

Chapter 6

Color Vision

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Introduction

Color enriches all of our experiences. The beauty of the sunset is often given as an example how color enhances our experience. I recall one sunset in Cape May, New Jersey, one of the many lovely regions of the Garden State. It is at the very southern tip of the state, and actually looks west across the Delaware Bay. They have a rather cute tradition that you have to experience, but for our purposes it brought my family to the shore to watch the sunset. The day was beautiful with the orange-red sun falling into dusky blue of the bay, with a bright orange streak going from sun to me. The sky varied from an already darkening indigo on the eastern sky to the pale hazy blue around the sun. Take a minute to imagine this scene, or any other spectacular sunset you have experienced. Now imagine this scene again but without the color. I doubt it would get many of us up out of our chairs to watch a sunset in shades of gray.

[? Direction]

What is Color

Color is such a complicated experience, that is very hard to put into words what exactly color is. However, color is often described by calling on three dimensions of the color experiences: Hue, saturation and brightness. **Hue [to glossary]** refers to the color quality of the light and corresponds to the color names that we use, such as orange, indigo, cyan, etc. In fact, in common usage, when the word color is said, hue is meant. I called hue the quality of color. Let me explain that term. A quality is a value that changes, but it does not make the value larger or smaller. For example, when intensity changes it gets larger or smaller. But when hue or color changes, it does not make sense to say that say red has more or less hue than green. But certainly red is very different than green. Saturation refers to the purity of the light. The more saturated the stimulus, the stronger the color experience, and the less saturated, the more it appears white or gray or black, which are called achromatic (no color). Brightness is the same experience of intensity that has been referred to before.

Open [Interactive Illustration 6.x, Dimensions of Color \[link to media\]](#) to see how these three dimensions alter our experience of color. When you first open the media, you will see on the right half of the screen will be two versions of what you may remember from elementary school, the color circle. Instead of dots around the outside that you might remember, this is a continuous version with hue varying all the time around the circle with green at the 12:00 position. Saturation is also represented on this circle. The most saturated colors are on the outside of the circle, and the colors lose saturation gradually until the center where the colors are completely desaturated, which is a neutral color, which is white in this example.

Each color circle controls the rectangle to the left of its respective circle. Both color circles work identically, so I will describe how to use the top circle. The color of the square is determined by the dark gray dot that is on the color circle. The closer to the middle of the circle, the less saturated will be the square, and the clock position of the dot on the circle determines the hue. You can control the hue of the dot by using the **Hue** slider below the color circle. As the slider goes from left to right, the dot will go around the hue values of the color circle in a clockwise direction, starting from the 12:00 position and ending up back there. You can control the saturation of the rectangle by using the **Saturation** slider below the **Hue** slider. This slider will move the dot from the outer edge of the circle to the middle, as it moves from right to left. Try both of these sliders and see how these two dimensions independently tell you a great deal about a color. One suggestion might be to adjust the **Saturation** slider to one value. Then adjust the **Hue** slider through its entire range. Repeat the process but at a different saturation value. Regardless of the saturation, as long as there is some, the same hues are always seen. You can also adjust the colors of the rectangle by clicking in or dragging your cursor on the color wheel.

The reason there are two of these color wheels and the extra two sliders vertically aligned on the far right side of the screen is to allow you to compare and contrast the effects of hue and saturation more directly, by being able to compare two stimuli right next to each other. To see how desaturation can remove all sense of color, pick two highly saturated colors that are different from each other. I usually pick two colors that are at opposite sides of the color wheel from each other. You are now going to use the **All Sat** slider on the far right side of the screen. This slider will make both stimuli have the same saturation whenever you move it. Move this slider to the top of its range to make both stimuli the most saturated possible. Then move the slider to the bottom. The stimuli are clearly different when they are maximally saturated. But as you move the **All Sat** slider down and the saturation of both squares decrease, the two stimuli become more and more similar. Finally, when the two stimuli are completely desaturated, the two stimuli are identical, even though they have different hues according to the wheel. Thus, in a very real

sense, these desaturated stimuli do not have any hue. You can see this point in a different way by making one of the color wheels and its stimulus have maximum saturation, say the top, and the other to be maximally desaturated. Then use the **All Hue** slider. This slider, like the **All Sat** slider, will make both color wheels have the same hue. Moving this slider will cause the color wheel that is maximally saturated to change the color of its rectangle as the **All Hue** slider moves. But for the desaturated color wheel, that rectangle and the dot on its color wheel do not change. For desaturated stimuli, hue is irrelevant and as a result often called achromatic.

[still part of the same media; should this be part of the same media? NEXT PART NOT DONE YET IN MEDIA]

Now click on the **Add Brightness** checkbox. This will convert the color circle into a color solid. The color circle is now in the middle at the widest point of the color solid. Brightness is the dimension that now goes vertically through the color circle. You can now change the brightness of the stimulus as well. In this simulation, because of the limitations of the monitor, you will only be able to decrease the brightness. Monitor luminance takes you up in brightness really only to about the level of the widest part of this color solid. [see if I can fake this - think this through]

Color, Color Mixing, and Newton.

Color has a very odd characteristic that is suggested by the color circle. Colors can be mixed. That may not seem odd but that is because you have done it for so long. Can you try to mix forms or motions? Try to mix pitches, to use an example from audition? Try to mix temperatures? These concepts do not make sense, do they? Most of our sensations and perceptions do not mix in the ways that colors do. Newton's classic experiments with the prisms illustrate the profundity of the idea that colors mix. Open [Experiment 6.x, Newton's Prism Experiments \[link to media\]](#) to try a simulated version of the most basic of Newton's prism experiments. In this experiment, you have a light source on the left side of the screen that projects a very thin beam of light across the screen to the right. Below the beam of light you have two **prisms** that you can move into the path of the light beam. In Newton's original experiment, he used a room and simply blocked all of the windows, except for a very narrow slit in one window and he projected the light on the opposite wall (Newton, 1730/1952). The narrow beam and the dark room are important, as you shall see. You move the prisms by simply clicking on them. First click on the left hand one to move it into the path of the light. The expected rainbow appears on the left. We know this will happen, because we have been told so many times before, but this is really an odd finding. White light, as was explained above, is completely desaturated and said to be without color. But by spreading out the light, suddenly the colors of the rainbow appear. These are the most saturated colors possible and form most of the outer rim of the color wheel. Where did these colors come from in a light that is without color? From our vantage point, it is clear that the white light is made up of many different wavelengths. The prism spreads these wavelengths out because lenses bend the shorter wavelengths more strongly than the longer wavelengths (you can see that in the figure). If you switch the prisms, you will see that the order of the colors in the rainbow will reverse. This spreading out is why the narrow beam and the dark room are important for the experiment. If you use a wide beam through the prism, the light would not spread clearly, but the red wavelengths from one part of the beam would be on the green part from another part of the beam, washing out the rainbow. Also with the light spread out, the rainbow will be much dimmer than the light coming into the prism, so a dark background helps make that rainbow much easier to see.

Next, put both prisms into the path of light. The light will spread out in between the two prisms but will recombine on the other side. Moreover, since the prisms are exactly the same, but just in opposite orientations, the light will resume its original path. So, this experiment demonstrates the mixing of light. It seems trivial now, but it was very important in the history of science precisely because mixing is such an odd thing to do in our senses. Color mixing is a sufficiently important topic that it needs to be examined more closely.

You have heard since your early years in school about color mixing, color circles and even color primaries. You were probably told that there are three primaries, red, yellow and blue. If this is what you have been told, your teacher was discussing what is called **subtractive color mixing [to glossary]**. Subtractive color mixing refers to the type of color mixing that occurs in paints, pigments, and color printers. There is also **additive color mixing [to glossary]** that occurs on computer monitors and televisions.

Additive Color Mixing. It is easier to explain additive color mixing, although you are probably more familiar with subtractive color mixing. To explain additive color mixing, open [Interactive](#)

Illustration 6.x, Additive and Subtractive Color Mixing [link to media]. In this illustration you will be able to manipulate three primaries for additive color mixing to see how it works. When the figure first opens, you will see in the center of the screen three overlapping circles: a red circle, a green circle, and a blue circle. Where the red and green circles overlap, yellow appears. Where the red and blue circles overlap, magenta appears. Where the green and blue circles overlap, the color cyan appears. Finally, where all three circles overlap, you see white (much like the Newton prism experiment). There are two ways to check that I am not cheating here. First and most direct is to use a magnifying glass or jeweler's loop to magnify the screen surface, and you will see that it is made up of dots of red, green and blue and no others. These dots are so close together at normal viewing distances that these dots fall within our spatial summation. As a result, the lights from the different dots have a combined effect on our visual system. The other way to check on this is a bit more indirect but does not require any extra hardware. You can click on any of the circles where they do not overlap another circle and drag it around the screen. Move the mouse slowly, and click on the red circle and drag it so that it no longer overlaps the other two circles. Watch in particular the areas of overlap and how they exactly follow the movement of the red circle. From these examples, the reason that this type of color mixing is called additive is clear: our eyes will add the effects of different colors together using spatial summation.

When you are done with this example, you can click on the **Reset Positions** button at the bottom of the screen. You can adjust the intensity of any of the primaries using the sliders on the right side of the screen. The slider with the red background controls the red primary, etc. Using these sliders you can see how using these primaries can generate a wide range of colors. See if you can get orange.

Subtractive Color Mixing. Subtractive color mixing works rather differently. Click on the **To Subtractive** button at the bottom of the screen. The background will go white and the colors of the primaries will change. In subtractive color mixing, a light with a lot of wavelengths has some of them subtracted out by any one of a number of means. Take a red book, for example. White light from the overhead lighting strikes the red book but it absorbs and subtracts most of the wavelengths of light, leaving only the long wavelengths of light. That is why this book appears red. For subtractive color mixing, the best primaries to use are cyan, magenta, and yellow (not the red, blue and yellow you were probably taught). If you have a color printer, you will find that these are the primaries used for it. Before we go any further, notice something about these primaries: the primaries for subtractive color mixing are the regions where two primaries overlap for the additive color mixing, and vice versa. Press the button that now says **To Additive** and check it out and then return to the subtractive color mixing. (As an aside you might see if you can find these primaries and where they occur in the color wheels in **Interactive Illustration 6.x, Dimensions of Color [link to media].**)

Subtractive color mixtures allow you to make all of the same colors that you would with an additive color mixture, but it is a bit more complicated. Why don't you try and see if you can make an orange again.

With subtractive colors, it is a little bit more difficult to predict what color will appear. That is because, among other factors, the background illumination affects the colors that are seen. When you have the subtractive color mixing primaries on the screen, you have some additional sliders on the screen. Find the sliders labeled **Background**. These sliders allow you to alter the light that the primaries subtract from. Since the background light is made by a monitor, you have the additive mixing primaries available to manipulate the background. You can change the background to any color that your monitor can possibly produce, using those sliders. Let us try one example. Make sure that the three primaries are at full strength for this illustration. Take the level of red in the background and gradually remove it until there is no red left in the background illumination. Before you do this task, see if you can predict what will happen. Then try this example and return to the text.

What happened? The background becomes cyan, because only blue and green are in the background. The cyan primary disappears, because the cyan primary subtracts red and there is no red in this stimulus to subtract. The magenta primary becomes blue. The magenta primary subtracts green wavelengths, leaving red and blue. But there is no red in the stimulus to leave, so the resulting color is now blue. Using that idea, see if you can explain why the yellow primary becomes green.

Effect of the Illuminant. The color that is associated with most objects in the world is generated by subtractive color mixing. That is because most objects reflect light and do not generate their own light which is needed for additive color mixing. Open **Media Figure 6.x, Effects of Illuminant [link to media]** for a chance to explore this issue. The main part of the screen is a picture of me and my children

from one vacation [examine for the best picture I have]. In this picture all of the objects, the people, the sea, the grass, the ground, all reflect light to be seen. What light they reflect is in part dependent upon the wavelengths of the light falling on the screen. The controls on the right allow you to adjust the color of the illuminant falling on all of these objects. The box on the lower right of the screen will show you the color of the illuminant, or what the color of a white sheet of paper would look like under this illumination. As you adjust the levels of the red, green, and blue in the illuminant, the square and the scene will adjust automatically so you can see the result of your change. If you remove the green from the illuminant, the grass becomes very similar to the orange t-shirt worn by the boy on the left. Try the other controls and in all of the different combinations possible to see what happens.

You might find this interesting but of little practical value. However, illumination changes all the time. The relative balance of long and short wavelengths in sunlight changes throughout the day (Silverstein & Merrifield, 1985 (see if I can get the reference for this data from them)). In addition, the illumination from your standard incandescent light and fluorescent light are very different (Can I get a figure for these values (and add buttons to mimic some of these changes)). While there are mechanisms in our visual system that can keep many of these events from affecting our vision (see Color Constancy in Chapter 9), these differences can cause many subtle visual discriminations. Recall from the illustration, how removing the green from the illumination made the colors of the t-shirt and the grass appear more similar. The appearance of color mixtures change under different illuminations and how the color mixture changes depends on the wavelengths making up that mixture and the light in the illuminant. So if you pick to different fabrics so that they match either others under fluorescent light, they may not match under incandescent light (ref?).

Color Matching Experiments

As can be seen, color mixing and matching is a complex set of phenomena. The first theory of color vision is the trichromatic theory, and it excels at explaining both how and why color mixing and matching works and even allows for precise predictions of color matching. Before getting into this theory, it might be useful to try out some color matching experiments so that you will have a context for what will be discussed below.

Open [Experiment 6.x, Color Matching Experiment \[link to media\]](#). In this experiment, you will be able to try some of the different features of a standard color matching experiment. This is an experiment, so you will be able to manipulate the features of the stimulus to see how these features affect your results. When you first open the experiment you will see the stimulus parameters setting window that you have seen before. You can use this screen to determine the features of the stimulus. The stimulus will be a small circle divided in half. The top half of the circle will be the standard and the bottom half will be the comparison that you will adjust to match to the standard. Surrounding the stimulus will be a background field, called the annulus in this version of the experiment.

The first feature of the stimulus that you can adjust is the size of the stimulus. It turns out that there are different color matching functions for very small stimuli and those that are larger (Silverstein & Merrifield, 1985), which principally has to do with the layout of the different classes of cones on the retina. If you are interested, you could examine these differences, but they will not be considered further here. For more information on this feature of color vision see XXXX (). In addition, the sizes of all of the objects are in percentages of the area where the stimulus will be drawn.

The next feature is the gap between the standard and comparison fields. What do you think the impact of putting a gap between the standard and comparison might be? Next is the color of the standard. The color of the standard is controlled by the strength of the red, green and blue elements, as in the additive color mixtures (which is the way that monitors work). The program randomly selects a color and you can use it, but you are free to choose any you wish. It might be easier to make your matches if you choose it so that at least one of the three primaries is at its maximum (255).

Next, you can choose the size and color (from a predetermined list to keep things simple) of the annulus background. As with simultaneous contrast, the surrounding colors can influence what we see. Another feature of the stimulus situation that you can change is the color of the background outside of the annulus to see if it has an effect. You can also test the full range of colors, or just a smaller range that is

called **Pseudo-Raleigh**¹. You can also select the number of trials in the test. The experiment will use the method of adjustment.

After selecting all of your values, or just using the defaults (which is advisable for now), press the **Done** button to start the experiment. When the experiment screen first appears, the stimulus will be on the left half of the screen. Remember, the top half of the central circle is the standard and the bottom half is the comparison. On the right half of the screen is the control for the comparison. If you are doing a full range match, you will have the color circle you have seen before. You can use it the exact same way as before, and dragging your mouse directly over the color circle works as well as using the **Hue** and **Saturation** sliders. If your standard has at least one of the primaries with a maximum (255) value, then those controls will be sufficient to make a match. If none of the primaries are at maximum, then there is the **Luminance** slider to adjust the last dimension of a color. If you are making a **Pseudo-Raleigh** match, then you will have two vertical sliders, one for the red primary and one for the green primary which you can adjust directly to make your match. When you have made your match press the **Match** button at the bottom of the screen. The next trial will begin with a new random color in the comparison.

Go ahead and try an experiment, and then return here. When you are done with the experiment, you can display your results in many different ways. The default display of the data is displayed with the table at the bottom of the screen giving you the values of the red, green and blue primaries on your monitor for the standard with the mean, standard deviation, and standard error for the comparison trials below. If the standard deviation and standard error cannot be computed (too few trials) a **-1** will appear in the proper cells of the table. You can see how well your average match agreed with the standard. At the top of the screen, the data is plotted in chromaticity coordinates which will be discussed later. The outer curved shape is a cousin of the color circle. The standard is the colored circle, in the color of the standard, and the light gray dots are your matches. You can also see the results in some other ways. One way which you might find interesting is the **RGB Distance** table, which can be selected using the drop down menu on the right hand side of the screen. The differences between the standard and the comparison when it matched the standard for each primary are added using an equation similar to the Pythagorean Theorem, but for a three dimensional triangle to give the absolute size of the error.^{2 3} The larger this distance value on average, the worse you matched the standard.

Experiments similar to this form the basics of much of what is known, scientifically, about color mixing. It is these types of experiments that form the background for the trichromatic theory that will be covered next.

The Trichromatic Theory and Color Matching

While there have been many theories of color vision throughout history, the first successful theory was the proposed by Thomas Young, the 19th century philosopher and scientist, and later further developed by Hermann Helmholtz, perhaps the 19th century's greatest scientist. Their theory is called the trichromatic theory. Breaking down the word trichromatic, you have tri which means three and chromatic which means colored. This theory proposes that color vision is based upon there being three elements in our visual system that respond differently to different wavelengths. Young and Helmholtz did not know about cones, but it is not a coincidence that we have three classes of cones. This theory emphasizes explaining how we make color matches. Matching is a common and even crucial activity. Examples of this color matching activity are a painter matching the color of paints to a color in the world, the matching of the color of fabrics, and the reproduction of colors in a photograph, movie or television. All of these tasks involve

¹ Raleigh matches are matches of long wavelength lights that can be made with only red and green primaries in normal color vision observers (REF, XXXX). The reasons for this will be clear when the trichromatic theory is explained (note the limits on the short wavelength cone). These are pseudo-Raleigh matches because a monitor cannot produce single wavelengths).

² The formula is $\text{error} = \text{Square root of } ((r\text{Match}-r\text{Standard})^2+(g\text{Match}-g\text{Standard})^2+(b\text{Match}-b\text{Standard})^2)$ where r, g, b refer to the primaries.

³ The color values in this and all color demonstrations are somewhat approximate. There are differences between how monitors and computers behave that I cannot control or anticipate while programming on my system.

color matching to some extent. Televisions do not reproduce the physical wavelengths of any object, but they often reproduce the color.

In fact, that is one often missed fact about the difference between the wavelengths of light and color. Each photon of light has one, and only one wavelength. They never blend. Colors mix, wavelengths do not.

In color vision then, a new phenomenon arises that does not have any relevance to the physical stimulus. This new phenomenon is the color match between two objects that are made up of dissimilar wavelengths. This match is called a **metamer [to glossary]**. To understand how matamers arise, an important principle needs to be understood. This principle is sometimes called the **Principle of Equal Action [to glossary]**. The principle of equal action's most important implication is that once a photon is absorbed all information about the wavelength of that photon is lost. Essentially the principle claims that once absorbed all photons have the same effect on the con. Regardless of the wavelength of the photon, if it is absorbed, the same number of neurotransmitters is released by the cone. These neurotransmitters do not have little tags on them telling the next cells, and ultimately the brain what wavelength of light was absorbed. At this point, it might seem that color vision is not possible. The trichromatic theory best explains the possibility of color vision. Color vision from the point of trichromatic theory is the ability to make discriminations based solely on wavelength, that is, no other feature of a stimulus, such as intensity, can mimic the experience of wavelength. This idea will be developed below.

Color Matching in a Monochromat

It is stated in most texts that when we are using our scotopic vision, we do not have color vision. In starting our discussion of what color vision is in the trichromatic theory, I will try to demonstrate what it means that when only rods are active, you are color blind. This argument will be the same for any organism that uses only one type of receptor to see.

Open [Interactive Illustration 6.x, Color Matching in a Monochromat \[link to media\]](#). In this illustration, you will examine how to make a match between two physically different stimuli in a person or animal, with only one type of receptor. Imagine an experiment where the participant is presented with two small circular patches of light. On the left side of the screen is the standard stimulus, which the experimenter determines. On the right is the comparison stimulus. The experimenter will set the wavelength of the comparison, but the participant will be allowed to adjust the intensity of the comparison stimulus. The task of this participant is to make the comparison look identical in all respects to the standard. In the interactive illustration, the screen can be divided into a right and left half. The left half of the screen represents what is happening with the **Standard** stimulus both physically, psychologically and physiologically. The same information for what is happening with the **Comparison** stimulus is presented on the right half of the screen. The two circles represent the appearance of the stimulus to the participant. For both the standard and comparison portions of the screen, you can break up the screen into four parts. From top to bottom you have: a bar graph showing the physical intensity of the stimulus, a small table calculating the how much of the light is absorbed by the receptor, and a plot of the spectral sensitivity of the receptor. On this last graph, the x-axis is wavelength and the y-axis is sensitivity or how likely that wavelength is to be caught by the receptor. Also on this graph is a vertical line indicating the wavelength of the stimulus. Towards the middle of the screen is a circle representing how the stimulus looks to this participant, so you can see the impact of the numbers in the table. Let us explore each of these elements of the screen in more detail.

At the top of the screen are two intensity graphs that indicate the intensity of the two stimuli being viewed. These are bar graphs that represent the physical intensity of the standard stimulus and comparison stimulus, respectively. The higher the bar, the more intense the stimuli will be. The bar gets brighter the higher it is, to serve as a visual reference of this fact. The numbers for intensity are arbitrary and it does not matter what units of intensity would be used, the basic idea holds true. If it helps, you might think of the intensity as the number of quanta of light per second entering the eye. You can adjust the intensity of the comparison using the vertical slider to the right of the spectral sensitivity plot of the receptor.

The **Activity Summary** table in the middle summarizes the response of the receptor to the incoming stimulus light. The first line of the table is the **Input Intensity** of the stimulus which comes from the bar graph. The second line is the sensitivity of the receptor to that wavelength which comes from the spectral sensitivity plot, and it is labeled **Sensitivity**. These two numbers are multiplied together to

give the number shown in the last line, labeled **Absorbed**. The greater the number of quanta absorbed, the brighter the stimulus will appear. Here is where the principle of equal action plays a very important role. If the number of quanta absorbed is the same for both the standard and the comparison, then the signals traveling from the receptor to the rest of the brain will be the same, and the two stimuli will appear identical. These bottom lines from the two tables are the values used to generate the two circles. Remember that these circles represent how the stimuli look the participant.

Below the **Activity Summary** tables are the graphs of the spectral sensitivity for the receptor. The curves represent the proportion of quanta that will be captured at each wavelength by that receptor. Notice that wavelengths near the middle of the range shown are absorbed more often than wavelengths at the extremes. The receptors are the same on both graphs because the same eyes will be viewing both stimuli. So the spectral sensitivity plots are identical for the two stimuli. The vertical line in the graph indicates the wavelength of the frequency of the light that is the stimulus. So, the graph below the **Standard** circle shows the wavelength that is present in the standard stimulus. The same is true, respectively, for the **Comparison** circle. Where the curve crosses that line indicates how sensitive this receptor is to that wavelength. If the sensitivity curve crosses the vertical line at the 50% point, then on average 50% of the light coming in will be absorbed.

On the comparison side, there are two sliders that surround the spectral sensitivity graph. The **Intensity** slider on the right side of the comparison graph controls the intensity of the comparison stimulus. The **Wavelength** slider at the bottom of the comparison graph adjusts the wavelength of the comparison stimulus. You can see the **Sensitivity** line in the table change with the changes in wavelength, and the **Input Intensity** line will change with the change in the **Intensity** slider. The resulting number **Absorbed** will be changed to represent the new values for the stimulus.

Your task is to act like a participant. You can only control the intensity of the stimulus. Using the **Intensity** slider and not the **Wavelength** slider, adjust the comparison intensity and see if you can match the comparison to the standard. The word **Match** will appear on the screen in red when you succeed. If you have trouble using your mouse to make the match, you can use the up and down arrows, if you have just used the **Intensity** slider. After awhile, press the **Reset** button and try the task again with a different randomly selected standard and comparison wavelength. After several trials of this exercise, don't change the standard, but choose a new wavelength for the comparison using the **Wavelength** slider. Then, again try to make a match between the standard and this new comparison, and see if the wavelength of the comparison has any effect on your ability to make a match. My question to you is, can you find any combination of standard and comparison wavelength where you cannot make a match? Try several matches and then return to the text.

What you will find, is that no matter what the wavelength of the standard and comparison are, you can always find a comparison intensity that causes a match to the standard. Think about that. Regardless of the wavelengths of the two stimuli, in a person with one receptor, it is always possible to adjust the intensity of one of them to make it look identical to the other one. That is an important implication of an animal or person with one receptor. There is no unique experience related to wavelength. Intensity alone can be used to make a match. In this case, there is no way that one can say that this person or animal with one type of receptor has color vision. This person or animal is called a monochromat for mon meaning one, and chromat meaning color. What happens for an organism with one receptor is directly analogous to watching a black and white television. Differences between objects occur because of differences in brightness. Color contributes nothing to the experience.

The situation is dramatically different, when the person or animal has two types of receptors. Let us now examine an organism with two different types of receptors.

Color Matching in a Dichromat

A dichromat is an animal or a person that has two different classes of receptors. The different classes of receptors are defined by the fact that each class of receptor has a significantly different spectral sensitivity function. Open [Interactive Illustration 6.x, Color Matching in a Dichromat \[link to media\]](#) and you will see what these statements mean. You will see a layout very similar to **Interactive Illustration 6.x, Matching in a Monochromat**. You will see the bar graph for intensity, the table for the effect of light on the receptors, the graph of the spectral sensitivity of the receptors, and the filled circles showing what this stimulus might appear like to this person. The most obvious difference between this

illustration and the one for the monochromat is the two spectral sensitivity curves on the graphs of spectral sensitivity. Each of these curves shows the spectral sensitivity of one of the two receptors in the eye. Let us call these receptors cones as they represent the spectral sensitivity of two of our cones. The curves are drawn in different colors for clarification purposes only. The cones can be distinguished by the wavelength of the light to which they are most sensitive, that is the wavelength of the light that they are most likely to catch. The cone with the cyan sensitivity has a peak wavelength at a shorter wavelength than the cone drawn in orange (or orangish-yellow). So to be clear, I will refer to these cones as the S (for short wavelength) and L (for long wavelength) cones. There are also some important changes to the table as well. In it there are now two columns, one marked **S** and one marked **L**. These two columns will summarize the response of each class of cone to the stimulus light separately. Examine the **Standard** for a moment. The **Intensity** is the same for both the S and L cones because it is just one stimulus and both cones, therefore, receive the same stimulation. However, each cone is differentially sensitive to that wavelength and thus each cone absorbs a different number of quanta of light at that wavelength, and this difference is shown in the **Sensitivity** row. As a result, each cone will absorb a different number of photons from the stimulus, and this difference is shown in the **Absorbed** row of the table. Assuming that the signals from each cone class is preserved in some fashion for the brain, there are now two signals going back to the brain about this stimulus. To make a match, now, the response of both cones has to be matched, not just one. If one cone matches, but the response to the other cone is different, then the brain can use the signal from the other cone to determine that there is a different stimulus in the world. There is also a third column in the table labeled **S/L**. This column will be discussed later, but you might observe it as you work with this illustration and see what its significance might be.

Imagine you are the participant in this experiment. As in the monochromatic experiment, you have the chance to adjust the intensity of the comparison stimulus. See if you can make a match. After you have tried awhile, adjust the wavelength of the comparison and try another. You can even press the **Reset** button and see if that helps you to find a condition where you can make a match. If you succeed, the word **Match** will appear with a red background just like in the monochromat situation. A strategy that might be useful would be to change the intensity of the comparison stimulus until the output of the **S** cone for both the comparison and standard stimulus match. Then examine the **L** cone response for the standard and comparison and see if they match. Then, just to check, reverse the process for the two cones. Make the match on the response of the two **L** cones and see if the **S** cones match. Can you find any comparison wavelength, again other than the same wavelength as the standard, where you can make a match to the standard on both cone responses? Try this task several times before returning to the text.

You will find that there is no way to match both cones, and the answer as to why you can't make this match is to be found in the third column under each graph of the cone responses. The **S/L** that heads this column refers to the ratio of the absorption and response rate of the S cone over the L cone to the stimulus. It is equivalent to the height of the two curves at each wavelength. The relative sensitivity of each cone at a given wavelength translates into their relative activity at that wavelength. If this ratio is different for the two stimuli, then there is no way for the activities of the two cones to be the same for any two different wavelengths. Since the spectral sensitivity curves for the two cones do not match up, this ratio will be different for every wavelength. This animal or person has color vision. If the two stimuli have different single wavelengths, then this person will be able to pick up this difference regardless of what is done to the intensity of the two lights, which is our definition of color vision for the trichromatic theory.

Let us try something new with this illustration now. Click the **Second Primary** checkbox, next to the **Reset** button at the bottom of the screen. Clicking this checkbox will change the configuration of the screen. From the participant's standpoint, the comparison stimulus has changed so that it is now made up of two wavelengths of light, and they will be able to adjust the intensity of each wavelength independently of each other. To simplify the discussion, I will call these two wavelengths in the comparison primaries. The reason for the word choice will be made clear later. Think about it for now. The wavelengths of the primaries in the comparison are now fixed at 475 nm and 620 nm in this experiment. The perception of the comparison is now the result of the effects of the two wavelengths, not one. This change to the comparison is shown on the screen in several ways on the comparison side of the screen. In the intensity bar graph, there are two bars, one each for the intensity of the two primaries. The blue bar is for the 475 nm primary and the red bar is for the 620 nm primary. This coding scheme is used

throughout the comparison side of the screen. On the graph of the spectral sensitivity of the cones there are now two vertical lines, again the blue line is for the 475 nm primary and the red line is for the 620 nm primary.

The participant's perception of the comparison is now determined by the sum of the effects of these two wavelengths. This fact is represented by the changes in the table. Basically, the table has split into two sets of columns under the comparison side, one for each wavelength. The columns for each primary is labeled with the wavelength of the primary and has a dim background color of blue or red to match the color coding of the rest of the information from the primary. But our perception of the stimulus is determined by the sum of the effects of each wavelength on each cone, think spatial summation from Chapter 4. This summary of the effect of each cone is on the bottom row of the table labeled **Total**. It is the value in this total row that must match the values in the **Absorbed** row of the standard. In addition, there are now two intensity sliders next to the graph of spectral sensitivities for the comparison. The left hand intensity slider adjusts the intensity of the 475 nm primary, and the right hand intensity slider adjusts the intensity of the 620 nm primary.

The participant's task in this experiment is to make a match of the standard by only adjusting of both primaries. There are two ways you can do this as you fill in for the participant. You can adjust the **Intensity** sliders directly, mimicking the way a participant actually would perform this experiment. The **Intensity** slider for each primary is labeled with the wavelength of the primary. It is worthwhile to try this method to some extent, to see how adjusting the intensity on one slider alters the comparison. While there are strategies to make this happen, it is relatively slow and time consuming. The easy way to make a match in this illustration is to press the **Match** button in the bottom of the screen next to the **Second Primary** checkbox. This button will cause a simple calculation to be performed that will give you the answer and display it on the screen. This **Match** button will work as long as the wavelength of the standard is between the two primaries of the comparison. Try it. You also now have a wavelength slider below the standard graph that will allow you to change the wavelength of the standard. Adjust the wavelength of the standard with the slider, or press the **Reset** button and see if you can find a standard that cannot be matched. Try several.

First, let us discuss what you will have found in your attempts to make matches to a standard with a wavelength between the wavelengths of the two primaries (475 and 620). Every time you pressed the match button or did it manually, you should have found a match. Any standard with a wavelength between these two primaries can be matched by these two primaries. You can see why this would happen. As you adjust the intensity of the two primaries, you will find that the ratio of their output would change. Eventually you will find the ratio of the output of the two cones for the comparison will match the ratio of the standard. Then the situation is like matching on a monochromat. You simply need to adjust the intensity of the two primaries, keeping the ratio constant until the outputs of both cones matched are simultaneously. At this point, the brain would have no way of perceiving a difference between the two stimuli.

Your attempts to make a match to a standard with a wavelength outside the range of the two primaries would be a different story. If you did it manually, you would not have found a match. Pressing the match button would bring up a little error window telling you that a match is not possible. (There is a mathematical solution to the match, but it would require negative light on one of the primaries. As I have never experienced a negative amount of light, it seems safe to say that this type of match is impossible.)

To summarize what has been discovered so far: With a monochromat, any wavelength can be matched by any one other wavelength by simply adjusting the intensity of that wavelength. With a dichromat, the organism now has true color vision. Two single wavelengths will never appear the same. However, matches still are possible, but it takes two wavelengths mixed together to match the other wavelength. See a trend here?

Trichromacy

The trichromatic organism has three cone classes. In the human case, the three cones have peak sensitivities shown in Table 6.x (Alpern & Wake, 1977; Stockman, Macleod, & Johnson, 1993). The cones are named according to the relative wavelength of their peak sensitivity; S refers to short, M to medium, and L to long. These cones also are often referred to as B for blue, G for green and R for Red. However, these names are somewhat misleading. These cones absorb light from a much broader spectrum of wavelengths than these names indicate, and even their peak wavelengths cannot be described accurately by

these colors. So for our purposes, we will follow the convention of calling the cones S, M, and L, for short wavelength cone, medium wavelength cone, and long wavelength cone.

Open [Interactive Illustration 6.x, The Trichromatic Theory \[link to media\]](#). In this illustration, the basics of the trichromatic theory will be illustrated. The color cyan represents the S cone throughout the figure, the color yellowish-orange (it depends upon your monitor) represents the M cone throughout, and the color magenta represents the L cone. The relative sensitivities of the three cones are shown in the graph on the left side of the screen, and the relative response of the cones is shown in the bar graph on the right. The table below the graph of the spectral sensitivities of the cones is analogous to what you have seen before. The table simply spells out what is being shown in the two graphs. The circle at the bottom shows a representation of what the stimulus looks like to this trichromatic observer.

The slider below the sensitivity curves controls the wavelength of the stimulus. As you move that slider across the range of frequencies that can be seen, you can see how the relative firing rates of the cones change in a regular and predictable manner for each wavelength, giving the brain access to this information in the environment. In addition, you can adjust the intensity slider on the right side of the sensitivity graph, and you can see that the relative firing rate, as shown in that graph, does not change as intensity changes. So, just as with the dichromat, there is not a separation of how intensity is processed in the brain (by overall response strength) and wavelength information is processed (by relative firing rate).

[I AM DEVELOPING A FIGURE FOR COLOR MATCHING A TRICHROMAT. IT IS NOT DONE BUT IS LISTED ON THE WEBSITE]

The CIE Diagram

In 1931, an international commission on illuminations, the Commission Internationale de l'Eclairage or CIE, presented the results of its efforts to codify the growing scientific knowledge of color mixing. They developed a system to predict the results of color mixing precisely based upon psychophysical experiments using the results from 300 participants. From these 300 participants, they developed the average observer called the [GETNAME]. This system is built around the trichromatic theory. Their initial results are shown in [Interactive Illustration 6.x, 1931 CIE Diagram \[link to media\]](#). The irregular shape is what is called the chromaticity diagram. The curved outer edge that goes from lower left through the top to the lower right represents the spectrum, those colors observed in Newton's prism experiment. The straight link at the bottom represents those colors obtained by mixing the longest and shortest wavelengths that can be seen. Other than the shape, the chromaticity diagram behaves just as the color circle. The outer edge represents the most saturated colors, and there is a white region in the middle (shown) where the colors become completely desaturated. In addition, color mixes are always found on a line connecting the two colors used to make the match.

Behind this image are a set of equations [could I put some of them into an appendix?] that are used to precisely specify the result of any mixture of any number of colors. To make this happen, and given that mixtures are always limited by the primaries used, the CIE chose imaginary primaries situated so that all possible colors can be determined in their system. The primaries are for computational convenience only and are **x**, **y**, and **z**. You can see the **x** and **y** on the figure, but not the **z**. When the CIE set up this system, they made the system behave very agreeably in that for every color, $\mathbf{x} + \mathbf{y} + \mathbf{z} = 1.0$. So **z** can always be found because $\mathbf{z} = 1 - (\mathbf{x} + \mathbf{y})$. Every color is precisely specified by two chromaticity coordinates (**x**, **y**) and its luminance.

The development of this system was instrumental in the development of color reproduction technologies such as photography, movies, and television. Recall that the first CIE system came out in 1931 and the first color films came out later in the 1930's (get the exact names). To make the CIE system work, it helps to understand the concept of the color gamut. Press the **Show Gamut** check box at the bottom of the screen. A triangle will appear on the chromaticity diagram, representing a color gamut for a typical television. The corners of the triangle are the chromaticity coordinates of the three primaries for the television. Since the mixture of two colors fall on the line between those two colors, the triangle encloses all possible colors that can be reproduced by that television. As can be seen, while many colors on the chromaticity diagram can be matched, there are entire regions of colors that cannot be copied by a television. [what other points do I want to make here].

The Number of Cones We Have

So far the presentation of the way our visual system works has been traditional in standard. To this point, you've been led to believe that there are three types of cones in the normal human visual system. Actually, the discussion of color vision has carefully stated that humans do not have three types of cones

but three classes of cone. In recent years, evidence has accumulated that there are actually several types of cones grouped into these three classes. Only one type of short wavelength cone has been discovered, but several have been discovered for both in middle and long wavelength cones. The evidence has come from many sources, both psychophysical and physiological (Dartnall, Bowmaker, & Mollon, 1983; Mollon, 1992; Neitz & Jacobs, 1990; Nathans, Piantanida, Eddy, Shows, & Hogness, 1986).

These findings do not change the basic picture that has been provided so far. It seems that even if an individual has more than one long or middle wavelength cone, the different types of cones behave in concert as a single cone class. Humans are still trichromatic. However, there is more variation in how different people perceive colors than had been previously believed. The variation in color perception across individuals may be even more pronounced in people with color deficiencies, even people with the same type of color deficiency.

Cones in Animals

[Some of the varieties and what it might mean for their vision.]

The Color Opponent Theory and Color Naming

Limits to the Trichromatic Theory

While the trichromatic theory has proven to be a very powerful theory, it certainly does not explain all that is known about our color vision. In this section, a few different color experiments and demonstrations will be performed to highlight some of the limitations of the trichromatic theory.

For the first experiment, open [Experiment 6.x, Color Naming \[link to media\]](#). In this very basic experiment, you will be asked to try to name or describe colors using a limited set. In the first set, you will be limited to the names of the three primaries for color additive mixtures (**Red**, **Green** and **Blue**). When the screen first comes up, you should see a blank screen with a **Start** button at the bottom of the screen. When you press the **Start** button, you will be presented with a color square in the middle of the screen and at the bottom of the screen, will be check boxes for the three primaries (**Red**, **Green** and **Blue**), a check box that says **Not Possible**, and a **Done** button. For this color, select those check boxes that you need to describe or name that color. For example, if you see a red, just check the **Red** checkbox. If you see a purple which looks like a mixture of red and blue, check both the **Red** and **Blue** checkboxes. Select whatever combination you need to describe that color. If there is something about that color you cannot describe with the three primaries, select the **Not Possible** checkbox. If there is a color that looks to be a mixture of red and some color you cannot describe with the three primaries, select the **Red** and **Not Possible** checkboxes. When you are done with a trial, press the **Done** button to clear the check boxes and go to the next trial. The colors are generated randomly, so the next color might appear similar, just select your colors again. There are 30 trials. At the end of the trials your selections will be summarized on the screen. Do this version of the color naming experiment and when you get your results, return to the text.

Your results page shows a small square with each color you judged, below which are shown the check boxes you selected. If you selected the **Red** check box then there will be a red **R** below it. The situation is similar if you selected the **Green** and **Blue** check boxes. In this case, you will have a green **G** or a blue **B** below the color box, respectively. If you selected the **Not Possible** checkbox, then the word **Cannot** will appear below the square. I will take a risk (rather small one actually) and suggest that there are some colors you could not find a match for. Examine those trials and see if you can find any pattern to those colors that you had trouble describing, and then return again to the text.

If your judgments are like most people's, you will have found that those colors that you had trouble describing have some element of yellow in them. Purples appear clearly as mixtures of red and blue. Aqua and cyan appear as mixtures of green and blue. But yellow, made from the additive mixture of red and green (go back to [Interactive Illustration 6.x, Additive and Subtractive Color Mixing \[link to media\]](#) if you need to check this statement out) does not appear as a mixture of red and green. Moreover, colors such as orange appears as a mixture of yellow and red, not as a lot of red and a little green, which is what an orange is. Yellow, unlike all other mixtures in additive color mixing, does not appear as a mixture. If the trichromatic theory explained all that was needed to be understood, then yellow should appear as a mixture, just like the purples. Yellow is what I will call a unique hue, along with red, green and blue. If this is the case, then let us repeat the color naming experiment but now adding a **Yellow** checkbox to the

list of colors to select. It will be right after the **Blue** checkbox. To start this version of the experiment, simply press the **Start** button which is below the results on the screen. Again there will be 30 trials, and the results will be displayed in the same manner, but now with the chance for a **Y** to appear below the color square. When you have completed your trials, return to the text.

First, did you find any colors you could not describe? Most will find that the addition of the yellow as an option to select, makes for a sufficient number of colors to do the experiment. Let us do some counting and see if there are any patterns in the data. In this case, we are not interested in those colors that could be described with just one of the color names, red, green, blue or yellow. We are interested in those that needed more than one color name. How many mixtures of red and blue did you find? How many of red and yellow? How many of green and blue? How many of green and yellow? Now how many of red and green? How many of blue and yellow? You should find that you do not find any mixtures for the last two (red and green, blue and yellow). We already discussed how red and green form yellow, which does not appear as a mixture of red and green but a unique hue. Red and green cancel each other out and become yellow. You can see this in [Interactive Illustration 6.x, Additive and Subtractive Color Mixing \[link to media\]](#). Also in this figure, you can see why you will not see a mixture of blue and yellow. If you think about it, the blue and yellow when mixed in that figure, become the white region in the middle of the mixture area. Blue and yellow cancel each other out and become a neutral color. If you look again at your results, you describe the colors with at most two color names drawn from the list of red, green, blue and yellow. In addition, red and green never show up together, and blue and yellow never show up together. These results are not predicted by the trichromatic theory, and have profound implications. This experiment is a very simple version of a famous large scale study carried out by Boynton & Fordon (1965; Bornstein, 1973; Quinn Rosano & Wooton, 1983; Sturnheim & Boynton, 1966).

The blue/yellow results above may remind you of something you may have learned earlier, perhaps in elementary school. Do you recall complementary colors? Complementary colors are pairs of colors that when mixed form a neutral color, a white or gray. Blue and yellow form a complementary pair. You can explore more about complementary colors on [Interactive Illustration 6.x, Complementary Colors \[link to media\]](#). When you open this figure, there are three color squares. On the left is a randomly selected color from the outer rim of the color circle. It is the **Standard** color, as labeled. On the left is a second color, labeled **Find the Complement**. The color of this square is controlled by the color circle below it. The color square in the middle is the **Mixture** of the two outer squares. The color circle works just as it has before, except that the all three color squares will be represented on it. The right hand color square is shown by the solid dot on the color circle just as before. The standard is shown by the dark circle on the outer edge, and the mixture will be the circle that always appears between these two colors (recall mixtures always falls on a straight line between two colors used to make the mixture). Your task is to find the complementary color to the **Standard**. When you have found the complementary color, the mixture will appear white. Once you have found the complementary color for that **Standard**, you can have a new **Standard** randomly selected by pressing the **New Standard** button. Try a few and see if a pattern emerges in what colors form complementary pairs.

What you should have found is that the best complementary color is directly across the color circle, so that the line from the two complementary colors goes through the center of it. The same pattern holds for the CIE diagram as well. From trichromatic theory, we developed the idea that it takes the presence of all three primaries to get to a neutral color. We are saying that for any color, there exists one other color that when mixed with the first color, the mixture has no color. There is a folding of color space from the line of wavelengths into something like the color circle or CIE diagram that is not immediately apparent from trichromatic theory. While complementary colors are not as problematic as the presence of a unique yellow, it does suggest something new may be going on. These complementary colors also show up in some other interesting visual effects. These effects have their own implications about color vision. Let us look at a couple now.

Consider first, the color aftereffects. You have probably seen them before, say an American flag in green and black stripes with a yellow field of black stars. After staring at it for awhile, you then looked at a white wall or piece of paper and you see the flag in desaturated versions of the proper colors. Fun, but what does this effect tell us about how our color vision works? Open [Experiment 6.x, Color Aftereffects](#) and you will be able to explore in more detail what occurs in a color aftereffect and begin to understand what it might imply about the nature of color vision. When you first open the experiment, you will see a

screen that will allow you to select the color of the stimulus to which you adapt. At the top will be a circle showing you the color currently selected (which is randomly selected by the experiment at the start), and at the bottom is the color wheel where you can adjust the hue and saturation of the color. You can pick any color you wish, but I recommend starting with a primary such as red, green, or blue, as we are very familiar with these colors. You control the color wheel just as you have all of the others that you have used. When you have selected the color that you want to test, press the **Done** button at the bottom of the screen. There is also a drop down menu that says **Single Test** at the present time. You will find out what that does later.

After you press the **Done** button, you will go to the ready screen. There will be a dark fixation mark in the center of a white field that will serve as the background for this experiment. At the bottom of the screen are a **Start** button and a slider where you can control the duration of adaptation. The adaptation is set for 30 seconds as a default and should work for most people. If your aftereffects are rather weak, you can lengthen this value, and for most people it will strengthen the aftereffect. Before you press the start button, it is important to understand what will happen during and after adaptation. After you press the **Start** button, the stimulus you chose will be presented centered on the fixation mark. Try to keep your eyes on the fixation mark during adaptation. After the adaptation period is done, the screen will go completely white, and even the fixation mark will be removed. You will probably still see something the shape of the adaptation stimulus right in front of where you are looking. Try to notice what color it is. If it fades, blinking often will make it appear more strongly again for a short period of time. At the bottom of this screen is another **Done** button. When you are clear as to what color your aftereffect is, press this button.

After you have pressed the **Done** button, you will see a screen that is basically the same as was used for examining complementary colors. The square above the word **Standard** is the color of the adapting stimulus. The color wheel below the **Find the Aftereffect** square, you should use to find the color of your aftereffect. The **Mixture** square is the mixture of the two color squares, just as it was for finding complementary pairs. Now that you have a sense of the experiment, go and try it and then return to the text. If you have trouble making this measurement, you can press the **Done** button at the bottom of the screen and start over, and the color that will be initially selected to run will be the color you just used.

Examine your color wheel carefully. What you will likely find is that your aftereffect is on the line connecting the adapting color and its complement or near it. Most likely you will find the aftereffect rather desaturated, so the mixture will not be a neutral color, but if you make your aftereffect more saturated (easily done with the **Saturation** slider), you will find the mixture of the adapting color and the aftereffect become a neutral color or very close to it. Repeat the experiment one or two more times to see if these results hold. Press the **Done** button and try the experiment again, picking a new standard color, just to make sure the result is not dependent upon some particular adapting color.

Again, no matter what color you choose, the aftereffect tends to be a desaturated version of complementary color. You can verify this by going to the screen at the start of the experiment where you pick colors, and using the drop down menu at the bottom of the screen select the **Comparison Test** version of the experiment. The color choosing page will change to show something very like the complementary color screen, but with two color wheels, one for the **Standard** and one for the labeled **Right Hand Standard**. In this version of the aftereffect experiment, you will adapt to two differently colored stimuli simultaneously. You use the left hand color wheel to choose the color of the stimulus that will be on the left hand side of the fixation mark, and the color wheel on the right to choose the color that will be on the right. You can choose any color you want for this **Right Hand Standard**, but for our purposes choose the complement. Remember you will know when you have the complement, when the **Mixture** is white. Then press the **Done** button. You will see the same fixation mark and the same controls at the bottom of the screen. When you press **Start** button, the two adaptation stimuli will appear, one to the left and one to the right of the fixation mark. After adaptation, you will have the same white screen. If you have picked your complements well, you should have the two colors flip from one side to the other on the screen, though desaturated, after adaptation.

This is an interesting outcome that color aftereffects move towards the complementary color. Aftereffects have been discussed before. Recall the Blakemore-Sutton effect. In the Blakemore-Sutton effect, there was no sense of a complementary spatial frequency. The spatial frequency of the aftereffect moved away from the adaptation spatial frequency. In many respects, the trichromatic theory is built like the model that was built for the Blakemore-Sutton effect. There is a range of frequencies to be detected and a limited number of detectors for that range of frequencies. So the question can be asked, why don't we get the same type of results with color aftereffects as with the Blakemore-Sutton effect? Before this question is answered, let us look at one more illustration where complementary colors come into play.

Open [Experiment 6.x, Simultaneous Color Contrast \[link to media\]](#) and you will be able to explore in more detail the influence of a surrounding color on our color perception. When you first open this experiment, you will see two squares on the left hand side of the screen. The top square is the standard, and the bottom square is the comparison. Each square has two parts: the center square, which is the square of interest, and the surround. On the right two-thirds of the screen is a CIE diagram, and when it first comes up it will allow you to control the color of the center square of the comparison. (As a note, if the CIE diagram is still a bit confusing to you, you can use the color circle that you have used before by selecting it from the drop down menu at the top of the CIE diagram. In all other aspects, the program will operate completely the same as will be described.) Your task is to make it match the central square of the standard. When it does, press the **Match** button at the bottom of the CIE diagram. The two central squares will be presented next to each other with the standard on top, and no surrounds. In addition, your results will be presented on a CIE diagram. There will be three dots in a row that will represent the colors of the standard and comparison surrounds (on the outsides of the row) and the central square of the standard. These dots will be in the same colors they are in the test figure. There will also be a magenta dot, which will represent your match. Go ahead and try it.

[DESCRIBE THE OUTPUT PLOT]

You will probably have found that the two central squares do not match each other nearly as well without the surrounds as with them. In addition, looking at the CIE diagram, you will most often find that the comparison central square plotted with the magenta dot will be closer to the comparison surround than the standard's central square. Basically, a surround makes the central region look more like the complementary color of the surround, just a little. Since the colors chosen are close to complementary colors to each other, this means that the comparison's central square looks a bit more like the standard's surround. To compensate for that, you make the comparison's central square have more of the color of the comparison's surround. Here again, complementary colors pop up showing this circular aspect of our perception found in the color wheel.

If you wish to explore this phenomenon more, first close the results screen. You can choose one of a few preset settings of test with the **Presets** drop down menu, or you can use the menu to the right of it which says **Comparison Center** at this moment. This drop down menu will change what is controlled by the CIE diagram (or color circle). You can then pick any colors you wish to do your test, but the menu must say **Comparison Center** when you actually do the test. The **Reset** button will randomize the starting position of the comparison central square.

Several phenomena have been described that suggest limitations to the trichromatic theory. As might be expected, there is a theory that has been proposed that will explain these phenomena. It is the Color Opponent theory of color vision.

Color Opponency

Findings like color naming, complementary colors, etc, led Ewald Hering (1964) to propose that color vision was not trichromatic but organized with four primaries, or what I prefer to call unique hues. These four primaries are organized in two sets of oppositional pairs (blue/yellow and red/green). Figure 6.x illustrates how Hering conceived of color working, based upon his theory. The top part of the illustration shows how Hering represented his four unique hues operating across all colors in the color circle. The blue and yellow unique hues are opposite to each other, and the red and green are also opposite to each other. His version of the color circle is shown below. This color circle is obtained by mixing the two color bands in proportion to their thickness. The oppositional properties of Hering's proposal explained many of the phenomena that we have just experienced. However, his theory did not predict the color mixes as accurately as did trichromatic theory, especially after the CIE system was developed. In addition, at that time there was not a good way to explain how opposition between two colors such as red

and green could occur in the nervous system. As a result and for a long time, Hering's color opponent theory was relegated to the status of almost an historical footnote, along with many other failed theories. There were those who tried to keep the theory alive (e.g., Hurvich & Jameson, 1957) but they were a minority.

However, the theory could no longer be ignored when the findings of Russell DeValois started coming out (DeValois, 1960, 1965; DeValois, Abramov, & Jacobs, 1966).

[to me build an interactivity over these basic finding]s.

Resolution

This is an interesting situation. There are two theories of color vision, trichromatic and color opponent, both proposed and often treated as competing explanations of color vision. Both theories have an impressive array of psychophysical and physiological data to support their position. For the trichromatic theory, there is all of the color matching data, the mathematically precise CIE 1931 chromaticity diagram, and the physiological data on the cone classes. For the color opponent theory, there is the color naming data, complementary colors, the color aftereffects, and the DeValois studies of the ganglion and LGN cells. It seems unreasonable to throw out either theory, but science has a principle to seek as simple an explanation as is possible. This principle is called the Law of Parsimony. Bitter arguments can erupt in scientific debates over which explanation is to be preferred, and is it not uncommon to argue for a particular theory because it is simpler. Well, one theory is going to be simpler than two. But the data forces the conclusion that both theories must be working at some level of the visual system. This situation is not unique. Just consider the wave and particle descriptions of light. Both descriptions are used. The same situation will also arise when we discuss the perception of pitch with hearing. It is true that science seeks the simplest explanations possible, but the explanations cannot be any simpler than nature is.

So somehow the two theories must work, and the question is how to integrate the two explanations into a larger, more coherent theory. Open [Interactive Figure 6.x, Early Color Vision](#) to see a simplified version of the modern integration of trichromatic and color opponent theories that will cover most of the issues discussed so far. When you first open the figure, a relatively complex screen is shown. Let us take this screen a little bit at a time to clarify all of the elements. The main part of the screen is the diagrammatic representation of the way that the trichromatic first stage of vision is processed to lead to the color opponent processing of color is thought to work. There are three main section of this illustration, and they are labeled across the top of the screen: **Stimulus**, **Cones**, and **Opponent Cells**. Going from left to right, the **Stimulus** is represented by a square below the word **Stimulus**, positioned about in the middle of the screen, vertically. There are lines going from the stimulus to each of the **Cones**, and matching the cones in color. The intensity of these lines reflect how strongly that stimulus is absorbed by that cone. Recall that the cones' sensitivities overlap, so more than one cone will absorb at least some of the light of almost any stimulus you can create on the screen. However, to simplify this demonstration, the degree of overlap in absorption is reduced considerably from what would be the case in actual cones. You can control the stimulus using the color wheel in the upper left hand corner. In addition, you can use the buttons below the color wheel. The **White** and **Black** buttons create a full-intensity white and a completely absent black, respectively. The buttons with a plus sign (+) in front of the letter will add a full intensity version of that color to the existing stimulus. The button with the letter alone changes the current stimulus to that color. So the **+R** button will add red to the existing color, the **R** button makes the color of the stimulus red. The **Random** button will randomly select a color for the stimulus.

To the right of **Cones** are the **Color Opponent Cells**. The lines from the cones to the color opponent cells reflect which cones are connected to which color opponent cells as well as the type of connection. White lines represent excitatory connections, and gray lines represent inhibitory connections. Examining this figure, the +B/-Y color opponent cell (**B/Y**) receives excitatory connections from the short wavelength cone and inhibitory connections from both the middle and long wavelength cones. There are also -B/+Y color opponent cells and the connections would simply be reversed (inhibitory from short and excitatory from middle and long). Only one type is represented to simplify the image. The connections to the +R/-G are more obvious. In addition to these two chromatic cells there is a cell that response to brightness (shades of gray). It is sometimes set to be an achromatic cell. This cell is labeled the **Nonopponent Cells** and is not really an opponent cell, as there is not an inhibitory connection to the cell. This cell also does not appear to receive any or at best a very weak input from the short wavelength

cone (Ref). This is one of several oddities associated with the short wavelength cone. The thicknesses of the lines indicate the relative strength of the signal from the cones to the color opponent cells. The color of the color opponent cell, the table to the right of the cell and the word to the right of the table all indicate the signal from the color opponent cells to the higher levels of the brain. For the **B/Y** cell, if the excitation exceeds the inhibition, then the cell signals blue to the more central areas of the visual system. This would be indicated by the cell being filled with blue that matches the strength of this signal, the table would indicate a positive result, and the word **Blue** would appear to the right of the table, again in an intensity roughly indicating the strength of the signal. If the inhibition is stronger than the excitation on this same cell, then the cell would be filled with yellow, the result would be negative, and word **Yellow** would appear. (As an aside, to balance out the fact that two cones input inhibition to this cell with the fact that only one cone inputs excitation, the inputs from the middle and long wavelength cones are cut in half, only for the purpose of this illustration). A similar pattern is used for the **R/G** cell. To the right of the tables showing the output of the cells is a box plot showing the output of the two color opponent cells. The **R/G** output is plotted on the vertical axis with red to the bottom and green to the top. The **B/Y** output is plotted on the horizontal axis with blue to the left. These directions are chosen so that the output matches the color wheel as closely as possible. Try it.

Also, below the illustration, there is text indicating the type of color vision the person has. In this illustration, the person will always be **Color Normal** so for this illustration you can ignore it but this text will be important in other figures. Across the bottom of the screen are several other controls. The three check boxes will cause any of the three cones to become adapted, and the last button will restore all cones to an unadapted state. These controls will be explained a little later.

This figure then describes the basics of the theory. Now, let us explore how this model works by working a few examples. Starting with the stimulus that is first present when the illustration first comes up, here is a stimulus that evenly stimulates the three cones. It is a balance of the three primaries. If you look at the two color opponent cells; their activity balances each other out, and there is no or zero output on both color opponent cells. This type of outcome would be equivalent to the cells firing at the background firing rate. The rest of the brain could not tell that there was any stimulus. On the nonopponent cell, there is a strong response. This cell is firing at its highest rate and the cell is filled with white to indicate that outcome. From the perspective of the more central regions of the visual system, there are no signals from either of the color opponent cells, but a strong signal from the nonopponent cell. This situation is equivalent to seeing white.

Next let us examine a chromatic or colored example. Press the **B** button to make the stimulus as strong a blue as possible. Looking at the chromatic channels, there is a strong excitation to the **B/Y** cell indicating that the stimulus is blue. There is almost no stimulation of the **R/G** cell, so it can be ignored. So here is a clear blue signal. Now, press the **Y** button. Here is an interesting result and one that helps explain why yellow is a unique hue. A yellow color stimulates the middle and long wavelength cone almost equally. On the **R/G** color opponent cell, the inputs from these two cones cancel each other out effectively, since the long wavelength cone is excitatory and middle wavelength cone is inhibitory. The output of the **R/G** color opponent cell is so weak as to be not noticeable. However, on the **B/Y** color opponent cell, the inputs from both cones are both inhibitory. The output on this cell, as can be seen from the figure, is a strong **Yellow**. That is the signal that is sent up to the more central visual system.

Contrast this outcome with another mixture of two cone outputs. Press the **M** button. This is a magenta. Notice that it is made of strong stimulation from the red and blue primaries. These maximally stimulate the long and short wavelength cones, respectively. The output of the short wavelength cone sends a lot of excitation to the **B/Y** cell and the output of the long wavelength cone sends a strong excitatory signal to the **R/G** cell, and a weaker inhibitory signal to the B/Y cell. As a result, you can see from the figure that the two color opponent cells send both a **Blue** and a **Red** signal to the more central regions of the brain. Each of the unique hues; red, green, blue and yellow, are associated with single signals from the color opponent cells. All other colors are associated with pairs of signals. This result directly matches the results we obtained from the color naming experiment.

Next, to examine the sense of complementary colors, press the **R** button. From the color circle, the complementary color for red is cyan. Cyan can be added to this stimulus by clicking the **+C** button. There are a couple of events to notice that happened on the figure. The complementary color added to the original color causes the three primaries to be about the same level. This leads to the result you saw when you first opened the figure. Both color opponent channels are canceled out and are not signaling anything to the rest of the visual system. Only the achromatic nonopponent channel is signaling. The achromatic nature of the mixture of two complementary colors is determined by the lack of response on the color opponent channels. However, this occurs when there is a balance of activity on the three cones.

The way that color aftereffects can also be explained with this model. Press the **White** button, since adaptation is tested by looking at a white stimulus. Looking at a red stimulus will primarily adapt the long wavelength cone. You can simulate adapting this cone by pressing the **Adapt Long** check box. The lines from the long wavelength cone are dashed to indicate the adaptation. To simulate the effect of the fatigue of that cone due to adaptation, the output is half what it normally would be. Look at the response of the cones. There is a weak **Blue** response and a moderate response of **Green**. This is the same balance of activity as the cyan response. Check the responses of the color opponent cells to a true cyan stimulus to check out the claim. The weaker chromatic responses plus a strong achromatic seed in the aftereffect than the true cyan stimulus response indicates that a desaturated cyan is perceived which is what was observed to be the aftereffect to a red stimulus. These are just a few examples. You can play with this model and see how it can explain many of the effects talked about. You might even discover some of this simplified version's limitations.

Color Deficiency and Color Blindness

Most of what is called color blindness is not strictly color blindness at all. Blindness refers to a lack of vision. So color blindness should refer to a complete lack of color vision. However, most of the people who are said to be color blind have some form of color vision but it is deficient in some respect to normal color vision. Color deficiencies are genetic defects and usually involve the genetic information for the cones. This information travels on the X chromosome in a region disproportionately likely to have a mistake (Woods & Krantz, 2001). These errors are of different types, and it is the type of errors that determines the type of color deficiency. It is important to remember that males have only one X chromosome and females have two. As the genes that lead to color blindness are on it, this means that males only need one of these genes and females need two of these genes. As a result, males are far more likely to have a color deficiency. These types of traits are known as sex linked traits.

Anomalous Trichromats

Open up [Interactive Illustration 6.x Anomalous Trichromacy](#) to see how the type of color deficiency known as **anomalous trichromats [to glossary]** works. Anomalous trichromats have three different types of cone pigments, so they are real trichromats. However, one of the cone pigments does not match the normal observer's cone pigments. There are three types of anomalous trichromats, depending upon which cone pigment is different. As a useful mnemonic it will be helpful to know that the cones are numbered in reverse order of the wavelength of the cone's peak sensitivity. So it is 1 for the long wavelength cone, 2 for the middle wavelength cone and 3 for the short wavelength cones. Also, the prefix *protan-* is derived from Greek for 1, *deutan-* is derived from Greek for 2 and *tritan-* is derived from Greek for three. So the names for the types of anomalous trichromats are protanomalous, deuteranomalous, and tritanomalous for people with different long wavelength, middle wavelength, and short wavelength cones respectively.

The interactive figure shows a model of the cone sensitivities and the strength of their cone responses. On the left is the **Standard Observer**, who will always have the standard set of cones. On the right is the **Comparison Observer** who can be either normal, as at the beginning, or one of the three types of anomalous trichromats. You can select the type of **Comparison Observer** using the drop down menu at the bottom of the screen that says **Normal** at start indicating that the **Comparison Observer** has a normal set of cones to start with. You can select the wavelength that will stimulate each observer separately, using the sliders right below the graphs of the cone sensitivity functions. You can have both observers stimulated by the same wavelength by using the controls at the bottom of the screen. The **All Wavelength** slider will make both observers be stimulated by the same wavelength, whatever

wavelength is selected. The buttons with the numbers, **480**, **500** and **600**, will cause both observers to be stimulated by a light with that wavelength (in nm).

To start with, you should use the **All Wavelength** slider while both observers have the normal compliment of cones. As can be observed, and as expected, both observers show the same responses to the stimulus which will lead to the observers seeing the same color. Select a **Deuteranomalous** trichromat from the dropdown menu at the bottom of the screen. If you watch the middle wavelength cone as you select this type of observer, you will see that this cone shifts towards the long wavelength cone (the curve also becomes desaturated a little bit to help discriminate it from the regular cone). Now, the middle and long wavelength cones are very similar to each other. Their peak sensitivity is only separated by 6 nm (DeMarco, Pokorny & Smith, 1992; Ebe, Isobe, & Motokawa, 1951). You can easily see some of the ways this person's vision is affected by using the **All Wavelength** slider. You can also use the three wavelength buttons for a quick view of the effects. Press the **480** button. As you can see, because of the shift in the middle wavelength cone, the response of this cone is much weaker than for the normal observer. If you look at the two circles that simulate the appearance of this color for the two observers, you can see that there is not enough green in the deuteranomalous observer's perception of this color. You can see a similar effect by pressing the **500** button. Pressing the **600** button changes the situation. With the stimulus falling on the far side of the peak of the middle wavelength cone for both observers, there is two strong a response on the middle wavelength cone for this stimulus when compared to the normal observer. So instead of an orange, there is a yellow. There is a different balance in the activity of the cones for each color in the anomalous trichromat. They would have a different color mixing function as presented in the CIE diagram. So television and movies will not look right to a person with a tritanomalous color deficiency. However, playing with the tint function on the TV will often help the situation, but to the detriment of the color normal observer who is sitting with the anomalous trichromat. Explore the other types of anomalous trichromats and see how their color vision is impaired when compared to the color normal observer.

Dichromats

When people use the term color blind they are usually referring to **dichromats [to glossary]**. In a dichromat, the person will be missing one of the three regular cone classes. So the person has only two cone classes remaining and from the discussion earlier, it was concluded that these people do have color vision (refer to [Interactive Illustration 6.x, Color Matching in a Dichromat](#) for a review). Open [Interactive Illustration 6.x, Dichromacy](#) to see a simulation of how color vision works at the cone level in dichromats. This figure will strongly resemble Interactive Illustration 6.x, Anomalous Trichromacy, especially when it starts up. The layout is the same, and the only changes are in one button and what is listed in the drop down menu. The **480** button now reads **450**, because this wavelength better serves to illustrate dichromacy. Also, when you activate the dropdown menu there are three new options **Protanope**, **Deuteranope**, and **Tritanope**. Recall what those prefixes mean. These terms refer to which cone class is missing, namely the long wavelength, middle wavelength, or short wavelength cone classes, respectively. Use the **Deuteranope** selection on the dropdown menu so that this will match what was used for anomalous trichromats. First use the **450** button. There are two blues and they differ, but not by a great deal. Next click on the **500** button. Here the hues are very different from each other. Without the input of the middle wavelength cone, the perception is dominated by the long wavelength cone. A similar but less dramatic result is obtained for the **600** button. Do not take the actual colors too seriously, as this is a simulation where a television monitor had to take the place of individual wavelengths, meaning a deuteranope would probably not see these two circles as the same. Still, the general outcome holds.

Open [Interactive Illustration 6.x, Color Deficiencies](#) to see simulations of how different forms of dichromacy might experience different scenes (based on information from Benzschawel, Brill & Cohn, 1986 & Teufel & Wehrhahn, 2000). The first image, when the illustration is opened is a color wheel to help you see how the different forms of dichromacy alters perception across a wide range of colors. On the left hand side of the screen is one copy of the image that will always stay as a normal observer will see the image. On the right/center is a second copy of the image that will be modified as the different forms of dichromacy are simulated. Below this image is a representation of spectral sensitivity of the three cone classes. At the beginning, and as each image is brought up, all three cones classes will be operating so you

should see three curves, one for each of the short, medium and long wavelength cones. On the right hand side of the screen, you can select which cones will be removed to simulate the different types of dichromacy. First, click on **Long Wavelength Cone** to deselect this cone and then press the **Adjust Image** button to process the right hand image to simulate how a protanope might see this color wheel. It might take a few moments so be patient. When the simulation processing is complete, the label below the **Modified Image** should say **Protanope** and you should only see the curves for the short and medium wavelength cones on the graph below. Looking at the color wheel notice how where the reds should be, you get ever dimmer colors until it is very dark where the purest red should be in the color wheel. No click on **Middle Wavelength Cone** to reselect the **Long Wavelength Cone** and deselect the **Middle Wavelength Cone** and again press the **Adjust Image** button. Now the simulation is that for a **Deutanope**. In this case, the greens are gone from the color wheel and that section of the color wheel looks uncolored. Finally, repeat the process but deselect the **Short Wavelength Cone**. The blues are gone and the where the purest blue should be it is quite dark, almost black.

With the rest of the images in this illustration, you can see simulations of these different forms of dichromacy for a variety of different real world images. You select these images using the **Image** menu at the top right corner of the screen. Table 6.x lists what type of image will be shown for each of the different images. Trying these images will help you build some experience with how dichromats view different scenes. Dichromats don't always view all scenes that differently from the color normal population. Try **image01.jpg** on the illustration. It is a picture of blueberries on a plant. Mostly the image is made up of green leaves and the blueberries. So, if you set up the image to be viewed by a protanope, deselect the **Long Wavelength Cone**, the image does not change much at all. However, the deutanope will see the leaves quite differently and for the tritanope, the blueberries lose most of their color. Conversely, a tritanope will see **image11.jpg** pretty similarly to normals. See if you can figure out why. If you have your own images you wish to try to simulate for how different dichromat types might see, try Vischeck (<http://www.vischeck.com/>) where you can upload your own images and have them use their color blindness simulation (Dougherty & Wade, 2008).

Table 6.x
Listing of Images Available in Interactive Illustration 6.x: Color Deficiencies

Image Name	Description	Image Name	Description
image01.jpg	Color Wheel	image09.jpg	My Face
image02.jpg	Blueberries on Plants	image10.jpg	Another, more pleasant face
image03.jpg	Sunset on Lake Ontario	image11.jpg	Anemones in a Tidepool
image04.jpg	Coast of Maine	image12.jpg	Cardinal on a Snowy Day
image05.jpg	Street in Paris	image13.jpg	Rocky Coast
image06.jpg	Welsh Countryside	image14.jpg	Sunset on Lake Zurich
image07.jpg	Camp Fire in Dark	image15.jpg	Deer in my Back Yard
image08.jpg	Sunrise through windows		

Both the protanopia and deutanopia, while not identical color deficiencies, are often called red-green color blindness. Tritanopia on the other hand is often called blue-yellow color blindness. Open [Interactive Illustration 6.x, Early Color Vision and Dichromacy](#) to see how the loss of a cone affects the color opponent system and give these color deficiencies their names. This activity operates almost identically to Interactive Illustration 6.x, Early Color Vision. The differences in this figure is found in the controls at the bottom of the screen. You can, instead of adapting cones, add and remove one cone at a time. The type of dichromacy will be indicated in the text below the **Opponent Cells**. Then you can

change the **Stimulus** to see what happens to the output of the color opponent cells as a result of these different forms of dichromacy.

Next, open [Interactive Illustration 6.x, Color Confusions in Dichromacy](#) to explore and learn more about the exact nature of the color deficiency. This figure will look a lot like Interactive Illustration 6.x, Early Color Vision, but there will be the CIE diagram on the right instead of the controls for the monitor primaries separately. Remember that you can change the color of the input by dragging the dot around on the side. The dot will only appear when you are inside the gamut defined by these three primaries. Move the dot around to get a feel for how this figure works while the visual system is **Color Normal**, as indicated at the bottom of the screen.

After you are comfortable with the figure, you can remove the cones and explore the nature of the color deficiency. First, remove the medium wavelength cone by clicking the **Remove Medium** check box at the bottom of the screen. The text **Color Normal** will be replaced by **Deuteranope**, to indicate the type of color deficiency that this person has. In addition, there will be green lines crossing the CIE sloping from the lower right to the upper left side of the diagram. These lines represent approximations of what are called color confusion lines for a deuteranope. Colors that fall on these lines tend to be confused with each other. If you drag the dot along one of these lines, you will see that the output of the two color opponent channels tend to have a similar balance of activity on all points on this line. It is the balance of the activities of these channels that are the basis of the color confusion. More to the point, however, notice how the lines tend to go from the red region (lower right) of the CIE diagram to the green region of the CIE diagram (top left). Thus, these two colors seem to be what is most confused.

Now press the **Restore Cones** button at the bottom of the screen, and then press the **Remove Long** check box to make the observer a protanope. There will be color confusion lines again drawn on the CIE diagram, but they will now be red. If you drag the dot along these lines again, the balance of the output of the color opponent channels tends to be very similar all along the length of the color confusion line. Also, notice how, while the lines are not the same as for a deuteranope, they still go from red to green. Again, this person tends to confuse reds and greens, just different ones. The appearance will be different, but there is a similarity. This was observed in the simulations of what a protanope and deuteranope sees.

Use the **Restore Cones** button once again and then click on the **Remove Short** to make the observer being simulated a tritanope. The color confusion lines go from blue to yellow regions of the CIE diagram indicating that this person tends to confuse blues and yellows. Thus, this person is described as blue-yellow color blind.

Other Types of Color Deficiency

There are several other types of color deficiencies, but they are much rarer. However, a brief look at these types of color deficiencies will help round out this discussion. First, a person might be missing two classes of cones. This person would be a cone monochromat. Reopen [Interactive Illustration 6.x, Color Confusions in Dichromacy](#), if you have closed this figure. Select any two of the cones and remove them. Then, as you move the dot around the CIE diagram, you will see that while the intensity of the color changes, the balance of activity coming out of the two opponent cells will always be the same (within rounding error). This is what was seen very early in this chapter with the illustration on color matching in a monochromat. In the daytime, this person will usually have only one functioning receptor. Thus, this person truly is color-blind.

Some people only have rods. These are rod monochromats. They have many more difficulties with their vision than just being color-blind. They only have a functioning scotopic vision. Rods are not very functional in daylight, so bright lights are a real problem. They will also have poor acuity and many other of the features of scotopic vision.

Application Issues with Color Deficiencies

Figure 6.x is a photograph of a standard stoplight. The stop portion is red, the warning portion is yellow, and the go portion is green. Reopen [Interactive Illustration 6.x, Color Confusions in Dichromacy](#), if you have closed this illustration and make the observer a protanope or deuteranope by selecting either the **Remove Long** or **Remove Medium** checkboxes at the bottom of the screen. Using the CIE diagram find a red, yellow and green. Notice, they tend to follow along the color confusion lines of either type of color deficiency. The occurrence of color deficiencies is a difficulty faced by anyone trying to use color to design something. The issue is problematic on graphic arts but potentially very

dangerous if a safety issue is involved. For example, yellow (or amber) and red are used for alerts in airplane cockpits. It is very important to distinguish these two types of colors, as they signal very different levels of severity of the problems. In airplanes, this situation is resolved by only allowing color normal observers to become commercial pilots (REF). However, that sort of screening is not possible for drivers of cars and many other pieces of equipment used by the general public. As a result, color cannot be used to signal any safety information by itself. There has to be some other way that the information can be perceived, and perceived quickly. For example, the red light is always at the top and the green light is always at the bottom. The position of which light is on a stoplight is every bit as reliable as the color. A stop sign is a unique octagonal shape that is very clearly different from other road sign shapes so that is useful even when it is in orange, as it might be in some construction zones.

Frequencies of Color Deficiencies and Some Possible Implications

In males, a color deficiency is relatively common. Table 6.x shows the relative frequency of the different forms of anomalous trichromats and dichromats. Piantanida (1988) estimated that about 8% of the males have some form of color deficiency, most of which involve the short or middle wavelength cone. While the National Eye Institute does not consider dichromacy or anomalous trichromacy as a color defect (National Eye Institute, 2002), as seen in the last section, dichromacy at least can be a real problem. So if color vision is so important to us, why are nearly 10% of the male population affected with this problem? From an evolutionary standpoint, if a trait confers a survival advantage, then those without that trait should die of and that trait should no longer be represented, except in very low numbers, in the population's gene pool. Yet there are a sizable number of people with color deficiencies.

Another way to think about the relatively high frequency of color deficiencies is that there some type of advantage conferred by having some of the color deficiencies. It is a question along this avenue that prompted the research of Morgan, Adam and Mollon (1992). Morgan et al. were responding to reports that people with color deficiencies could penetrate camouflage that was used during World War II that was effective against color normal observers. There was other anecdotal evidence as well, but no experimental evidence that supported these claims. Morgan et al. tried to design an experiment where those with color deficiencies would outperform color normal observers. How they did this was to create a grid. Some of the bars are horizontal with the rest are vertical. The horizontal bars formed a small square inside the larger grid. This grid was flashed on a monitor for a brief period of time, and the subject's task was to indicate which quadrant contained the small grid of horizontal bars. If the grid was made up entirely of green bars the participant able to get about 90% of the trials correct. If the grid was made up randomly of red and green bars, color normal performance fell to 50% or lower. Deuteranopes, however, were able to still perform at about 90% correct. The study seems to suggest that under some circumstances, some forms of color deficiencies may be able to perform some color related tasks better than those with normal color vision. You can try a few trials that resemble this experiment. Open [Experiment 6.x, Color-Camouflaged](#) [link to media]. When you first open this experiment, you will see a setup screen and you can set up the conditions of the experiment. The first variable you can adjust is the number of trials. The default setting is the number of trials in the condition that was run in the actual experiment. The next variable you can adjust is the duration of the stimulus. The stimulus should be very briefly presented. You might try making the stimulus duration longer, and see what happens to your ability to detect the small square of horizontal bars. What might it imply if it becomes easier to detect a small square if the stimulus lasts longer? Another variable you might adjust is the interstimulus interval or the period of time between trials. Or you can adjust the overall size of the grid, which is called size of stimulus on the setup screen. If you make the grid larger, each bar in the grid becomes larger. You can also adjust the difference between the height and width of the bars. This difference is in the number of pixels or dots on the screen. Finally, you can adjust the brightness of the background for the grid and the color of the grid as well. Recall the grid will have a main color, and green is selected here like in the original experiment. There was also a masking color and red is selected here like in the original experiment. Next to the color selectors, you will see two flashing squares. The first square is labeled **Background/Main** and the second one is labeled **Background/Mask**. In order to do this experiment, it is important that your ability to detect vertical from horizontal elements depends upon differences in color and not differences in brightness. To minimize the brightness differences between each color and the background, this experiment asks you to do a task known as **flicker photometry** [to glossary]. In flicker photometry, the luminances of two flickering stimuli are adjusted to minimize the flicker. To illustrate this point, use the background slider and adjust it

first to the lowest point at the top, and then the lowest point at the bottom. Notice how the flickering is greater at the extremes. The first task is to adjust the background luminance so that it is the same perceived brightness as the mask color. After this step, the next step is to adjust the luminance of the main color, until the flickering of it with the background is at a minimum.

You are now ready to run the experiment. Since you are in demonstration mode, you can actually pick the condition at this point. Clicking the **Camouflaged?** checkbox at the bottom of the screen, select the camouflage condition. If this checkbox is unchecked, then the experiment is run with the main color. For each trial, you will first be presented a fixation mark. Then the grid will be presented. After the grid has been removed, a response box will appear. In this box, you indicate in which of the four quadrants the small horizontal box of rectangles appeared. The quadrants will be upper left, upper right, lower left, and lower right. After you have run each condition, the experiment will tell you how many trials you got to correct. See if your results match Morgan et al.

Effects of Color

Chromatic Adaptation: McCollough Effect

There is a very interesting phenomenon associated with adapting to color stimuli. This phenomenon was discovered by Celeste McCollough (1965). In all of the adaptation effects that have been examined so far, the adaptation effect lasted for only a short period of time, usually three seconds to a minute in duration. Celeste McCollough (1965) discovered an adaptation effect that lasts, while weakly, for days. This aftereffect differs from the color aftereffect that we examined before, in that the color stimulus alternates with black bars. Open [Experiment 6.x, McCullough Effect](#), to see how this aftereffect works.

On the first screen, you see the variables that you can adjust to determine the conditions for the experiment. The first variable that you can adjust is the **Duration of Adaptation**. In this slider, you will determine the total period of adaptation in seconds. During adaptation for the McCullough effect, you will not be viewing a single stimulus but an alternating sequence of two stimuli. This duration of adaptation is the total duration of adaptation, and each stimulus will be adapted for half the total adaptation period. The next experimental variable that you can adjust is **Number of Times Each Stimulus is Presented**. The next two settings are the color of that portion of the two stimuli. The first stimulus will be alternating colored and black vertical bars. The second stimulus will be alternating colored and black horizontal bars. After you have determined the colors of the two stimuli, you can determine the **Bar Width of Adaptation Stimuli**. You can also adjust the **Bar Width of Test Stimulus**. The final variable you can adjust is the **Test Type** conducted after adaptation. For now leave the test type in **Demonstration** mode.

In demonstration mode, the experiment will proceed as follows: after you picked your conditions and pressed the **Done** button, the adaptation stimuli will start being presented on the screen. Stare in about the middle of this stimulus, but it is ok if your eyes move. After the adaptation period, the test stimulus will appear. The test stimulus is made up of both vertical and horizontal black and white bars. It might be tilted in your perception. To test this possibility, tilt your head 45 deg to one side and see if the grating looks different, and how it looks different. Or you can use the **Orientation** slider at the top of the screen. You can also change the width of the bars and see how that affects your perception. Try this demonstration experiment and then return to the text.

If your experience is typical, then you should see in the vertical white columns of the test stimulus a pale green which is the complement to the magenta color used in the vertical bars of the adaptation stimulus. In the horizontal white columns of the testing stimulus, you should see a pale red to be the complement of the cyan used in the horizontal bars of the adaptation stimulus. When the bars or your head was tilted 45 degrees the aftereffect disappeared. Tilting your head 90 degrees, makes the aftereffect reappear, but with the aftereffect colors in the opposite bars than in the first case.

This deals with these basic results first. What does the fact that the aftereffect depends upon the orientation of the test bars tell us? One obvious implication is that this aftereffect depends upon the spatial features of the stimulus. This fact is not true of any of the other aftereffects that have been examined. The connection between the aftereffect and the orientation of the bars has led some researchers to conclude that the McCollough effect occurs at a more central portion of the visual system than the other aftereffects. Now

that you have observed the basic aftereffect, return to this experiment in one or two days. When you run the experiment this time, set the **Adaptation Duration** to 0 seconds. This setting for duration will allow the test stimulus immediately without having to readapt. See if any of the aftereffect is still present after this much longer delay than was used for any other aftereffect.

Behnam's Top and Fechner Colors.

Another interesting color phenomenon is illustrated by Behnam's Top. Open [Interactive Illustration 6.x, Behnam's Top and Fechner Colors](#) to see Behnam's Top and how it works. When you open this figure, what you will see is a circular black and white pattern. Half of this circular figure is solid black. The other half of this circular figure is made up of a series of broken arcs. When you press the **Start** button at the bottom of the screen, the top will spin, and if you look carefully you begin to see faint colors in the broken arcs. Using the controls at the bottom of the screen you can adjust variables such as the **Size, Speed, Line Width** and **Direction** of spin. You can alter these variables and see how they affect your perception of the color. In fact, it may be necessary to adjust the speed of the top to get the best perception of color. The fact remains, however, that a black and white stimulus leads to the perception of a color of though weakly. These colors from a black-and-white stimulus are called Fechner colors. There is no complete explanation for Fechner colors, although one explanation has to do with some of the unusual properties associated with the short wavelength cone (Ref??).

Color Assimilation

Open [Interactive Illustration 6.x, Color Assimilation](#) and you will see a figure that is very similar to one visited in Chapter 5. Recall Interactive Illustration 5.x, Brightness Assimilation in the last chapter. When you first open the figure, you will see horizontal blue and gray bars on the left side, and alternating yellow and gray bars on the right side. The gray bars are the same on both sides, and it is the appearance of these bars that is of interest. In the brightness assimilation illustration, the tendency of surrounding areas to make the central region have a similar brightness was discussed. This result was contrary to what was expected with simultaneous contrast. Earlier in this chapter, Simultaneous Color contrast was presented, illustrated, and discussed. In that case, a surrounding color will make a central color move towards its complementary color. So with color assimilation, what should the surrounding color's effect be on the central color? Open the figure and see if your expectations are matched.

The choice of blue and yellow as the first colors was not an accident. They are complementary colors. In the simultaneous contrast situation, the blue and yellow regions will drive a central gray region towards the other color in the pair. Here, they will tend to assimilate the gray towards themselves, so most will report that the gray on the left will appear tinged with blue and the gray on the right will appear tinged with yellow. As in the brightness assimilation demonstration, you can alter the widths of the assimilation bars (the blue and yellows ones at the start), the gray bars (just referred to as the bars in the figure), and the gap size. In addition, you can change the colors of any three of the regions: the **Left Color** bars which started out blue, the **Right Color** bars which started out yellow, and the **Main Color** bars which started out gray. These colors are controlled by the color wheels right below the stimuli. For example, change the **Main Color** to a green and see if the effect still works for a colored stimulus, as well as for a neutral stimulus.

Color Filling-in. If you are interested, you can explore another phenomenon from Chapter 5. Open [Interactive Illustration 6.x, Color Filling-in \[NOT DONE\]](#) to see if filling in works as well when colored stimuli are used, as when just luminance changes are used. The colors that are blended together are controlled with the two color circles at the bottom of the screen. If you wish to minimize the brightness difference between the colors, use the **Test Colors** check box next to the color wheels. When that box is clicked, there will be a small flickering square. The two colors selected to be used are the colors that are flickering. You can use this to pick to colors that are equally bright by minimizing how noticeable the flicker is. When the flickering box is present, the main stimulus is not updated, but it will be when you clear the checkbox and the flickering stimulus is removed.

Summary

This chapter has described in a basic way how humans and other animals see in color. At the beginning of the chapter, the nature of color was discussed and how color is different from purely a wavelength. The next section of the chapter was a discussion of color matching as the fact that colors to be mixed and matched is one of the ways that color differs from wavelength. There were two types of color

mixing that were discussed. The first was additive color mixing, which occurs when two or more lights of different colors are added together as in your color monitor in front of you. Subtractive color mixing was also discussed. Subtractive color mixing occurs when pigments like paint are mixed together. The way color mixing and matching works was codified in the early 1930's by the CIE. This development led directly to color movies.

The trichromatic theory is the best theory that explains the way color mixing and matching works. The trichromatic theory explains color vision by the fact that we have more than one type of cone. In fact, normal human observers have three classes of cones. These three classes of cones each respond to different regions of the wavelength spectrum. It is the balance of activity across these three cones that must be matched to make a color match. However, there are several features of our color vision that the trichromatic theory is unable to explain. These limitations can be summarized by the question, why is there a color wheel? There is not a spatial frequency wheel. So why is there a color wheel? These limitations are explained by the color opponent theory. The color opponent theory proposes that there are four unique hues: red, green, blue, and yellow. These unique hues are ranged into two color opponent systems: red vs. green, and blue vs. yellow. At one time, these two theories were thought to be in competition. But now it turns out that the trichromatic theory explains the cone level of our visual system, and color opponent theory explains the operation of our ganglion cells and LGN.

Next, color deficiencies were discussed. Most of what we called color blindness is not really color blindness but color deficiencies. The color deficiencies usually deal with some change in the cones. For anomalous trichromats, one of the cone classes is different than what is found in normal color observers. For dichromats, one of the cone classes are missing. The last section of the chapter covered several interesting effects of color. These included the McCullough effect, Behnam's Top, color assimilation and color filling in.

Table 6.x. Peak Wavelength Sensitivities for the Human Cone Classes (Average)

<u>Cone</u>	<u>Peak Wavelength (nm)</u>
S	419
M	531
L	558

(I need a reference for this)

Table 6.x Relative Occurrence of Different Color Deficiencies

Color Anomaly	Percentage Occurs in	
	Males	Females
Anomalous Trichromats		
Protanomalous	1.0	0.02
Deuteranomalous	5.0	0.4
Tritanomalous	0.005	0.01
Dichromats		
Protanopes	1.0	0.02
Deuteranopes	1.0	0.1
Tritanopes	0.05	0.005

Ref?

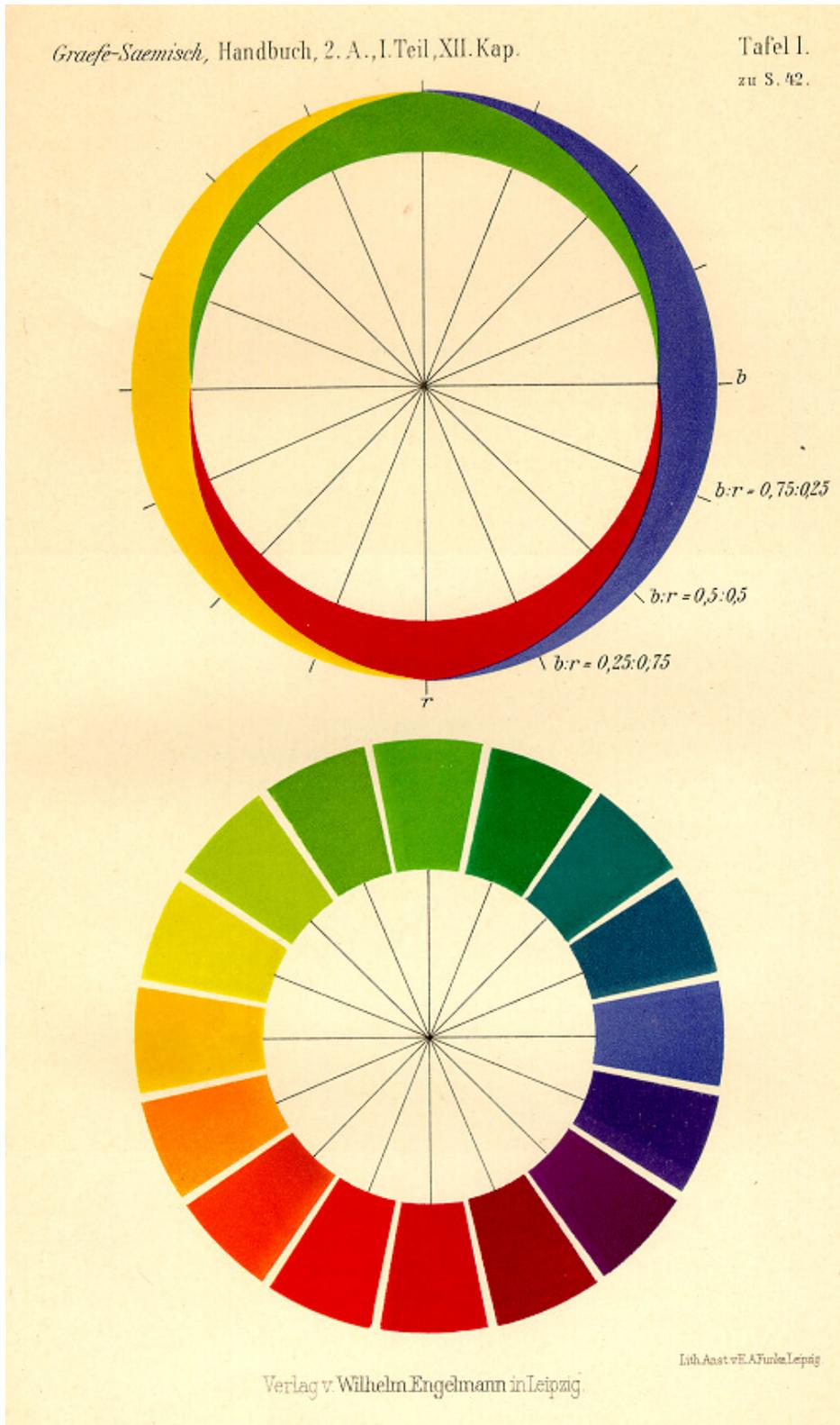


Figure 6.x, Hering's Color Opponent System.