system. Due to space considerations, we will not spend much time on such models, but it’s important to know that TSD is one of the critical foundations of quantitative psychophysical theory. For further reading, see the still very relevant original text of Green and Swets (1966) and the concise update provided by Macmillan and Creelman (2004).

2.5 Identity Matching

Our third example of an Identity experiment (Class A) is identity matching. The situation is similar to a discrimination experiment in which one compares two stimuli. But now, the goal is to determine the pair of stimuli that are identical rather than just barely discriminable. For example, using the method of adjustment, one might adjust one or more attributes of a 1st stimulus until it appears identical to a 2nd standard stimulus. At match, the stimuli need not be physically identical, but must be perceptually identical in all respects. Identity matching differs from discrimination in the question asked of the observer. For a discrimination task, the observer is asked to adjust the 1st stimulus until it looks just different than the 2nd stimulus. For an identity matching task, the the observer is asked to adjust the 1st stimulus until it looks identical to the 2nd stimulus. We return to identity matches in Chapter 7 and its examination of color matching.

2.6 Animal psychophysics

In Chapter 1, when we discussed three types of questions, you may have noticed a potentially major limitation. That is, Type 1 questions concern the system properties of visual perception – What and how well do we see? Obviously, Type 1 questions are usually studied by testing human subjects. In contrast, Type 2 questions concern the properties of the visual substrate – the optics, photochemistry, anatomy, and physiology of the visual system. Since we can’t do invasive experiments on human subjects, we usually study the substrate – particularly the physiology of single cells – in animals. And Type 3 questions concern trying to explain system properties on
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Figure 2.6: The effect of stimulus intensity on $d'$. The five panels show the effect of increasing the intensity of the stimulus from a low (A) to a high (E) value within the threshold range. The noise alone distribution remains constant in all five panels. As the stimulus intensity increases, the signal + noise distribution shifts rightward, and $d'$ increases. Two possible criteria, $c_1$ and $c_2$, are also shown. For $c_1$, the subject has chosen to hold the False Alarm rate constant at about 40%. For $c_2$, he is holding it constant at about 5%. The percents of Hits and False Alarms vary lawfully together with variations in $d'$ and $c$. In a signal detection experiment, the numbers of Hits and False Alarms are the dependent variables. If the shapes of the two distributions are known, the pattern of covariation of Hits and False Alarms allows estimation of both $d'$ and $c$. 
the basis of substrate properties. But how can we assume that animals see as we do, or that our physiology works like that of the experimental animal we study? And if not, won’t our causal stories always be potentially flawed?

Part of the answer to this question is yes – to some extent we have to live with this problem. But the other part is no. True, we can’t do invasive experiments on human subjects; but we can in fact do psychophysics on animals. Many different species of animals have been tested successfully, including cats, fish, fruit flies, and (most importantly for our purposes) non-human primates.

Although other approaches are possible, the most straightforward approach to animal psychophysics is to use a physically-referred task – a task in which there is a right and a wrong answer. Suppose you train a monkey subject to sit in a primate chair facing a stimulus screen and two response buttons. On each trial of the experiment, the stimulus occurs either on the right or on the left; the monkey presses the right or left button, and he gets feedback – he is rewarded with a drop of water – for pressing the correct button. If he pushes the wrong button, he gets no reward. He may even get a “time out” – say a ten-second period during which no trials are run. (If he’s thirsty, this matters to him.)

Initially the experimenter presents high-intensity, easily visible stimuli, and the monkey is trained to use the buttons to respond right or left. Once the monkey gets, say, 90% correct or more over a series of trials, one uses lower and lower intensity stimuli, backing up to higher intensities if his error rate goes up, and progressing toward lower intensities again when he does well. Eventually his performance will stabilize, and he will generate a forced-choice psychometric function of the kind shown in Figure 2.3C, just as a human subject does.

When old world monkey subjects are tested, the resulting psychophysical data often resemble the data from humans very closely. The parts of vision science that involve causal stories about human vision rely heavily on this similarity.

2.7 Linking propositions for identity experiments (Class A)

We now return to the topic of linking propositions. In the same chapter in which Brindley (1960) introduced the Class A versus B terminology to refer to differences in psychophysical tasks, he also introduced the concept of what he called a linking hypothesis. Brindley was at the time a visual physiologist, and his question was, what is the role of psychophysical data in elucidating the physiology of vision? He argued that mental terms (perceptual terms, hence psychophysical data) and physiological terms were from different realms of discourse, and could not be used in the same sentence without introducing some form of special statements by means of which their meanings could be linked. Rather than referring to these statements as axioms, Brindley called them linking hypotheses.

Brindley further argued that most of the linking hypotheses in use in the vision science of his day were quite arbitrary, and that a careful physiologist would not want to pay attention to arguments that depended on them. Hence, he was ready to exclude most of psychophysics and perception from vision science. However, he found one linking hypothesis which he felt was rigorous enough and safe enough to include among the premises of his science, and by allowing its use he allowed detection and discrimination experiments (Class A experiments) to slip into the science. The linking hypothesis Brindley found acceptable was as follows:

“Whenever two stimuli cause physically indistinguishable signals to be sent from the sense organs to the brain, the sensations produced by these stimuli...must be indistinguishable” Brindley (1960,
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In other words, identical incoming physiological signals must yield identical perceptions. [What do you think of the logical status this statement? Is it a tautology? Could it be false?]

In 1984, DT wrote a paper elaborating on the concept of such linking statements (Teller, 1984). Since she felt that such statements are not usually hypotheses, she instead called them linking propositions – that is, statements that can potentially play many different roles in scientific argument, and whose truths and uses need to be individually evaluated. She defined a linking proposition as a claim that a particular mapping occurs, or a particular mapping principle applies, between perceptual and physiological states.

2.7.1 Family structure

Following the “and conversely” statements of Müeller (1896), DT also argued that relational linking propositions come in families, with different family members building on different experimental outcomes and allowing different directions of inference between psychophysics and neurophysiology. Specifically, she argued that a family of relational linking propositions has four members that relate to each other as shown in Figure 2.7A. The family is composed of (1) an Initial proposition; (2) its Contrapositive; (3) its Converse, and (4) its Converse Contrapositive. In abstract terms, the initial proposition (1) is: A implies B (if A is true, then B is true). The Contrapositive (2) is: not-B implies not-A (if B is not true, then A is not true). The Converse (3) is: B implies A (if B is true, then A is true). And the Converse Contrapositive (4) is: not-A implies not-B (if A is not true, then B is not true).

What are the relationships among these four statements? Students who have taken a course in logic will remember that the Initial statement and its Contrapositive – (1) and (2) –can be inferred
from each other: if one is true, the other is also true. An example: if the Initial statement is, *if it rains the sidewalk will be wet*, the Contrapositive is, *if the sidewalk isn’t wet, it didn’t rain*. The same is true of the Converse (3) and the Converse Contrapositive (4). Importantly, however, the Converse (3) does not follow from the original statement (1): *if the sidewalk is wet, it rained* is not a logical inference, as the sidewalk could be wet for other reasons (perhaps the sprinklers are on)

### 2.7.2 The identity family

Following this format and the inspiration provided by Mueller’s laws, Teller (1984) then formulated several families of relational linking propositions. The first family, with which we are concerned in this chapter, is called the *Identity family*, and is shown in Figure 2.7B. In order to use symbols that are more mnemonic for physiological vs. perceptual states, we will substitute the Greek letter \( \phi \) (phi, for physiology) for the A’s in Figure 2.7A, and the Greek letter \( \psi \) (psi, for psychology) for the B’s.

With these symbol substitutions and formalizations, the Initial Identity proposition (1) becomes: *Identical physiological states imply identical perceptual states*. The Contrapositive Identity proposition (2) is: *Non-identical perceptual states imply non-identical physiological states*. The Converse Identity proposition (3) is: *Identical perceptual states imply identical physiological states*. And the Converse Contrapositive Identity proposition (4) is: *Non-identical physiological states imply non-identical perceptual states*. As before, the Initial proposition and the Contrapositive can each be inferred from the other, as can the Converse and the Converse Contrapositive; but the Initial proposition and the Converse are logically independent.

Are the Identity propositions analytically true, or just highly likely; or are they relatively safe speculations, or risky ones? The Initial Identity proposition has the same content as the only linking hypothesis that Brindley found acceptable; that is, “Whenever two stimuli cause physiologically indistinguishable signals to be sent from the sense organs to the brain, the sensations produced by those two stimuli must be indistinguishable.” Moreover, Brindley argued (and DT would agree) that his acceptable linking hypothesis is probably analytically true and tautological (it follows from the definitions of the other concepts involved). The Contrapositive, being logically identical to the Initial proposition, would also have the same logical status – true and tautological.

The Converse and Converse Contrapositive, however, are not quite as necessarily true. For example, the Converse of Brindley’s linking hypothesis would be something like this: Whenever the sensations produced by two stimuli are indistinguishable, these two stimuli must be sending identical signals from the sense organs to the brain. This statement is not necessarily true, because the signals could start out different in the retinal image but become identical at some later stage of processing; and because even if the neural states remain distinguishable, two different neural states could in principle map to the same perceptual state (a many:1 mapping between neural and perceptual states could occur). In fact, with only one possible exception (see later), Initial and Contrapositive Identity propositions seem to DT to be the only general linking propositions that are analytically true, and therefore completely safe to adopt as premises. All the rest are riskier.

We now return to causal stories. Notice that the second (2) and third (3) Identity linking

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5DT’s all time favorite example of the fact that an initial statement doesn’t imply its converse arose when she was a graduate student. A fellow graduate student remarked one day that he didn’t mind being mis understood, because to be great is to be misunderstood. DT undertook the delicious responsibility of pointing out to him that unfortunately, converses being what they are, to be misunderstood was not necessarily to be great.
propositions allow physiological conclusions to be drawn from psychophysical experiments. These two propositions are starred in Figure 2.7. Detection and discrimination experiments determine whether the sensations produced by two different stimuli are discriminable (non-identical), or not discriminable (identical). If two stimuli are discriminable in a psychophysical experiment, Contrapositive Identity (2) insists that these two stimuli have sent non-identical signals from the sense organ to the brain. Most people find this proposition difficult to doubt, as Brindley did. On the other hand, if two stimuli are not discriminable, the Converse Identity proposition (3) suggests that they have sent identical signals, or more sensibly, that the signals differed initially but were rendered identical at some later stage of processing. Thus, any identity psychophysical experiment allows us to draw a conclusion about the probable identity or non-identity of physiological states, depending only on the outcome of the experiment – which stimuli are discriminable and which are non-discriminable – and our willingness to employ either the Contrapositive (2) or the Converse (3) Identity proposition in our argument.

Finally, notice that these Identity arguments are the same as some arguments we introduced less formally in Chapter 1. We argued initially that if a subject can discriminate between a grating and a homogeneous field, information about the spatial structure of the grating must be retained through all levels of the visual system. There is a Contrapositive Identity proposition embedded in the premises of this argument. Similarly, we argued that if the subject could not discriminate between the grating and the homogeneous field, information about the spatial structure of the grating must have been lost somewhere within the visual system. There is a Converse Identity proposition embedded here.

2.7.3 Application of Identity propositions to Identity experiments (Class A)

How, exactly, do we apply Identity propositions to the data from detection experiments, in which there is only one stimulus? Terminological issues can make this question confusing. The trick is that in this context, vision scientists think of the background alone as one “stimulus”, and the background plus the test stimulus as the other “stimulus”. Some intensities of the test stimulus are below the threshold region; these are marked NOT SEEN in Figure 2.2. In terms of signal detection theory, this means that the noise distribution is indistinguishable from the signal-plus-noise distribution. When such discrimination failures occur – when we are below threshold – a Converse Identity proposition will be included as a premise in any argument from perceptual data to physiological conclusions. We will conclude, slightly speculatively (as is always the case with Converse propositions) that the two physiological states arising from background and background-plus-test-stimulus are indistinguishable.

Other stimuli are above the threshold region; they are marked SEEN in Figure 2.2. In this intensity region, the noise distribution is very different from the signal-plus-noise distribution. In this case, a Contrapositive Identity proposition will be included as a premise in our arguments. Since the perceptual states are distinguishable, we can conclude with confidence that the physiological states are distinguishable. Thus, just as the psychometric function marks the transition from not seeing to seeing, it marks the transition from using Converse to using Contrapositive Identity propositions in drawing physiological conclusions from perceptual data.

For discrimination experiments, very similar arguments hold. When two suprathreshold stimuli are physically different but indiscriminable, we use Converse Identity any time we argue that the physiological states are indiscriminable. When the two stimuli are discriminable (as most
pairs of stimuli are!) we use Contrapositive Identity in arguing that the physiological states are
discriminable. The former is slightly speculative, whereas the latter is (as Brindley said) very
difficult to doubt.

As a final comment on linking propositions, consider again the definition of Identity experi-
ments (Class A). Typical Identity experiments require comparisons between very similar stimuli.
Often called near-threshold judgments, they also commonly involve judgments that have a correct
answer. But these are not the defining characteristics. Instead, the defining characteristic of Iden-
tity experiments is that they require the judgment of whether two perceptions are identical or not
identical. Thus, the defining characteristic of an Identity experiment is the identity relation at the
heart of the Identity proposition. Brindley goal in defining Class A experiments was to distinguish
the experiments that allow the application of the Identity linking proposition.

2.8 Two system properties of scotopic vision

Now that you have been introduced to psychophysical methods for measuring thresholds, the next
question is, what kinds of substantive questions can be investigated with measurements of thresh-
olds?

As it turns out, an individual threshold value usually has little in the way of theoretical implica-
tions beyond the general one of information retention and information loss. However, experiments
in which sets of thresholds are measured often give important hints about physiological processes.
In such experiments thresholds are measured as a function of some stimulus parameter or param-
eters. As an example, we now turn to an important set of thresholds: detection thresholds as a
function of the wavelength\(^6\) of the stimulus.

What we experience as “white” light usually contains a large range of wavelengths, the com-
ponent wavelengths of which we experience as colors. As a student at Cambridge in the 1660s,
Isaac Newton noticed a beam of sunlight coming through the shutters of his room. He passed the
beam through a prism, and saw that the light now produced a rainbow of colors. That is, he had
shown that sunlight can be broken down into its component wavelengths by passing it through
the prism, which bends or refracts light differentially according to its wavelength. In the case of
natural rainbows, internal reflections in water droplets act as the prism did for Newton.

As Newton showed, at moderate and higher light levels we can discriminate among lights of
different wavelengths – different wavelengths map to different perceived colors. But you also may
have noticed that if the light is sufficiently dim the colors fade away, and all that is left is shades
of gray. [If you have not noticed this phenomenon, toss some shirts or towels of different colors
around your room tonight, and see whether you can discern their colors when the room is nearly
dark and your eyes have adjusted to darkness.]

In fact, vision turns out to have very different properties at low vs. high light levels. The term
scotopic vision refers to vision at low light levels, at which no colors are perceived, and the term
photopic refers to vision at higher light levels, at which colors are perceived. We will spend the
remainder of this chapter discussing two of the major properties of scotopic vision.

\(^6\)The wavelength of light is usually specified in nanometers (nm). One nm is \(10^{-9}\) meters. We will say more about
the nature and specification of light in Chapter 4.
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2.8.1 The scotopic spectral sensitivity curve

The absolute threshold is the smallest amount of light a subject can detect when her eyes are fully adjusted to the dark. To begin our exploration of the effects of wavelength, we ask, does a person’s absolute threshold vary with the wavelength of light?

The quickest way to answer this question is to use the method of adjustment with a series of stimuli that vary in wavelength. We use a calibrated light source so that the physical energy at any given wavelength is known. We put the subject in a dark room for an hour before we start. Then, we present each of the wavelengths in turn, and ask the subject to adjust the intensity of the light until he just barely sees the stimulus. The subject does this, say, ten times for each wavelength, and we take the mean of these ten settings. We then plot this threshold value as a function of the wavelength at which it was measured. Of course, more elegant psychophysical techniques could also be used.

The results of the experiment, plotted in terms of thresholds, are shown in Figure 2.8A. This data set forms what can be called a scotopic spectral threshold curve. Alternatively (and more commonly), the data are plotted as scotopic spectral sensitivity, where sensitivity is defined as 1/threshold. With a logarithmically spaced ordinate, the conversion is particularly simple, because the threshold curve can simply be inverted to get the sensitivity curve. The same data plotted as sensitivity are shown in Figure 2.8C. We will use sensitivities rather than thresholds from now on.

This data set has several interesting features. First, the highest sensitivity is always around 500 nm (closer to 490 nm to be more exact). Second, sensitivity varies enormously with wavelength. Compared to the sensitivity at 500 nm, sensitivity declines by a factor of roughly 100 as we change the wavelength from 500 to 400 or to 600 nm; and by another factor of roughly 1000 as we change the wavelength to 700 nm. So the change in sensitivity for lights of 500 vs. 700 nm encompasses five orders of magnitude.

Third, the scotopic spectral sensitivity curve is a relatively simple U-shaped curve. And fourth, its shape is extremely stable. For example, it doesn’t matter what psychophysical technique we use. All of the results reveal the same simple curve, possibly shifted up and down the ordinate, but of exactly the same shape. Similarly, backgrounds of various intensities and wavelengths shift the curve up and down; but over a broad range of conditions, the shape of the curve remains unchanged.

In sum, we have discovered a new system property of human vision. Absolute threshold experiments for lights of different wavelengths reveal a smooth, stable spectral sensitivity curve, with its maximum at about 500 nm, and with very large and characteristic losses of sensitivity with changes in wavelength.

2.8.2 Failures of wavelength discrimination: Metamer sets

Here’s a second set of system properties for scotopic vision. Suppose that you set up a row of test lights of different wavelengths, each one set to its own threshold, and ask the subject to discriminate among them. The subject cannot do the task at absolute threshold, where the lights are barely visible, but this seems hardly fair. So let’s set the intensity of each stimulus to twice its detection threshold. The new stimuli are indicated by the lowest dotted line, marked 2x for ”two times threshold”, in Figure 2.8B. The stimuli all look slightly brighter than they did at absolute threshold, but they all still look whitish, and remarkably, the subject still cannot discriminate among them. Similarly, the stimuli along the second dotted line (10 times the absolute threshold), or the third (100 times the absolute threshold), or any similar line in between, are indiscriminable,
Figure 2.8: Spectral threshold and spectral sensitivity curves. A and B: Spectral threshold curves; C and D. spectral sensitivity curves. A: Absolute thresholds and chromatic thresholds as a function of wavelength. The abscissa shows the wavelength of light; the ordinate shows the relative intensities of the lights of different wavelengths needed for absolute thresholds (lower curve), or for chromatic thresholds (upper curve). B. Scotopic equivalence classes as equal multiples of thresholds. C. Absolute thresholds and chromatic thresholds plotted as spectral sensitivity curves. D. Scotopic equivalence classes plotted in terms of sensitivities. By convention, the maximum of a spectral sensitivity curve is labeled zero (0), with decreases in sensitivity away from the maximum labeled with negative log values (-1, -2, etc.).
until we reach a limit (about to be described) for each wavelength of light. (Stimuli from any two different dotted lines are discriminable because they vary in brightness.) In short, at scotopic light levels, wavelength information is lost. [How would one use identity matches to measure these indiscriminable lights?]

Vision scientists are so impressed with the fact that very different physical stimuli can be indiscriminable, that we use several special terms to describe this phenomenon. Such sets of stimuli have been called equivalence classes, emphasizing the idea that the signals arising from them must be rendered equivalent within the visual system. They are also called silent substitution sets, emphasizing the idea that one could be substituted for the other with no change of the neural signal. In addition, the term metamers is also used to describe lights of different wavelength compositions that are indiscriminable. The sets of lights indicated by each of the dashed lines of Figure 2.8 are metamer sets. The challenge, of course, is to explain why these losses of information occur.

2.8.3 A model of scotopic vision: The funnel analogy

Based on the universal linking proposition (Chapter 1), we posit that the system properties of scotopic vision arise from the physiological properties of the visual system. But specifically, how? As psychophysicists, we are entitled to use the system properties of vision as a basis of theory and speculate about how the visual physiology might work.

Here’s a theory of how the scotopic spectral sensitivity curve might come about. Suppose that there were an anatomical stage of the visual system composed solely of a set of identical elements, and that each element had a spectral sensitivity curve matching that of the psychophysically defined scotopic curve in Figure 2.8. Under these assumptions, the system as a whole would necessarily show a spectral sensitivity curve that matches the scotopic curve. So we may choose to adopt the hypothesis that such elements, and such a processing stage, exist, and decide to go look for them.

But how shall we explain both the scotopic spectral sensitivity curve and the loss of wavelength information at the same time? It seems kind of odd – as though the system is influenced by wavelength yet loses wavelength information. But a gadget that would have the right properties can be created by combining a funnel with a counter (Figure 2.9). This analogy may seem a bit silly to those with some physical sophistication, but it will come in handy when things get more complicated later.

Let us assume we have an ordinary kitchen funnel. The funnel is a bit misshapen, being widest at the middle and narrowest at the bent corners. We add a counter to its output spout. To make the analogy, we metaphorically place the funnel under the wavelength scale of the scotopic spectral sensitivity curve, with the widest part at about 500 nm. Along the wavelength scale, we think of curtains of marbles of different colors, perpendicular to the page, raining down on the funnel at a specified rate. The probability that a marble of any given color will be caught is determined by to the width of the funnel at each particular wavelength. But once a marble is caught, it just rolls down to the spout of the funnel, and gets counted by the counter.

In the early days of science, what a challenge it must have been to sort out the effects of physical variables from the effects of our own sensory systems. What visual sensations would Newton have seen if he had used his prism in moonlight instead of sunlight? (Moonlight, of course, is reflected sunlight.) If the whole spectrum looked white, what conclusion would he have drawn about the nature of light? Might he have decided that light has different properties when it is dim, or comes from the moon? Or would he have placed the cause correctly, within his own visual system?
2.8. TWO SYSTEM PROPERTIES OF SCOTOPIC VISION

Figure 2.9: The funnel analogy. In this analogy the visual system is modeled by a funnel with a counter attached. Curtains of marbles, perpendicular to the page, rain down upon the funnel. The funnel varies in width, providing an analogy for the fact that sensitivity varies with wavelength. But the counter only counts the marbles, providing an analogy for the loss of wavelength information that creates scotopic metamasers.
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Figure 2.10: Scotopic metamerism. A and B are lights of two different spectral compositions and intensities. If the intensities of A and B can be adjusted to make the two stimuli indiscriminable, A and B are called metameris. In the funnel analogy, lights A and B are indiscriminable because they make equal counts, \( R_A \) and \( R_B \), on the counter.

This analogy is also easy to express mathematically. Let \( R \) be the total number of marbles caught by the funnel – the count on the counter at the base of the funnel. For each wavelength \( \lambda \), let \( Q_{\lambda} \) be the number of marbles that arrive per unit time in the curtain of marbles incident at the mouth of the funnel, and let \( r_{\lambda} \) be the width of the funnel at that wavelength. The catch of marbles at any wavelength, then, is just the number of incident marbles of the color corresponding to \( \lambda \), multiplied by the probability that a marble of that color will be caught.

\[
R = Q_{\lambda} r_{\lambda}
\]

For several wavelengths – say, 450, 500, and 550 nm – presented together, we just add up the individual catches of marbles:

\[
R = Q_{450} r_{450} + Q_{500} r_{500} + Q_{550} r_{550}
\]

For the whole spectrum of wavelengths, we keep adding to get a final expression:

\[
R = \sum Q_{\lambda} r_{\lambda}, \text{ or for the continuous case, } R = \int Q_{\lambda} r_{\lambda} d\lambda
\]

The conditions that lead to metamerism in scotopic vision can now be formally stated. Suppose we have two patches of light, A and B, as shown in Figure 2.10. If the catches of marbles from the two patches are identical, the lights must be metameris. Why? Because the model system only has signals corresponding to \( R_A \) and \( R_B \). There’s no way for the system to encode the information that the two physical stimuli are different. So by necessity:

\[
\text{If } R_A = R_B, \text{ then } A \equiv B,
\]

where \( \equiv \) is the symbol for a metameric match.
2.9. **CHROMATIC THRESHOLDS AND PHOTOPIC VISION**

2.8.4 Univariance: A single value for both intensity and wavelength

This analysis introduces an important assumption about the elements that account for the scotopic sensitivity function. These elements are univariant. By *univariant*, we mean that they can be expressed by a single variable: one number. In the funnel and counter analogy, the only thing that mattered to the counter was the number of marbles. Wavelength information was lost. Similarly, in this mathematical model, the lights are represented by a single-valued function $R$. With a single univariant function, one cannot code for more than intensity. Wavelength information must be lost.

2.9 Chromatic thresholds and photopic vision

Now, let’s relax our testing techniques for a while, and just let the subject tell us what things look like (or look at them ourselves). Let’s present two dim stimuli, a spot of 500 nm and a spot of mixed wavelengths that looks white, and set them both to intensities just above their absolute thresholds. The subject tells us they both look white, and equally bright. Now we double the intensities of both lights together, and keep doubling them, each time asking the subject to tell us what he sees. What will happen?

At first, the subject continues to say that both spots look white, with the brightness of both spots increasing together as intensity is increased. But after the intensities have been increased about a thousandfold (3 orders of magnitude), the subject suddenly says, "OH! The one on the left just turned green!" The intensity at which the 500 nm light changes from looking white to looking green defines the subject’s *chromatic threshold* – the threshold for the onset of color sensation – for 500 nm light. We have passed from the scotopic to the photopic realm.

This experiment can be repeated for each wavelength. Interestingly, the intensity range between the absolute threshold and the chromatic threshold varies with wavelength. The lowest absolute threshold occurs at about 500 nm. But, as shown in Figure 2.8, the lowest chromatic threshold occurs at about 555 nm, and chromatic thresholds increase as the wavelength increases or decreases from this value. Moreover, the shape of the chromatic threshold curve is not a simple U – it is asymmetrical, with a shallower rise at shorter wavelengths.

In sum, as we turn up the intensity of each light past a critical level, the system properties change. The *photopic spectral sensitivity curve* has its maximum at about 555 nm, and is more complex in shape than was the scotopic curve. It is also labile – its shape is affected by the method and conditions of measurement, as we will see in the next chapter. And above all, we become able to discriminate among different wavelengths of light – scotopic vision gives way to photopic vision: wavelength information is preserved, and color vision occurs.

2.10 Summary: Explaining properties of the scotopic system

In Chapter 2 and 3 we introduce the field of psychophysics – behavioral methods for quantifying the mappings between physical stimuli and perceptions. In the present chapter we have concentrated on the kinds of identity experiments that Brindley called Class A – detection, discrimination and identity matching. We described four examples of methods for measuring thresholds, and reviewed some of the advantages and limitations of each. We also introduced the theory of signal detection which provides a mathematical model that allows the separation of sensory from cognitive parameters.
Next, we returned to the concept of a linking proposition. We reiterated the claim that arguments from psychophysics to physiology, or vice versa, will always involve linking propositions. We elaborated on a family of relational linking propositions – the Identity family – that deal with information retention and information loss. We argued that Identity propositions enter into physiological conclusions based on detection and/or discrimination data. The properties of the Identity family set the stage for examination of other, less intuitively obvious linking propositions in future chapters.

Finally, we used sets of threshold measurements to define two system properties of scotopic vision. Sets of detection thresholds were used to define a scotopic spectral sensitivity curve, and sets of discrimination failures were used to define metamer sets among supra-threshold but still scotopically detected stimuli. These two system properties may be seen as intuitively contradictory – the scotopic visual system is influenced by the wavelength of light, yet loses all information about it. In any case, these system properties are in need of physiological explanation.

We then invoked the Universal linking proposition to infer that elements that produce these system properties will be found within the visual system. We made use of our psychophysicist’s speculation license to design a gadget, described by the funnel analogy, that would mimic scotopic vision. In fact, neural elements with the right characteristics will emerge without warning within the next several chapters. Keep the system properties of scotopic vision in mind, and when you think you spot the neural elements that explain them, make a note of them (but unless you are Archimedes, do not jump out of the bathtub and run up the street yelling “eureka!”).

In the next chapter we turn to psychophysical techniques for studying the appearance of visual stimuli using examples from photopic vision.