CRC Chapter on Visual Psychophysics and Color Appearance
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INTRODUCTION

What is color appearance, and how does it relate to digital color imaging? Color appearance is, as the name suggests, the study of how a given color stimulus is perceived by a human observer. While seemingly straightforward at first glance, color appearance is governed by the extraordinarily complex human visual system. How a stimulus appears is a function of many variables, ultimately including the spectral properties of the stimulus and the light source it is viewed in, the size, shape, and spatial properties and relationships of the stimulus, the background and surround, observer experience, and the adapted state of the observer.

Consider a relatively simple color imaging system that consists of a CRT computer display, and a color printer. The desired goal of the system might be to have color images displayed on the CRT monitor match the hard copy color images printed. It might be thought that using standard CIE tristimulus colorimetry to assure that the XYZ values displayed by the monitor are the exact same as those on the printed-paper would be enough to assure a visual match. As it turns out, this tristimulus match between the monitor and paper would look very different to a human observer. This is because CIE colorimetry was designed with a very specific goal, that two simple stimuli that have identical tristimulus values match for an average observer, under a single specified viewing condition. The above mentioned color imaging system violates the assumptions that basic colorimetry requires. The two stimuli, in this case the CRT and print images, are complex stimuli viewed in wildly disparate conditions.

What is needed in the above situation is a method for ensuring that the *appearance* of the two images is identical. In order to do this, we first must understand what governs the appearance of a stimulus. This chapter focuses on just that problem. In order to fully understand how colors are perceived, it is important to understand the tools used to study color appearance.

In this chapter, we examine the terminology of color, and color appearance. This includes appearance attributes such as hue, chroma, lightness, brightness and saturation, as well as viewing condition attributes such as surround and background. We also examine several of the factors that influence color appearance, and how they might cause basic tristimulus colorimetry to fail. Since color is ultimately the result of human perception, it is important to understand the tools used to quantify perception. Examples of these tools, and techniques, known as visual psychophysics are described.

Ultimately we would like to be able to describe, and predict the color appearance of complex stimuli, under various viewing conditions. Towards this goal there is the formulation of chromatic adaptation models, and ultimately color appearance models. Several of these models and their historical formulation are described.

The study of color appearance is truly complex. This chapter barely scratches the surface of such a large and diverse field. The interested reader is encouraged to look at the more in depth text on color appearance, by Fairchild[1], as well as the references presented here. In addition, this topic can still be considered one of active research.

TERMINOLOGY

In any field of study, it is important to have a common vocabulary so that knowledge and insight might be communicated accurately and precisely. In the study of color and color appearance this vocabulary is often muddled, as terms such as lightness and brightness are often confused and casually interchanged by the average user. Why might this be more so the case when discussing color, rather than other subjects? Perhaps it is the very nature of color itself. Almost every person has experienced and discussed color, often at a very early age, though the means of discussion are often varied. Even in education, treatment of color is inconsistent. To the grade-school child color might be made up of three primaries: red, blue, and yellow. The printer is taught that the three primaries are cyan, magenta, and yellow, while the television engineer is taught that color is made up of red, green, and blue. Still different, the physicist might be taught that color is made up of a certain portion of the electromagnetic spectrum. While all of these can be considered correct, they also can be considered incorrect.

In the field of color appearance, the de facto standard for vocabulary comes from the *International Lighting Vocabulary*, published by the CIE.[2] Hunt provides very useful insight into the need for a standardized vocabulary, and also describes the work that led to the publishing of the CIE document.[34] To add to this mixture, there is also a relevant American Society for Testing and Materials (ASTM) document that describes appearance.[5] The definition of terms presented below comes directly from these important works.

Color

Perhaps some of the confusion in the field of color appearance stems from the very nature and definition of color itself. Few people, when asked, can give a precise definition of what exactly color is. It is almost impossible to do without using an example, as evident from the CIE definition.

> **Color:** Attribute of visual perception consisting of any combination of chromatic and achromatic content. This attribute can be described by chromatic color names such as yellow, orange, brown, red, pink, green, blue, purple, etc., or by achromatic color names such as white, gray, black, etc., and qualified by bright, dim, light, dark, etc., or by combinations of such names.

This definition provides little satisfaction to the casual reader. To comfort those readers, it also provides little satisfaction to the scientists who study color. That the definition of color contains the word color makes for a circularity that can be confusing. The authors of this definition were well aware of this confusion, and added a note that sums up the need for the study of color appearance.

> **Note:** Perceived color depends on the spectral distribution of the color stimulus, on the size, shape, structure, and surround of the stimulus area, on the state of adaptation of the observer's visual system, and on the observer's experience of the prevailing and similar situation of observations.

Many of the aspects described in this note will be discussed in much further detail later in this chapter.

Perhaps the most important information that is encompassed in this definition of color is the first sentence. Color is an attribute of visual perception. All terminology discussed in this section are similarly attributes of perception. That is to say, without the observer, there can be no discussion of color. The study of color appearance and color appearance models is an attempt to generate physically realizable measurements that correlate with these perceptual attributes.

Related and Unrelated Colors

The definition of color is further enhanced with the notion of related and unrelated colors. Though simple enough, these definitions are critical to gaining a full understanding of color appearance.

> **Related Color:** Color perceived to belong to an area of object seen in relation to other colors.
>
> **Unrelated Color:** Color perceived to belong to an area of object seen in isolation from other colors.

These definitions are rather straightforward. Related colors are viewed in relation to other color stimuli, while unrelated colors are viewed in isolation. Color stimuli are rarely ever viewed in complete isolation, so most color appearance models are designed to predict related colors. However, many color vision experiments that have been used to gain an understanding of the human visual system have been performed using simple unrelated color stimuli. It is important to understand the differences between these stimuli, when trying to utilize models designed to predict one specific type of color.

There are many color perceptions that only exist for related or unrelated colors. One very interesting case is for the perceptions of colors such as brown and gray. These colors only exist as related colors. It is impossible to find an isolated brown or gray stimulus, as evidenced by the lack of a brown or gray light source. These lights would appear either orange or white, when viewed in isolation. Likewise, all of the "relative" perceptions defined below only exist for related colors.

Hue

Hue is perhaps the easiest of the color terms to understand. Still, it is almost impossible to define hue without using examples. The CIE recognized this in their definition.

> **Hue:** Attribute of a visual sensation according to which an area appears to be similar to one of the perceived colors: red, yellow, green, and blue, or to a combination of two of them.
>
> **Achromatic Color:** Perceived color devoid of hue.
>
> **Chromatic Color:** Perceived color possessing a hue.

Hue is often described with a "hue circle," as shown in Figure 1. One important note of this description, and the definition given by the CIE, is the notion of unique hues. That is, red, yellow, green, and blue. These hues follow the opponent color theory first postulated by Hering in 1920.[6] Hering noted that certain hues were never perceived together. That is to say, there is no perception of a reddish-green, or a yellowish-blue. This formulated the fundamental notion that human color vision is encoded into red-green and blue-yellow channels. The interested reader is encouraged to read more thorough explanations, as found Kaiser and Boynton, Wandell, and Hurvich.[7,8,9]

The inclusion of the definitions for achromatic and chromatic colors is also important. Though often described as an interval hue circle, there is no natural meaning for a hue of "zero." Achromatic colors describe colors that are devoid of any hue information, but this definition does not extend to a meaningful interval hue scale. The meaning of different numerical scales will be described later in this chapter.

Brightness and Lightness

The attributes of brightness and lightness are very often exchanged for each other, despite the fact that they have very different definitions.

> **Brightness:** Attribute of a visual sensation according to which an area appears to emit more or less light.
>
> **Lightness:** The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.
>
> **Note:** Only related colors exhibit lightness.

Brightness refers to the absolute perception of the amount of light of a stimulus, while lightness can be thought of as the relative brightness. The human visual system generally behaves as a lightness detector, which can perhaps be better described with an example.

A very simple example can be seen with a typical newspaper. This paper, when read indoors, would have a certain brightness and lightness. When viewed side by side with standard office paper, the newspaper often looks slightly gray while the office paper appears white. When the newspaper and office paper are brought outdoors on a sunny summer day, they would now have much higher brightnesses. Yet the newspaper still appears darker than the office paper, as it has a lower lightness. The physical amount of light reflected from the newspaper might be more than a hundred times greater than the office paper was indoors, yet the relative amount of light reflected has not changed. Thus the relative appearance between the two papers has not changed.

The above definitions include a note, stating that only relative colors can exhibit lightness. This is the reason that there cannot be a gray light source. When viewed in isolation the light source would be the brightest stimulus in the field of view, and would thus appear white.

Further on in this chapter will be a discussion of color appearance models, which attempt to predict these appearance attributes. The various color appearance terms can get easily confused. Often it is convenient to represent the relative terms with simple equations, in order to gain a better understanding. Equation 1 shows the simple mathematical construct for lightness.

$$\text{Lightness} = \frac{\text{Brightness}}{\text{Brightness (White)}} \tag{1}$$

Colorfulness and Chroma

The definitions of colorfulness and chroma are very similar to those of brightness and lightness, in the fact that colorfulness is an absolute perception, while chroma is relative.

> **Colorfulness:** Attribute of a visual sensation according to which the perceived color of an area appears to be more or less chromatic.
>
> **Note:** For a color stimulus of a given chromaticity and, in the case of related colors, of a given luminance factor, this attribute usually increases as the luminance is raised, except when the brightness is very high.
>
> **Chroma:** Colorfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting.
>
> **Note:** For given viewing conditions and at luminance levels within the range of photopic vision, a color stimulus perceived as a related color, of a given chromaticity, and from a surface having a given luminance factor,

> exhibits approximately constant chroma for all levels of luminance except when the brightness is very high. In the same circumstances, at a given level of illuminance, if the luminance factor increases, the chroma usually increases.

Essentially, colorfulness describes the amount or intensity of the hue of a color stimulus. Similarly, chroma is to colorfulness as lightness is to brightness. This is also shown in Equation 2. Similarly to lightness, the human visual system generally behaves as a chroma detector. It is interesting that the appended notes attached to the above definitions are much longer than the definitions themselves. When the luminance of the viewing conditions increases, the chroma tends to remain constant as the brightness of a white stimulus is increasing as well. However, in this same situation the colorfulness generally increases. This can be visualized by thinking of an outdoor scene. On a sunny day, everything looks very colorful, while on a cloudy day everything appears less colorful.

$$\text{Chroma} = \frac{\text{Colorfulness}}{\text{Brightness (White)}} \tag{2}$$

Saturation

Saturation is often confused with colorfulness and chroma, though it has its own unique definition.

> **Saturation:** Colorfulness of an area judged in proportion to its brightness.
>
> **Note:** For given viewing conditions and at luminance levels within the range of photopic vision, a color stimulus of a given chromaticity exhibits approximately constant saturation for all luminance levels, except when brightness iv very high.

Whereas chroma is defined to be colorfulness of an area relative to the brightness of a similarly illuminated white stimulus, saturation is colorfulness relative to the brightness of itself. So while only a related color can exhibit chroma, both related and unrelated colors can exhibit saturation.

The standard definition of saturation, as given above, can be seen in Equation 5. This definition can be supplemented with an alternate definition, which is used in some color appearance models. This definition says saturation is the ratio of chroma and lightness. This is shown in Equation 3.

$$\text{Saturation} = \frac{\text{Chroma}}{\text{Lightness}} \tag{3}$$

By substituting the above definitions of lightness and chroma, Equations 1 and 2 respectively, we have get Equation 4.

$$\text{Saturation} = \frac{\text{Colorfulness}}{\text{Brightness (White)}} \cdot \frac{\text{Brightness (White)}}{\text{Brightness}} \tag{4}$$

This equation can be simplified to the standard definition of saturation, as shown in Equation 5. It is important to note that for unrelated colors, the ratio of chroma and lightness cannot be used to describe saturation, as those terms are only valid for related colors. When dealing with unrelated colors, Equation 5 must be used.

$$\text{Saturation} = \frac{\text{Colorfulness}}{\text{Brightness}} \tag{5}$$

Digital Color Reproduction: Brightness-Colorfulness or Lightness-Chroma

When dealing with color reproduction, often it is sufficient to represent color as trichromatic, as witnessed with the success of the CIE-based colorimetry. Colorimetry is only valid when dealing with color matches in identical viewing conditions. If the viewing conditions change, as when going from a CRT monitor to a print, colorimetry becomes insufficient. When this is the case, it becomes necessary to specify the actual color appearance. Complete specification requires five perceptual dimensions: brightness, lightness, colorfulness, chroma, and hue. It should be noted that the specification of saturation is not necessary. Saturation is redundant, and can be inferred from the other percepts.

Many times when designing imaging systems it might appear that specifying all five color appearance attributes is also redundant. This is not the case, however, as was described by Nayatani et al.[10] In this article, Nayatani et al. describe the distinction between brightness-colorfulness (absolute) matches and lightness-chroma matches. For most imaging applications it is often sufficient to attempt for a lightness-chroma match, rather than the absolute brightness-colorfulness match. This can be illustrated by visualizing a common imaging system, such as consumer photography. Often times people photograph an outdoor scene, in bright sunlight. The photograph is then printed and viewed in an indoor environment, at much lower luminance levels. In this case, it is physically impossible to achieve an absolute brightness-colorfulness match so that the measured energy coming off the print is the same as the original outdoor environment. This same situation can be easily reversed, if the original photograph was taken indoors, and then reproduced and viewed outdoors. In this situation, while physically possible to reproduce the absolute attributes, it is undesirable. The reproduction would have to be unreasonably dark, in order to match the absolute attributes of the indoor scene. For these cases, and for most general imaging applications, it is desirable to create a lightness-chroma match for these reproductions so that the relationship between objects in the scene is held constant.

VISUAL PSYCHOPHYSICS

In order to gain an understanding of color, one must foremost have a basic understanding of the human visual system. Traditionally study of the human visual system generally falls into two categories, physiology and psychophysics. The study of the physiology of the human visual system involves examining the functionality of the receptors and neurons of the eye and the brain. This study is beyond the scope of this chapter, though there are several excellent texts on the subject.[7,8,9] Visual psychophysics is a technique for examining the relationship between physical measurements of a stimulus with the perception of that stimulus. More details of the experimental methods described in this chapter can be found in various texts, notably by Fairchild[1], Bartleson and Grum[11], Gescheider[12], Torgeson[13], Thurstone[14], and Engeldrum[15]. Physiology and psychophysics are not the only means used to study the human visual system. To fully understand the complicated nature of vision, one must combine the effort of many disciplines. This includes, though is not limited to, physics, optics, chemistry, genetics, biology, and anatomy. The remainder of this chapter, however, will focus on the use of psychophysics to study color appearance.

Definition of Psychophysics

Psychophysics is the scientific study of the relationships between physically measured stimuli and the sensations and perceptions of those stimuli. *Psychophysics* can also be defined as the methodology used to study the above mentioned stimulus-sensation relationship. An example of this study might be the relationship between physical amounts of light (stimulus) and perceived brightness (perception). Psychophysics can be used to generate quantitative measurements of color sensation and perception, though those are often thought of as being very subjective. These measurements of perception, when produced from a carefully designed experiment, are just as objective as any other physical measurement (such as temperature). The difference between physical and psychophysical measurements tends to lie in the uncertainty of those measurements. Whereas a physical measuring device tends to have relatively small amounts of uncertainty, psychophysical experiments might have higher uncertainties. Care must be taken to understand and consider these uncertainties.

Psychophysical Techniques

There are many different experimental techniques that can be used to measure perceptions of stimuli. For visual experiments studying images, and color appearance these tend to fall into two broad classes, threshold and scaling experiments. There are many other types of experiments that can be used, including categorization, recognition, and reaction time, though those will not be discussed here.

Threshold techniques include detection, discrimination, and matching experiments. They are designed to measure visual sensitivity to small changes in stimuli, or perceptual equality. An example of a detection or discrimination technique used in imaging science is for developing and testing image compression algorithms. An original image might be viewed with a compressed image to determine if the difference can be detected. An example of matching would be to have a person adjust the amount of compression of an image until it appears to match the original.

Scaling techniques are designed to produce a relationship between physical and perceptual magnitudes. The above-mentioned relationship between physical amounts of light and perceived brightness falls into this category. Another example might be the relationship between perceived image sharpness with measured spatial frequency information in the image.

Hierarchy of Scales

When creating a scalar relationship between physical and perceptual magnitudes, it is important to consider the nature and properties of that scale. Various psychophysical techniques might produce different types of scales, each with different mathematical properties and utilities. It is very important to understand what mathematical operations are permitted, or vast misinterpretations can result. Four types of measurement scales will be defined, each with varying mathematical complexity and power. These scales are: nominal, ordinal, interval, and ratio.

Nominal Scales: These are the simplest form of numerical scales. Numbers are used as names for objects. An example of this type of scale would be the numbers on players on a sports team. The values of the numbers have no meaning, other than to identify the different players. Any mathematical operation performed on this type of scale is arbitrary (for example, doubling every player’s number has no meaning). In color appearance, a nominal scale can be given to color names, such as reds, greens, yellows, and blues. This scale can then be used for determining the category of a given color stimulus.

Ordinal Scales: These scales have magnitudes of order associated with them. Objects can be ranked in ascending or descending order based on the magnitude of a certain trait. An example of this type of scale would be the Olympic medals, where gold, silver, and bronze medals are given out for 1st, 2nd, and 3rd place respectively. It can easily be determined that the order of the contestants, but the any other relationship between them is unknown. For instance, did the gold medal long jumper jump twice as far as the silver medal jumper. Or was the difference between the gold and silver jump the same as the difference between the silver and bronze. A color appearance example of this type of scale might be the sorting of a series of paint chips in order of lightness. The resulting scale would only reveal that one paint chip was lighter than others, but there would be no information as to how much lighter. The only mathematical operation that is valid for an ordinal scale is the greater-than/less-than operator. Any other operation should be considered arbitrary.

Interval Scale: An interval scale is any scale that has equally spaced units, or intervals. For example, in this type of scale if one sample is judged to be one unit away from an anchor, and a second sample is judged to also be one unit away, though in a different direction, the differences between the anchor and the first or second sample is still said to be as perceptually equal. There is no meaningful zero in an interval scale, meaning the value of zero is arbitrary. A real world example of this would be the Fahrenheit and Celsius temperature scales. The zero value in the Celsius scale is arbitrarily defined to be the freezing point of water, while in the Fahrenheit scale it is said to be 32 degrees below the freezing point of water. Since the zero is arbitrary, it is impossible to perform multiplication and division on an interval scale. For example, we cannot say that 64 degrees Fahrenheit is twice as warm as 32 degrees. We can say that the temperature difference between 32° and 42° is the same as that between 52° and 62°. All of the mathematical operators that are valid for nominal and ordinal scales are also valid for interval scales. Interval scales, however, also allow for addition and subtraction.

Ratio Scales: Ratio scales hold the most mathematical power of all the scales. They have all the properties of the previous three scales, with the addition of a meaningful zero point. The meaningful zero adds the ability to equate valid ratios. A real world example of a ratio scale would be the meter scale for height and length. It should be obvious that zero means there is no magnitude of height. In this case, 8 meters is indeed twice as long as 4 meters, and half as long as 16 meters. Ratio scales also allow for the multiplication of constants, without losing the meaning of the scale. An example of this would be converting between meters and centimeters, or meters and feet. In color imaging, it is often desired, yet impossible, to calculate a meaningful ratio scale. A hue scale is an excellent example of this. While it is relatively easy to calculate an interval scale of hue, it is difficult to determine the meaning of zero hue. Thus, zero hue is often arbitrarily assigned a location on the scale (e.g., red).

Threshold & Scaling: A Historical Perspective on Weber, Fechner, and Stevens

To properly study the psychophysical techniques used in color imaging applications, it is often beneficial to begin with some history of the technique. Three pioneers of psychophysics who still are making their mark in color science today are Weber, Fechner, and S. Stevens.[16,17]

Weber began his work in the early 19th century, studying the perception of lifted weights. He asked subjects to lift a given weight, and then added weight until the subjects were able to notice a difference between the new weight and the original. This experiment was repeated with many different starting weights. Weber noted that as the starting weight increased, the amount of added weight necessary to produce a noticeable change also increased. His experiments tended to show that for a given starting weight, I, the change in weight necessary elicit a perceptual difference, ΔI, followed a constant ratio $\Delta I/I$. This stimulus change is often referred to as a Just Noticeable Difference, or a JND.

This simple relationship was found to hold approximately true for many different stimuli, and has since become known as Weber's Law. These findings turn out to be rather intuitive, and are quite common in everyday life. For instance, often times when in a crowded places with loud music people are forced to yell to be heard by others. When the music suddenly stops, this person yelling is instantly heard by everyone. The sound level coming from the person's mouth does not change, but because the background stimulus suddenly drops, the change necessary to be heard becomes much smaller. Other examples include the inability to see a candle in sunlight, though the candle appears bright when placed in a darkened room. This is an example of light adaptation, and will be discussed further in the chapter. Weber's law helps explain these phenomena.

Later in the 19th century, Fechner proposed a method for extending Weber's law to create a scale of sensation.[16] Fechner theorized that a JND was a unit of sensation, and thus he could integrate JND's to create an appropriate scale of sensation. Fechner attempted to create a transformation from a physical intensity scale (such as measured weight) to a perceived sensation scale (perceived heaviness) where each JND was of equal size for all perceptual magnitudes. Fechner adapted Weber's law, and assumed that the ratio $\Delta I/I$ was held constant in the limit. By integrating over that equation, for all stimuli I, it is possible to calculate a metric that equates equal ratios on the physical scale with equal increments on the perceptual scale. This solution ends up being a simple logarithmic relationship, $S = k\ Log\ (I)$, where S is the perceived sensation, k is some constant, and I is the measured physical intensity. This solution became known as Fechner's law.

The logarithm expressed by Fechner's law represents a compressive non-linear relationship between the input stimulus intensity, and the corresponding perceptual sensation. The compressive nature essentially means that as the stimulus intensity increases, the perceived sensitivity to the stimulus decreases. Going back to the person shouting in the loud room, since the intensity of the background is so high the sensitivity to the sound decreases, and the person must shout to be heard. When the music suddenly stops, the sensitivity increases and the person shouting can suddenly be heard by everyone.

Fechner's law relies on several fundamental assumptions. First, it assumes that Weber's law is indeed valid, for all stimulus intensity (in the limit $\Delta I/I$ is a constant). His other assumption is that JND's are indeed a valid unit of sensation, and that JND's can be integrated to form a magnitude scale. While the general compressive trends described by Fechner's law are often valid for many perceptions, they often do not follow the exact logarithmic shape. Perhaps it is because the two main assumptions often break down in real-world situations, so Fechner's law is not always accurate. Nevertheless, his contributions to the field psychophysics and vision science are quite substantial.

Nearly 100 years later, S. S. Steven's performed a series of experiments testing the limits of Fechner's law. He used magnitude estimation experiments to derive relationships for over 30 different physical stimuli with their resulting sensations. It was found that most of the relationships formed straight lines when plotted on a log-sensation log-intensity plot, rather than the logarithmic relation predicted by Fechner's law. The different perceptions did not all form lines of the same slope. When plotted in log-log space straight lines indicate power functions in a linear space, where the slope indicates the exponent of the power function. From these plots, Stevens suggested that the relationships between physical stimuli and their corresponding perceptual scales could be defined as power functions, where the exponents vary for different perceptions. The general form of this is shown below:

$$S = kI^{\gamma} \tag{6}$$

where S represents the perception, k is an experimental constant, and γ is the exponential power value. An exponent greater than one results in an expansive relationship, where as the physical stimulus increases the perception increases at a greater rate. This is often the case when the stimulus might result in danger, such as the perception of pain. An exponent less than one results in a compressive relationship, such as that described by Fechner's law.

The power function relationship between physical and perceptual scales has become known as the Stevens' power law. It has been used to model many perceptions in color imaging, such as the prediction of lightness in the CIELAB color space. More details on that will be explained further in the chapter.

Weber, Fechner, and Stevens formed the basis for many of the psychophysical techniques still used to develop and test color and appearance today. It is important to note the specific differences between Weber's goals, and Fechner and Stevens' goals. In determining the amount of weight necessary to elicit a noticeable change in perceived weight, Weber was determining the threshold of detecting a change, or a just noticeable difference. Fechner and Stevens extended this to determine a scale of perceptual differences. These two techniques represent the main areas of psychophysical study, for general color appearance.

Psychophysical Methods: Threshold Techniques

Weber's weight experiment was a classical psychophysical threshold experiment. Threshold experiments are designed to determine the perceptible limits to a change in a stimulus, or the just noticeable differences (JND). There are two differing types of threshold JNDs that can be calculated, absolute and differences. An absolute threshold determines the minimum amount of stimulus necessary to be detected. An example of this type of threshold might involve an observer in a blackened room trying and asked to detect a small flashing light. The threshold would be determined from no stimulus (the blackened room) to some stimulus (the flashing light). Difference thresholds determine the smallest change detectable from a given stimulus. Weber calculated a difference threshold, when he added more weight to an already existing amount of weight.

There are three classical types of psychophysical techniques used for determining thresholds. Over the years, many different experiments have been developed based on these types. One of the overall goals of any visual experiment should be simplicity. Simplicity often comes at a price, however. The three techniques presented here will be in order of simplicity, with their corresponding advantages and disadvantages also presented. The techniques presented here are:

- **Method of Adjustment**
- **Method of Limits**
- **Method of Constant Stimuli**

Method of Adjustment:

The method of adjustment is the most straightforward method for determining observer thresholds for a given stimulus. It this technique, the observer has control over the magnitude of the stimulus itself. They observer must adjust the magnitude of the stimulus to reach a desired goal, or criterion. Example criterion might include adjusting a stimulus until it is just barely perceptible (for an absolute JND), or adjusting a stimulus until it is different from another (for a difference JND). The threshold is then determined by taking the average adjustment across several trials, as well as across several observers. The standard deviation between a single observer and across several observers can also be taken, to provide an indication of the variance and precision.

An example of a method of adjustment experiment for color imaging might be in determining the level of image compression that can be applied before the observer notices a difference. For this type of experiment, an observer might sit at a computer screen that has two images on it, an original and a compressed image. The observer might have a slider that they can move to increase and decrease the amount of compression on the image. Their task would be to adjust the compression on the image until they just notice a difference between the original and the compressed version. They would do this several times, and the average would be the compression threshold for that given observer and image. The threshold might be different depending on the starting value of the compressed image. If the image starts out uncompressed, and the observer must increase the compression until they notice a difference, you might get one value. If the image starts out very obviously compressed, and the observer must decrease the compression until they just barely notice it, you would probably get a different value.

The method of adjustment technique is advantageous in that it is fast, and very easy to implement. It is also easy to calculate a threshold from the data it produces. There are several problems with this technique, though, as illustrated above by the different thresholds determined from the different starting points. This tends to show up as a bias, whereas if the observer starts from above the threshold (obvious compression) they might get a higher threshold than if they start below (no compression). This bias might result from a change in observer criterion from one trial to another, or from adaptation to the starting stimulus. The criteria must be carefully explained and understood at the beginning of the experiment, yet it still might vary across different sessions, or even different trials. This results in threshold data that is less precise than other methods. Due to this lack of precision and ease of implementation of this technique, the method of adjustment is often used as a pilot experiment to generate starting values for more some of the more complicated methods described below.

Method of Limits:

The method of limits provides more precise threshold data than the method of adjustment, with a slight increase in complexity. In this technique, the experimenter rather than the observer controls the presentation of the stimuli. The experimenter presents the stimuli at predefined discrete magnitudes. These magnitudes are presented in either a descending or ascending series. For a descending series, the stimulus is first presented well above threshold. The observer then must report, either verbally or through a response-recording device, whether they see the stimulus. If the observer sees the stimulus (responds “yes”) then a new stimulus with a decreased intensity is presented. This is repeated until the observer responds that they cannot see the stimulus.

For an ascending series, the first stimulus is presented such that it is definitely not detectable. The observer is asked to respond “yes” if they see the stimulus, or “no” if they cannot. If the observer responds “no” the stimulus intensity is increased. This is repeated until the observer responds that they can see the stimulus.

The threshold is determined to be the average of when the observer first detects the stimulus in the ascending series, or does not detect the stimulus in a descending series. It is not uncommon for the two series to produce different thresholds. This might be caused by adaptation to the presenting stimulus, or from expectation errors. Running both ascending and descending series for a given observer can be used to compensate for these errors. To further reduce the errors, it is possible to simultaneously run interleaved ascending and descending series.

Another issue with the method of limits is determining the discrete levels of stimulus intensity to present in the series. Since this is a threshold experiment, the only information comes from the “transitions,” or where the stimulus is first detected or undetected. Essentially, all of the other stimuli provide no information. Often times the method of adjustment is used to get a rough idea as to where the transition point occurs, so as to minimize the “wasted” trials. There is also the same possibility of a change in observer criterion as there is in the method of adjustment. Since the observer ultimately must respond yes or no as to whether they can see the stimulus, they can change their criterion for any given trial.

Method of Constant Stimuli

The method of constant stimuli attempts to overcome the observer variability by locking the observer criterion. This results in a more precise threshold number. In this method, the experimenter chooses a fixed number of stimuli at various intensity levels around threshold. The number of stimuli can vary, but it is typically between 5 and 7. The stimuli are then presented to the observer repeatedly in a random order. For each trial, the observer must respond whether they perceive the stimulus. Over the course of the experiment the frequency that each stimulus level is detected is recorded. From these data, a “frequency of detection” function can be derived. This is often referred to as a psychometric function, which relates the probability of detection with stimulus intensity level. An example of the psychometric function is shown in Figure 1. From this function it is possible to determine the threshold of detection, as well as the uncertainty. Typically, the threshold is chosen to be the stimulus level that has a 50% probability of detection. The psychometric function can be determined individually for each observer, through multiple repetitions of the trials, as well as for a population of observers.

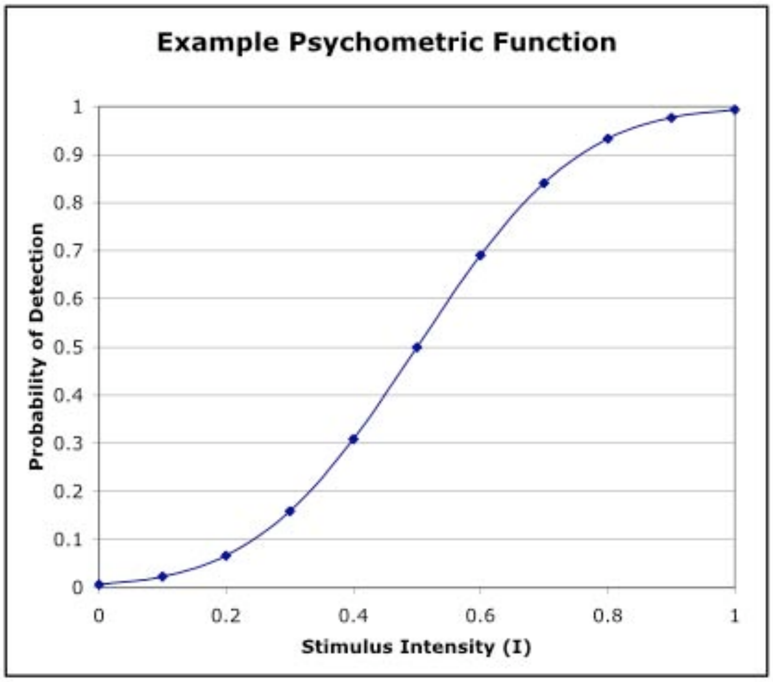

Figure 1. Example of a Psychometric Function

Generally, two types of constant stimuli experiments are run: yes-no, and forced choice. In yes-no experiments observers are simply asked to respond yes if they detect a given stimulus, or no if they do not. The psychometric function is then fit to the percentage of yes responses for each discrete stimulus level. An intensity that corresponds to 50% yes response is taken to be the threshold point. This method can be extended to a pass-fail technique for determining visual tolerances. In this situation, a reference stimulus is presented and observers either “pass” a stimulus that is less than the reference, or “fail” one that is greater. This technique has been used to develop color difference equations, which will be described later in the chapter. For that case, the reference stimulus was a color pair of known difference, and the observers were asked to pass color pairs that had less of a difference, and fail pairs that had a greater difference. These techniques can still suffer from changing observer criteria between trials.

A forced-choice experiment eliminates the observer criterion from the overall results. This is accomplished by presenting the observer with either spatial or temporal alternatives. For example, when attempting to determine the threshold of image compression, a pair of images is presented on a screen. The observer is then “forced” to choose which side of the screen the compressed image was presented on. This is known as two-alternative forced choice. Alternatively, the images could be presented in one of two time intervals. The observer is then forced to choose in which interval the compressed image was presented. A psychometric function is then plotted using the percentage of correct responses against the stimulus intensity level. In a two-alternative forced choice experiment, the psychometric function ranges between 50% and 100%, rather than 0% and 100% like a yes-no experiment. That is due to the “forced” response nature of the experiment, where each observer must always choose an interval or location. If the stimulus intensity is too low to be detected, then the observer must make a guess. When two alternatives are available, the guessing rate is 50%. A threshold level is typically taken to be at 75% correct. By forcing the observer to choose, their criteria cannot influence the results.

The increased precision available from the method of constant stimuli comes at a price of complicated experimental design. Ideally the discrete intensity levels need to be chosen so that the threshold falls in the middle of the range of intensities, and that the lowest and highest levels fall close to 0% detected and 100% detected, respectively. In order to maximize this range a pilot study is often necessary. This can be done using a small number of pilot subjects with a larger number of samples, or by using another method such as the method of adjustment. To obtain an accurate psychometric function it is also necessary to have many trials for each given intensity level. This can be accomplished by having a smaller number of observers do a large number of trials, or by having a larger number of observers perform fewer trials. Given the amount of time necessary to perform these experiments, it is often more desirable to have a larger number of observers. Another consideration is the seemingly arbitrary nature of selecting the threshold level. It has been suggested here to choose the 50% value of the psychometric function for a yes-no experiment, and a 75% level for a forced choice experiment. This threshold level can be calculated more precisely, at the expense of losing the actual psychometric function itself. These techniques are known as up-down staircase procedures.

Staircase procedures combine a modified method of limits with a forced choice experiment. They are designed to adaptively measure the threshold point on the psychometric function. An experiment begins with a stimulus of a given magnitude presented to an observer. This can be either a forced choice presentation, or a method of limits presentation. The observer is asked to respond to the presentation. A "yes" response, or a correct decision will cause the magnitude of the next stimulus to be decreased. A "no" response, or an incorrect decision will cause the magnitude of the next stimulus to be increased. In this manner the staircase narrows in on the transition threshold. There are many variations and rules that can be used with these techniques. These rules determine the overall precision of the threshold. Further details can be found in psychophysical texts. [11,12,13]

Matching Techniques:

Matching techniques are generally similar to the method of adjustment, with only the goal different. Whereas the method of adjustment is used to determine the threshold level of a just noticeable difference, a matching experiment is used to determine when two stimuli are not perceptibly different. This technique has been used extensively in the color imaging community, and is the technique used to generate the CIE XYZ system of colorimetry. In that situation, observers controlled the mixture of three light sources to match a separate monochromatic light source. An example of this is shown in Figure 2.

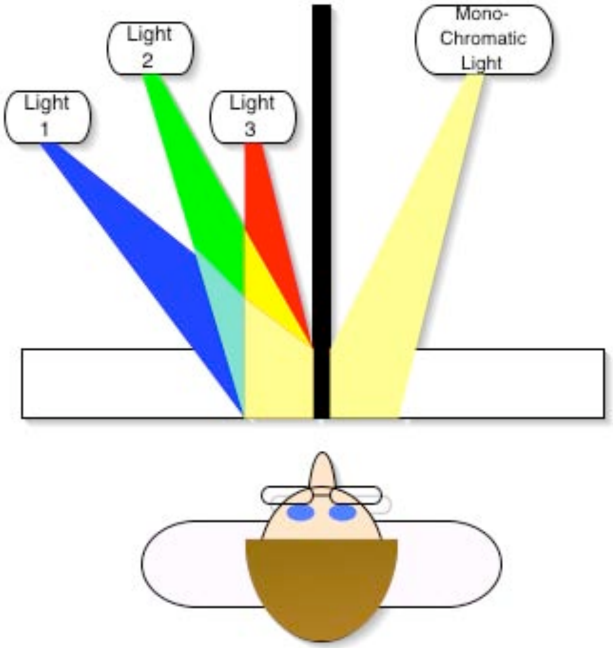

Figure 2. Example of a typical color matching experiment. The observer adjusts the three light sources on the left to match the single source on the right.

Matching techniques have also been used in the study of chromatic adaptation and color appearance. These techniques include asymmetric matching, where the stimuli are presented separately in disparate viewing conditions. An example of this would be viewing a reference color under a daylight illumination, and then attempting to match the color under incandescent illumination.

Psychophysical Methods: Scaling Techniques

Threshold data can be useful when attempting to determine information such as color tolerances, or compression limits. Often times the goal is to generate a scale of perception, rather than a single threshold. Scaling experiments are used to derive relationships between sensations and physical measurements of stimuli. Examples of scaling techniques were described briefly above in the discussion of Fechner and Stevens' work. There are several scaling techniques used to generate these relationships. Depending on the dimensionality of the scale, there are different techniques available. One-dimensional scaling is used when both the perceptual attribute and the physical measurement are one-dimensional. Examples of this include scaling of lightness with luminance, where lightness is the perceptual attribute, and luminance is the physical measurement. It is possible that an attribute being scaled actually consists of several distinct attributes, such as in the case of image preference. Image preference might result from several distinct variables, such as color fidelity, sharpness, and contrast. As long as the same criteria are used for each trial, one-dimensional scaling techniques can be used. Often times it is difficult to control the criteria, so more robust multi-dimensional scaling techniques should be used.

One-dimensional scaling techniques come in a variety of flavors. Some of the most common techniques for color imaging application are as follows:

- Rank order experiments
- Rating and Category scales
- Partition scaling
- Magnitude and Ratio estimation
- Paired comparison

Rank order experiments are generally simple to implement and perform. A series of stimuli are presented to an observer, and they are asked to arrange the series in order of increasing or decreasing magnitudes. The magnitudes lie on the one-dimensional attribute that is being scaled. With enough observations the data can be used to easily derive an ordinal scale of that particular attribute. Remember the only mathematical operations that are valid for an ordinal scale are greater-than and less-than. Thus the spacing between individual samples might not be equal. With enough samples and trials, it is possible to calculate an interval scale based on the law of comparative judgment, which will be described in more detail below. This involves many assumptions and simplifications, and does not always produce accurate results. Interval scales should be generated at your own risk.

Rating and Category scaling experiments allow for relatively simple determination of both ordinal and interval scales. Perhaps the simplest technique is the graphical rating scale. Observers are presented with a stimulus, as well as a graphical scale with well-defined endpoints. The endpoints can be numerical, adjectival, or actual physical stimuli. For example, when attempting to scale chroma the endpoints might say “no chroma” and “highest chroma imaginable,” or simply 0 and 100. Observers are then asked to graphically mark where on the scale the current stimulus lies. The interval scale is then measured from the graphical scale. An example of scaling colorfulness using actual physical stimuli, along with a graphical scale is shown in Figure 3.

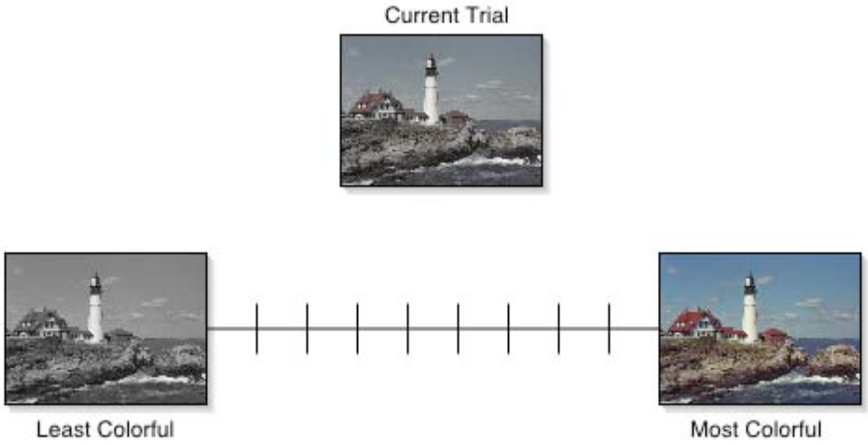

Figure 3. Scaling experiment using physical stimuli as endpoints.

Rating can also be performed without the benefit of the graphical scale, as an observer might be told the numerical endpoints verbally. When presented with a stimulus, they would then rate the perception by assigning a number between the endpoints. Another similar technique is called category scaling, or adjectival rating. This technique is useful when dealing with a large number of samples. An observer views a large sample population, and is asked to separate the samples into predetermined categories, or adjectives. An example of categorical scaling that is often used is for sorting various hues into color names. An observer might be asked to place the samples into distinct color names such as red, green, yellow, blue, pink, orange, brown, black, gray, and white. This would result in a nominal scale of hue. More powerful scales are possible, such as an ordinal scale, if care is taken to select categories that can be considered equal intervals along the attribute being scaled. While this might be difficult when scaling hue, consider scaling colorfulness. The categories, or adjectives, given there might be: “no colorfulness,” “mildly colorful,” “medium colorful,” “very colorful,” and “most colorful imaginable.” If these categories are close enough together so that the categories stimuli are placed in are not the same for every person or observation, it is possible to generate an interval scale. This involves further statistical assumptions and the use of the law of categorical judgements.[13,14]

Partition scaling and fraction scaling, are relatively straightforward experiments for the calculation of interval or ratio scales through a method of bisection. For example, in a partition scale experiment for image compression algorithms an observer would be shown two images of different compression, Images A and B. They would be asked to select a third image such that the difference between the third and Image A was the same as the difference between the third and Image B. Through successive bisection as described above, a complete interval scale could be calculated. When there is a distinct meaningful zero along the magnitude that is being scaled, it is possible to generate a ratio scale using these techniques. For instance, when scaling brightness an observer might be presented with two spots of light and told to choose, or adjust, a third spot that is halfway between the first two spots. Alternatively, they might be flashed a spot of light, and told to set a spot that was half as bright. Since there is a meaningful zero for brightness, no perceived light at all, this technique through enough bisection can create a ratio scale of brightness.

The above-mentioned fractional scaling can also be considered a form of *ratio estimation*. The easiest ratio estimation experiments are *magnitude estimation or production*. In a magnitude estimation experiment, an observer would be shown a stimulus, and asked to assign a numerical value to that stimulus based on the magnitude of the sensation being scaled. In magnitude production, the observers are given a magnitude number, and they must adjust the stimulus so that it represents that perceptual magnitude. More complicated ratio experiments include the fractional brightness experiment described above, where an observer was asked to generate a stimulus that was half as bright as the previous stimulus. Another ratio estimation technique given two or more stimuli would be to have an observer state the perceived ratios between all the stimuli. For color imaging applications, where there is often not a known meaningful zero, ratio estimation often proves too difficult.

Although it is often difficult to generate ratio scales in color imaging applications, interval scales can be generated with great success. A powerful technique for generating interval scales is *paired comparison*. Observers are presented with two stimuli, and are asked to make ordinal judgments based on the pair. For example, given a pair of compressed images an observer might be asked which image appears more compressed. This is only valid if the observers understand image compression, and how compression artifacts might be manifested. It might be more desirable to have the observers choose which image is of higher quality, thus scaling quality as a function of compression. Alternatively, an observer might be presented with an original reference image, and then asked which of the two compressed images looks most similar to the standard. This will create an interval scale of similarity, in regards to the image compression. Paired comparison experiments work well when there are a smaller number of samples, and a well-defined ordinal criterion. In order to create an interval scale from these ordinal data every possible pair of stimuli must be presented. That is, every stimulus must be compared with every other stimulus. For n stimuli, this leads to $n(n-1)/2$ experimental trials. Thus the total number of trials increases very rapidly as the number of stimuli increase. Thurstone’s laws of comparative judgment can then be applied to generate interval scales.[14] The law of comparative judgment has several underlying assumptions, among them that the perception of any stimulus results in a discriminal value on some psychological continuum and that due to internal fluctuations, these discriminal processes result in a normal distribution of values. Assuming this normal distribution, then the average and standard deviation of the values relate directly with the average and standard deviation of the perception itself. Thus, it is possible to convert the ordinal data derived from the paired comparison, using the power of the normal distribution, to a meaningful interval scale. The normal distribution also allows for the computation of statistically meaningful scales of similarity and differences between any given stimuli. There are several other simplifications and assumptions that can be made regarding the analysis using Thurstone's law. Bartleson & Grum[11] and Torgeson[13] give excellent details of all of these assumptions, as well as worked through examples.

VIEWING CONDITION TERMINOLOGY

Along with the standard color terminology given above it, is also important to have a sound understanding of the vocabulary used to describe the scene in which a stimulus is viewed. This scene is known as the viewing field, or more commonly as the viewing conditions. As you will see below, the viewing conditions can have a profound affect on the color perceptions. This section will define the common elements of a simplified viewing field, as shown in Figure 4. These elements are divided into four distinct components: stimulus, proximal field, background, and surround.

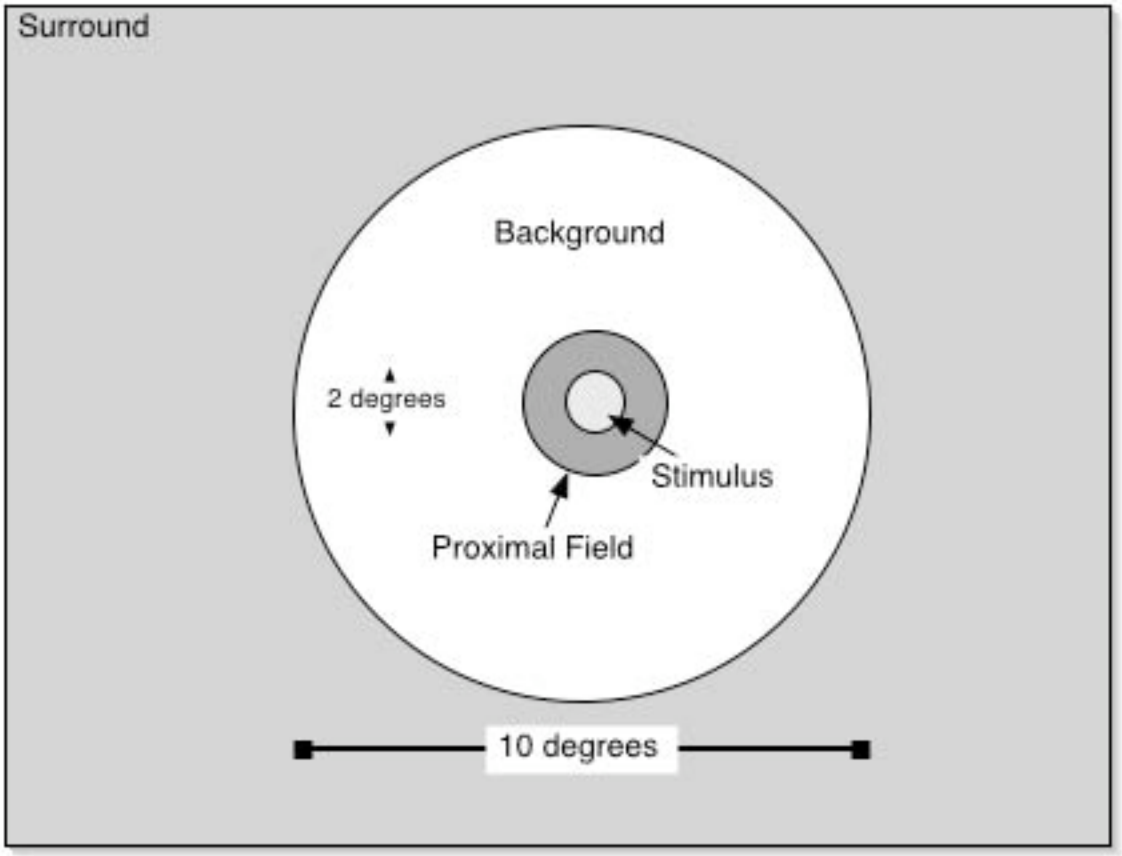

Figure 4. Specifications of the typical viewing field

Stimulus

The stimulus is the color element of interest. In standard colorimetry, the stimulus is typically a small uniform color patch, which subtends 2° of visual angle. The CIE has a separate system of colorimetry designed to handle larger color patches, the CIE 1964 supplemental standard observer. Most color appearance research has been performed using similar sized uniform color patches. Ideally the stimulus would be described by the full spectral representation. Often times this is difficult to do, if not impossible. When the spectral power distribution is unavailable, the stimulus is usually described using a standard device-independent space, such as CIE XYZ tristimulus values, or LMS cone responsivities.

For color imaging, the definition of the stimulus is somewhat blurred. Is the stimulus a single pixel, a region of pixels, or the entire image? While often more convenient to assume the entire image is the stimulus, that might be an oversimplification. Currently there is no universally correct definition of the stimulus for complex scenes. Therefore when using images for research, care should be taken to fully describe the manner in which they are being used.

Proximal Field

The proximal field is considered to be the immediate environment extending from the stimulus for about 2° in all directions. The proximal field can be useful for measuring local contrast phenomena such as spreading and crispening. These phenomena are described in detail later in this chapter. Ideally the proximal field would also be described both spatially, and with a full spectral power distribution. The question of defining the spatial proximal field becomes very difficult when dealing with digital color images. Should the proximal field for any given pixel be considered all of the neighboring pixels? In most real world applications, the proximal field is just assumed to be the same as the background.

Background

The background is defined to be the environment extending from the proximal field, for approximately 10° in all directions. If there is no proximal field defined, then the background extends from the stimulus itself. Specification of the background is very important in color appearance, as it is necessary to model color appearance phenomena such as simultaneous contrast. Specifying the background with color patches is relatively straightforward. Specifying the background with color images suffers from the same problems as specifying the stimulus and the proximal field. For any given image pixel, the background actually consists of many of the neighboring pixels. There are two different assumptions that researchers generally use when determining the background for color imaging applications. The first is to assume that the entire image is the stimulus, so that the background is the area extending 10° from the image edge. Another assumption is that the background is constant, and of some medium chromaticity and luminance, e.g. a neutral gray. Alternatively, the mean color of the image itself can be used as the background. Since most imaging applications strive to reproduce images of constant spatial structure and size, many of these concerns disappear. Care must be taken when calculating color appearances across changes in image sizes, though. Braun and Fairchild describe the impact on some of these background decisions.[18]

Surround

The surround is considered anything outside of the background. For most practical applications, the surround is considered to be the entire room that the observer is in. Color appearance models tend to simplify the surround into a few distinct categories: dark, dim, and average. For instance, movie theaters are usually a dark surround, while televisions are viewed in a dim surround. More detailed discussion on the effect of the surround is given below.

Modes of Viewing

Any changes in the above mentioned viewing fields might result in a change in the color appearance of a stimulus. The following sections on color appearance phenomena explain some of these changes in detail. Other factors that cannot be readily explained by the simplified viewing field also have an effect on the perceived appearance of a stimulus. The perception of color is not adequately explained by the physics of light alone, as the human observer is the critical factor ultimately responsible for any sensation. The human visual system relies both upon sensory mechanisms, governed by biological and physical processes, as well as cognitive interpretations. These cognitive mechanisms are not fully understood, though we are able to recognize some behaviors. Perhaps one of the most important cognitive affects on color appearance is termed as the *mode of appearance*. The mode of color appearance is a difficult concept to grasp at first, and might be best described with an example.

Picture taking a walk outside on a clear winter night with only the full moon providing light. The snow on the ground probably will look very white, despite the fact that it is being illuminated almost entirely by the blue night sky. If you were to come across a house in the distance, the windows of the house might look bright orange. This orange light would be from the incandescent light bulbs found in most houses. If you were inside the same house, the light would not look nearly as orange, and would most likely appear white. At the same time, the snow outside the window might look particularly blue. These are examples of changing modes of viewing, from object mode to aperture mode.

There are five modes of viewing that affect color appearance: illuminant, illumination, surface, volume, and film. These modes of viewing are described briefly below, though a more complete description can be found in *The Science of Color*, published by the Optical Society of America.[19]

The *Illuminant* mode of appearance is color appearance based on the perception of a self-luminous source of light. Since illuminant-color perceptions generally involve actual light sources, they are often the brightest perceptible color in the field of view. Examples of this are looking at a traffic light, or an actual desktop light bulb. The immediate assumption that the brightest objects are actual light sources can lead to some interesting phenomena when non-illuminant objects in a scene appear much brighter than the surrounding scene. These objects might actually be perceived in an illuminant mode, and are often described as glowing. Examples of an object appearing to glow might be when there are fluorescent objects involved. Fluorescence is found in an object that absorbs energy (light) at one wavelength, and emits the light at much longer wavelengths. Fluorescent objects are often referred to as “day-glow” objects, because they absorb light from non-visible portions of the spectrum, and emit light in the visible portions, thus appearing much brighter than the surrounding scene.

The *illumination* mode of appearance is similar to the illuminant mode, except that perceived color appearance is thought to be as a result of the illumination, rather than properties of the objects themselves. Consider the traffic light example given above. Clearly, when looking at a traffic signal there is no doubt that the red, yellow, or green color is being emitted from the light itself. Thus, the light is viewed in illuminant mode. The pedestrian waiting for the light to turn might be bathed in red light, and look quite red themselves. Generally people do not assume that the pedestrian is very sick, because of their red color. Instead, they recognize that the pedestrian is red because they are illuminated by the red traffic signal. The perceived color is a result of the prevailing illumination reflecting off the pedestrian's skin. There are many clues that a typical observer of a scene has, when determining if color is a result of illumination. These clues include the color of the shadows, the color of the entire scene, as well as the color of the observer themselves.

The perceived color of an observer or a pedestrian as described above is an example of the *surface* mode of appearance. In this mode, the color of a surface is perceived as belonging to the object itself. In the case of the pedestrian above, the observer "knows" that the color of their skin and clothes belongs to them, and they are able to partly discount the color of the red traffic light. This is an example of "discounting-the-illuminant," and is described in further detail below. Any recognizable object provides an example of the surface mode of appearance. It requires both a physical surface, and an illuminating light source.

The *volume* mode of appearance is similar to the surface mode, except the color is perceived to be "belonging" to a bulk or volume of a transparent substance. An example of volume mode appearance can be found in the perceived color of liquids, such as beer. The color of beer is not thought to be just on the surface, but rather throughout the entire glass. As the beer is shaken up, forming a thick head, the air bubbles cause light to scatter, increasing the perceived lightness while decreasing the transparency. This is an example of a volume color changing into a surface color. Volume color requires transparency as well as a three-dimensional shape and structure (the shape and structure of a glass of beer, for example).

The final mode of appearances, the *aperture or film mode,* encompasses all remaining modes of appearance. In the film mode, color is perceived as an aperture that has no connection with any object. In the moonlit walk example above, the orange window was perceived in an aperture mode of viewing. The observer did not believe that the window was glowing, or that it was an actual light source. Rather, the window was perceived as an aperture. Any object can switch from surface mode, to aperture mode, if there is a switch in focus from the surface itself. This can be accomplished purposely, by using an aperture screen or a lens system.

COLOR APPEARANCE PHENOMENA

This section deals with examples of stimuli that do not follow the predictions of basic colorimetry. The CIE system of colorimetry was developed using a color-matching experiment, similar to the magnitude adjustment experiments described above. Essentially, colorimetry states that if two stimuli have identical tristimulus values, then those two stimuli will match each other for a given viewing condition. Colorimetry does not attempt to predict if the colors will match if any aspect of the viewing condition changes. This section will illustrate several examples of where the color matches will indeed breakdown, as various elements of the viewing conditions described in the previous section are changed. Among the changes in viewing condition are changes in: illumination level, illumination color, surround, background, and viewing mode. The examples shown here illustrate the limitations of basic colorimetry and the need for advanced colorimetry, often called color appearance modeling. The foundations of most color appearance models stem from the study of these phenomena, so it is important to briefly review them here. The recognition and understanding of these color appearance phenomena are also important for a color imaging system designer, as many of these examples show up in everyday imaging applications. This section will describe several distinct forms of color appearance phenomena, including: spatially structured, luminance, illuminant color, and surround effects.

Spatially Structured Phenomena

Perhaps the most easily recognized color appearance phenomenon is that of *simultaneous contrast*. Figure 5 illustrates an example of simultaneous contrast. The four small gray patches are the same throughout the image. The two patches on the solid gray background look identical, while the patches on the white and black background look distinctly different. The patch on the white background looks darker, while the patch on the black background looks lighter. Simultaneous contrast causes the color of a stimulus to shift in color appearance when the color of the background changes. The change in color of the stimulus tends to follow the opponent color theory of vision. That is why in Figure 5 the patch on the white square looks darker, and the patch on the black square looks lighter. Simultaneous contrast can also be found with chromatic samples, as well as achromatic. In those cases, following the opponent theory, a red background would tend to induce a green color shift, a green would induce a red, a blue induces yellow, and yellow induces blue. Texts by Albers[20], Fairchild[1], Hurvich[9], and Kaiser & Boynton[7] go into further detail regarding this phenomenon.

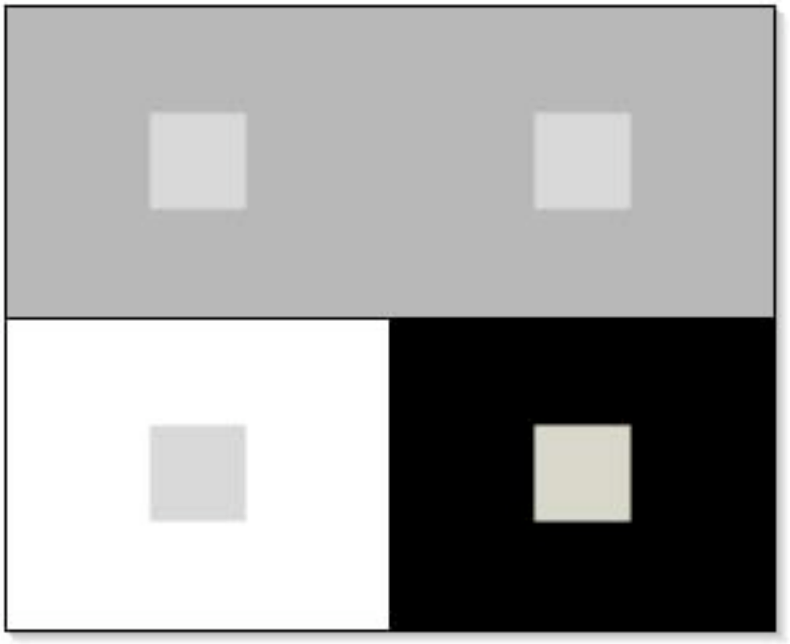

Figure 5. Example of simultaneous contrast. The four small gray patches are identical.

Figure 6 illustrates the complex spatial nature of simultaneous contrast. The centered ring in each of the circles is identical, as is the local contrast. The simultaneous contrast is shown to be much more apparent in the second circle pair. This suggests that spatial structure has a strong influence on simultaneous contrast. Robertson[21] and Shevell[22] present interesting examples, as well as some models of this spatial relationship. As the spatial frequency of the stimulus increases the contrast effect actually ceases, and in some cases reverses.

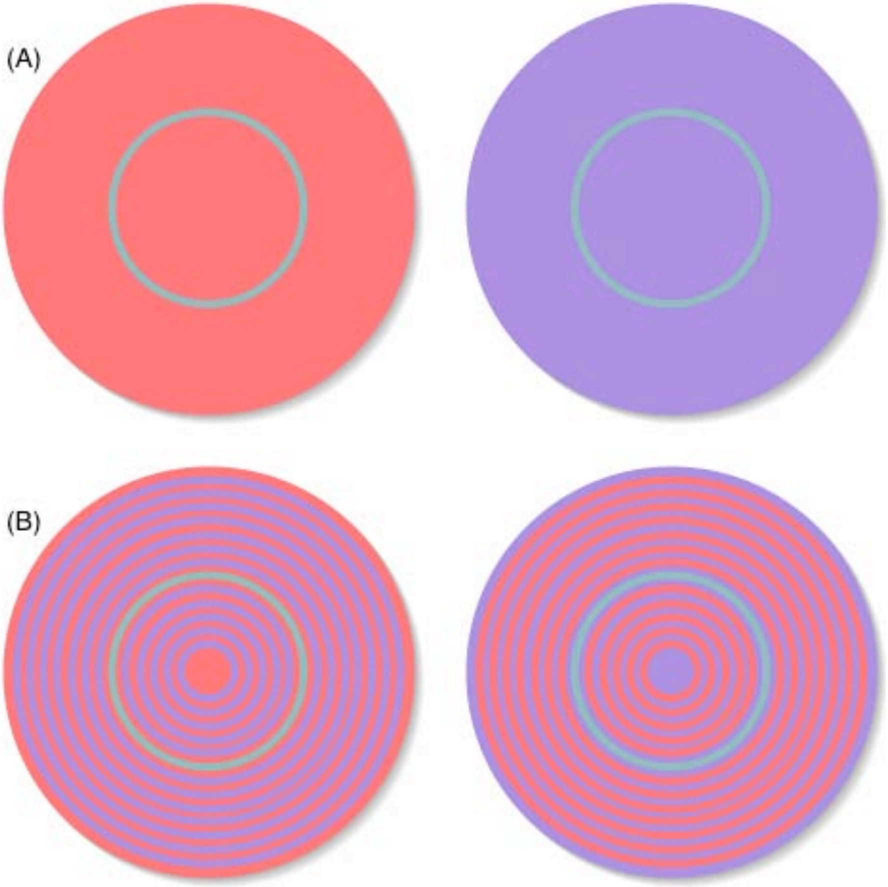

Figure 6. A spatially complex example of simultaneous contrast. The small inner-rings are identical in size and color. The effect of the simultaneous contrast should be greater in the bottom pair (B).

At a high-enough spatial frequency, simultaneous contrast is replaced with *spreading*. With spreading, the color of a stimulus actually mixes with the color of the background. Recall that with simultaneous contrast the color of a stimulus took on the opposite color of the background. Often times it is hypothesized that spreading is caused by blurring of the light coming from the background with the light coming from the stimulus. While this might be true for very high frequency stimuli, such as halftone dots, it does not fully explain the spreading phenomena. Spreading can occur when the stimuli are very distinct from the background. An example of this can be seen in Figure 7.

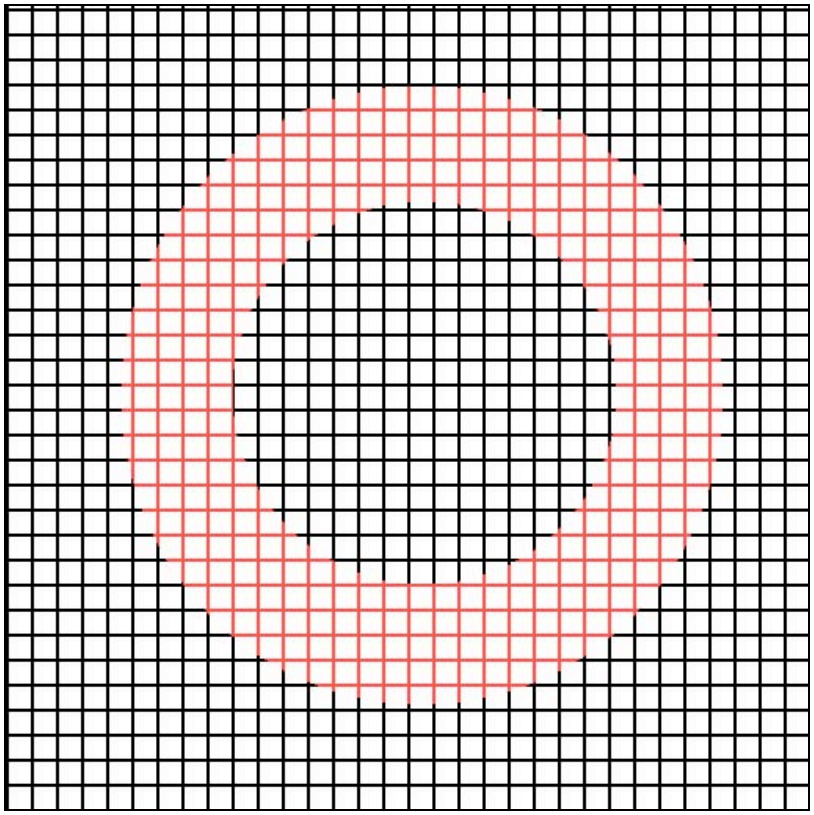

Figure 7. An example of spreading. There are only red and black lines, though a faint pink circle should be evident. Adapted from Kuehni.[23]

Research is ongoing to understand the transition point between simultaneous contrast, and spreading, and the overall effects of spatial frequency on color appearance.[22] Related, though more complex, phenomena to this include neon spreading, and the watercolor effect. Neon spreading combines spreading with the perceptual attribute of transparency, and is illustrated in Figure 8. Bressan[24] gives an excellent review of neon spreading. The watercolor effect, as seen in Figure 9 can also create strong spreading illusions.[25]

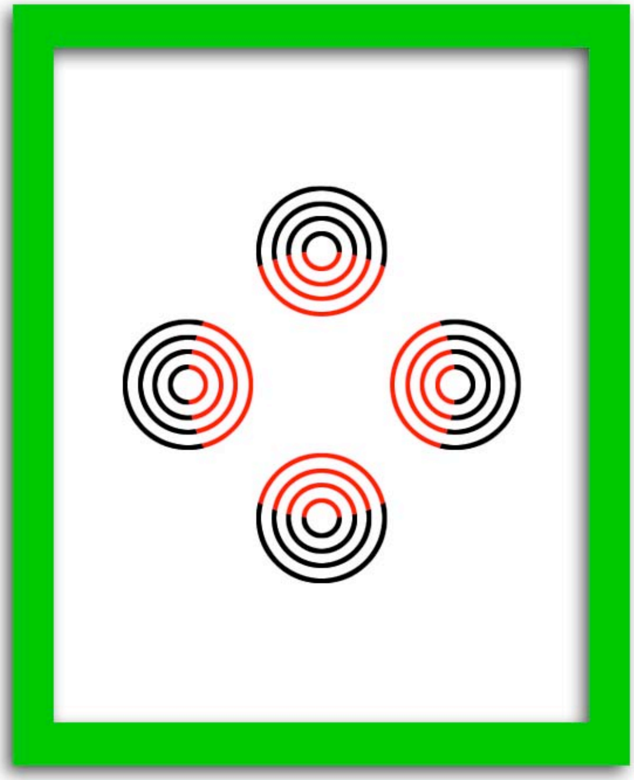

Figure 8. An Example of neon spreading. There appears to be a transparent pink circle in the center of the figure.

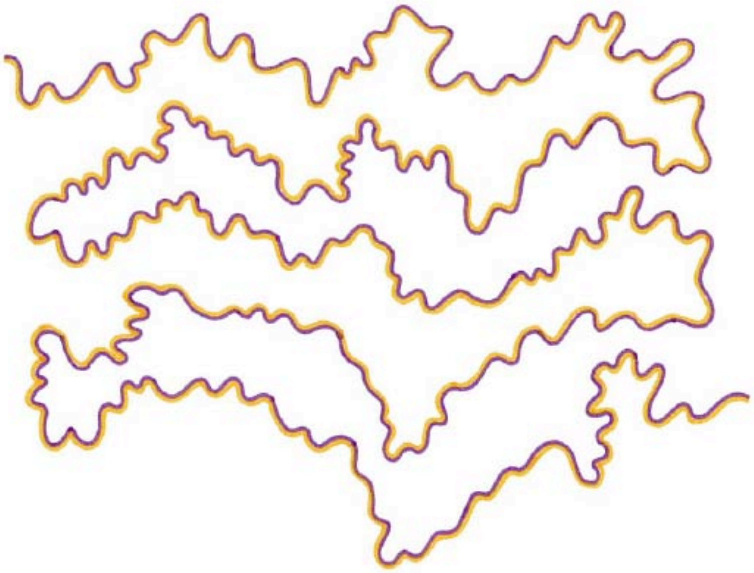

Figure 9. An example of the watercolor effect, where there appears to be surface colors caused by thin colored lines. Reproduced from Pinna *et al.* [25]

Simultaneous contrast can also give rise to an increase in perceived color difference between color stimuli. This effect is known as *crispening*, and can be seen in Figure 10. Crispening causes an increase in perceived color difference when the background that the stimuli are on is close to the color of the stimuli. In Figure 10 the differences between the small gray patches are the same for all three backgrounds, but the difference looks the biggest on the gray background. Similar effects can be seen for color patches, as well. More details can be found in papers from Semmelroth[26] and, more recently, Moroney.[27]

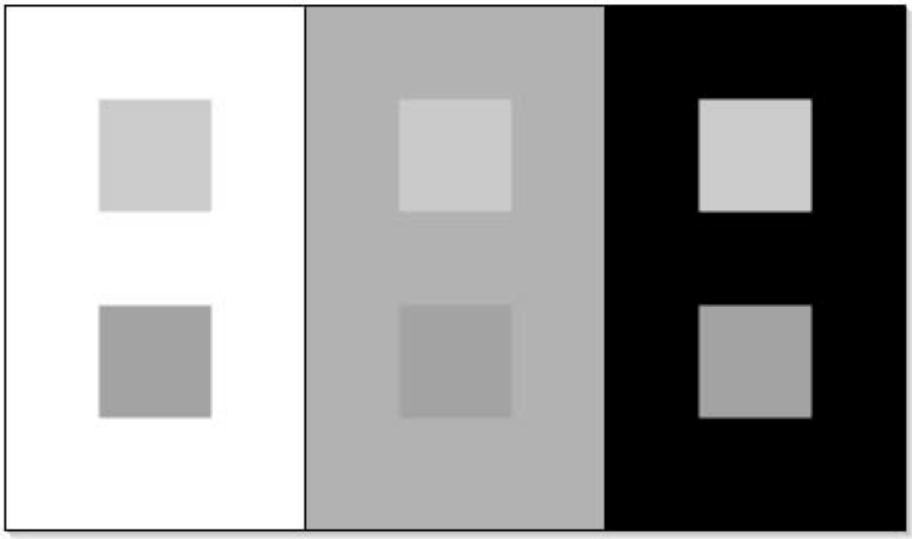

Figure 10. An example of lightness crispening. The color difference for the pairs of small squares are identical for each background, though they appear greatest on the gray background.

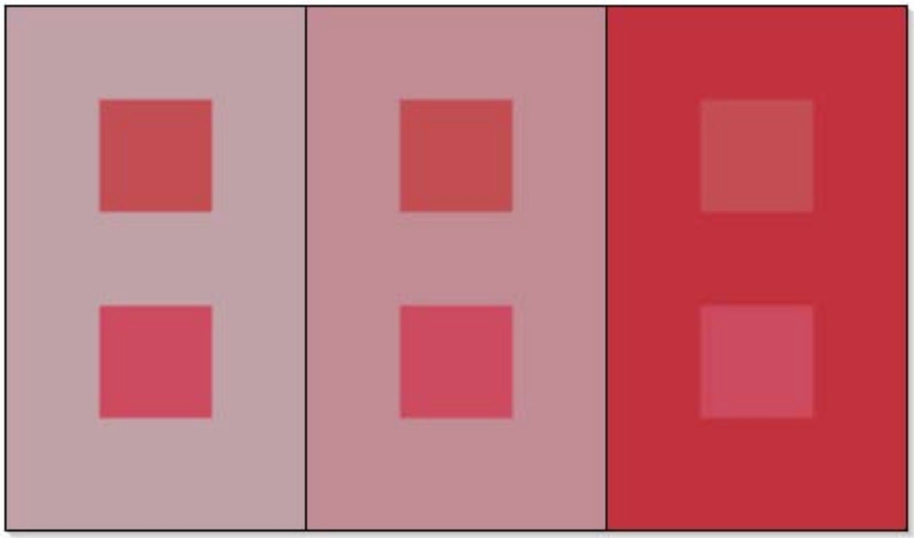

Figure 11. An example of chroma crispening. The color difference of the small pairs are identical, but should look greatest on the background of most similar chroma (far right).

Luminance Phenomena

The above color appearance phenomena deal with color changes as a function of spatial structure and background. Profound color changes can also occur when the illumination the stimuli are viewed under changes. This can include luminance level changes (dark to bright) or when the color of the illumination changes. Luminance changes are very common in everyday life. The classic example is to think about a bright sunny day, and a dark overcast day. Objects tend to appear very bright and colorful on sunny day, and somewhat subdued on an overcast day. These occurrences can be well described by both the Hunt effect and the Stevens effect.

The *Hunt effect* states that as the luminance of a given color increases, its perceived colorfulness also increases. This effect was first identified in a study by Hunt on the effects of light and dark adaptation on the perception of color.[28] Using a variation of a matching experiment called haploscopic matching, observers were given one viewing condition in their left eye and another in their right eye. Observers then used a method of adjustment technique to create matches on stimuli viewed in each eye. It was determined that when one eye had a very low luminance level, it took much more colorimetric purity to match a stimulus viewed at a very high luminance level. This indicates that colorfulness is not independent of luminance level. Going back to the sunny day analogy, that partially explains why objects appear much more vivid, or colorful, when viewed in bright sunny environment. Scenes also appear much more contrasty when viewed in a bright environment.

This increase in contrast has been examined closely in a classic study by Stevens and Stevens.[29] This study showed that as the luminance level increases, so too does the brightness contrast. This effect has been coined the *Stevens effect*. In this study observers performed magnitude estimation experiments on brightness stimuli, across many different luminance adapting conditions. This experiment has been described above in the discussion on Fechner's and Stevens' laws. The results showed that brightness tended to follow a power law relationship with luminance, thus forming the basis for Stevens' power law. However, this study also showed that the exponent of the power function changed as a function of adapting luminance level. Essentially, as the adapting luminance level increased bright colors tended to look brighter, and darker colors tended to look darker. So as the adapting luminance level increases the rate of change between the brightness of the dark and light colors increases. This rate of change is often considered the contrast of the scene.

While the Stevens effect illustrates the change in brightness contrast with luminance level, what happens when there is a color change as well? Brightness is often erroneously assumed to be a function of luminance level alone. This is not the case, and is well illustrated by the Helmholtz-Kohlrausch effect. The Helmholtz-Kohlrausch effect shows that brightness also changes as a function of saturation. That is to say, as a stimulus becomes more saturated at constant luminance, its perceived brightness also increases. Another way to describe this effect is say that a chromatic stimulus will appear brighter than an achromatic stimulus at the same luminance. If brightness were truly independent of chromaticity, then this effect would not exist. It is important to note that the Helmholtz-Kohlrausch effect is a function of hue angle as well. It is less noticeable for yellows than purples, for instance. Essentially this means that perceived brightness is actually a function of saturation and hue, and not just luminance. Fairchild and Pirrotta published a general review of the Helmholtz-Kohlrausch effect, as well as some models for predicting the effect.[30]

Another interesting relationship between luminance level and chromatic colors is the Bezold-Brücke hue shift. This phenomenon relates the perceived hue of monochromatic light sources with luminance level. It is often assumed that the hue of monochromatic light can be described completely by its wavelength. This is not the case, as the hue of a monochromatic light will shift as the luminance of the light changes. The amount of hue shift also changes both in direction and magnitude as a function of hue. Experimental results regarding the Bezold-Brücke hue shift can be found in work published by Purdy.[31] One important consideration for these hue shifts is that all the experimental data were obtained using unrelated colors. Recall that unrelated colors are stimuli viewed in complete isolation. Unrelated colors occur very rarely in everyday life. Hunt published a report indicating that the Bezold-Brücke hue shift disappears for related colors.[32] This must be taken into consideration when creating a model to predict color appearance.

Hue Phenomena

We have seen above how luminance changes can cause large shifts in the appearance of colored stimuli. This section examines two phenomena that result from changing the hue of the viewing conditions. These hue changes are less common than luminance changes, and often not very perceptible. They are included here because many models of color appearance models are capable of compensating for these effects.

The Bezold-Brücke hue shift illustrated that the wavelength of monochromatic light sources is not a good indicator of perceived hue. As luminance levels change, the perceived hue can also change. Another similar effect is the *Abney effect*. The Abney effect simply states that adding "white" light to a monochromatic light does not preserve constant hue. Another way of expressing this is to say that straight lines in a chromaticity diagram, radiating from the chromaticity of the white point to the spectral locus, are not lines of constant hue. Unlike the Bezold-Brücke hue shift, this effect is valid for related colors as well as unrelated colors.

Another interesting, though difficult to reproduce, phenomenon involving monochromatic illumination is the *Helson-Judd effect*.[33] This effect describes that non-selective (gray) stimuli viewed under highly chromatic illumination take on the hue of the light source if they are lighter than the background, and take on the complimentary hue if they are darker than the background. So a dark gray sample viewed on a medium gray background under red illumination will look somewhat green, while a light gray sample would appear pinkish. This effect almost never occurs in common practice, and is very difficult to reproduce in a laboratory setting. Nevertheless, some color appearance models take this into account. More details on this effect can be found in Fairchild[1] and Mori *et al.*[34]

Surround Phenomena

The Stevens effect demonstrated that contrast for simple patches increased as a function of adapting luminance. Around the same time, Bartleson and Breneman were studying the effects of luminance level and surround on complex stimuli, namely images.[35] They were able to generate similar results to Stevens and Stevens, in regards to changes in luminance level. More interestingly, they noticed interesting results regarding the change in the relative luminance of the image surround. Recall that the surround is considered to be the field outside of the background, or in practical situations the entire viewing room. Bartleson and Breneman determined that perceived contrast in images increased as the luminance of the surround increased. That is to say, when an image is viewed in a dark surround, the black colors look lighter while the light colors remain relatively constant. As the surround luminance increases the blacks begin to look darker, causing overall image contrast to increase.

These results modeled phenomena that were already taken into account in the photographic world. Traditionally, for optimum tone reproduction, photographic transparencies designed for viewing in a darkened room were reproduced with a much higher contrast than those designed for viewing as a print in a bright room. Hunt[36] and Fairchild[37] provide more in depth analysis of the history and prediction of optimal tone reproduction for complex images. In their original publication, Bartleson and Breneman published equations that predicted their results well. These equations were simplified later, to create equations for calculating optimal tone reproduction.[38] Such equations have been adapted and are included in many models of color appearance.[1]

Surround compensation can play a key part in the design and implementation of a color imaging system. For instance, in designing a scanner to convert movie film into video for display on a television, one must understand the effects surround will have on the final output image. Television is typically viewed in a lighter surround than a darkened movie theater. If the scanner does not take this change in surround into account, it is possible for the video to appear to have a much higher perceived contrast than the original film.

Color Constancy and Discounting the Illuminant

Illumination can vary dramatically throughout many different environments. This includes both the physical amount of illumination, as well as the color of the illumination. Several of the examples above illustrate how these changes in illumination can cause the appearance of colors to change drastically. At the same time, most people will readily acknowledge that the colors of objects do not change when moving from one viewing condition to another. A red apple will look red when viewed under bright outdoor illumination, as well as when viewed inside at relatively dark incandescent illumination. This is the effect known as *color constancy*. One of the mechanisms for color constancy is chromatic adaptation, which is described in much further detail below. Suffice for now to know that chromatic adaptation is a result of sensory adaptation, as well as cognitive behavior. The cognitive ability of an observer to interpret the color of an object based on the illuminated viewing environment is known as *discounting-the-illuminant*. Essentially this is the mechanism that allows for observers to “know” that the red apple is still red, despite potentially large changes in the color of the illuminant. Color constancy is an area of active research. The publications by Jameson and Hurvich[39], as well as Fairchild[1] provide good starting points for the researcher interested in the study of color constancy.

CHROMATIC ADAPTATION

The human visual system is capable of functioning across vast changes in viewing conditions, while providing relatively stable perceptions. The mechanism that allows the visual system to do this is known as adaptation. Adaptation allows the general sensitivity to any given stimulus to change, based on the conditions of the stimulus itself. There are three types of adaptation that are important for modeling vision and color imaging: light, dark, and chromatic. While light and dark adaptation describe the human visual system's capability of functioning across large changes in luminance levels. These changes need to be considered when building color-imaging systems that are designed to work across wide luminance ranges, though those types of situations are relatively rare. Chromatic adaptation is the ability of the human visual system to adjust to changes in the *color* of illumination.

The previous section described many color appearance phenomena, or examples where basic tristimulus colorimetry fails. Several of these examples represent changes in luminance level, such as the Hunt and Stevens effects. Many of the other phenomena described above can be considered second-order effects, as the situations in which they occur happen relatively infrequently. Chromatic adaptation, and the similar concept of color constancy, is perhaps the most important of the color appearance phenomena. This section discusses the theory of chromatic adaptation, and some of the mechanisms that enable adaptation. This section also describes some computational models of chromatic adaptation, and how those models can be used to calculate color appearance matches across different viewing conditions. These matches are important when designing color-imaging systems that are capable of reproducing colors for view in various conditions.

Light and Dark Adaptation

Light adaptation is the decrease in visual sensitivity as a function of overall amount of illumination. Essentially, the more light illuminating a scene, the less sensitive the human visual system becomes to light. This is a very common occurrence. Imagine going to an afternoon cinema matinee. When leaving the darkened theatre into the sunny afternoon light your visual system is often shocked, sometimes even to the point of physical pain. It is very difficult to see anything for a few moments, and then your visual system adjusts so that you can see objects normally. *Dark* adaptation is the opposite, as the human visual system becomes more sensitive to light as the overall amount of illumination decreases. This can be thought of as walking from the sunny afternoon light into a darkened theatre, and struggling to find your seat. After several minutes objects become recognizable as your visual system adapts.

Light and dark adaptation, though very similar, function at different speeds. The speed of adaptation is often referred to as the time-course for full adaptation. Light adaptation works at a much faster rate than dark adaptation. Consider the movie theatre discussion above. When leaving the theatre to go outside, it is somewhat painful for several seconds and then vision returns to back to normal. Dark adaptation can take several minutes before objects become noticeable. This indicates the mechanisms of dark adaptation are much more gradual than those of light adaptation.

So what are the physiological mechanisms that enable light and dark adaptation? One mechanism has been reproduced almost identically in photographic camera systems. This is the dilation and constriction of the pupil in the eye. For many years, cameras have had an aperture control that enables the photographer to adjust the amount of light that enters the lens. The human eye works in a similar manner. In ordinary viewing situations the pupil can range in diameter from about 3mm to 7mm. From these different diameters, we can conclude that the pupil can account for up to a 5x change in luminance level. Considering that the range in luminance levels from sunlight to starlight can differ upwards of 10 orders of magnitude, clearly the pupil dilation and contraction cannot be the only mechanism of adaptation. Other mechanisms include the transition from cones to rods, and vice-versa. In the human retina, there are two distinct types of photoreceptors, rods and cones. Rods are more sensitive to light, and are responsible for vision at low luminance levels. Cones are less sensitive to light, and are responsible for color vision at higher luminance levels. The transition from cones to rods can account for additional levels of adaptation. Additionally, this transition can explain the difference in the time-course of adaptation between light- and dark-adaptation mechanisms. The cones respond relatively quickly to increased levels of illumination, while the rods respond slower to decreased levels. Other mechanisms can account for light and dark adaptation, including receptor gain control, where the photoreceptors themselves become less sensitive to light at increased luminance levels. Receptor gain control is perhaps the most important sensory mechanism for chromatic adaptation, and will be revisited.

Chromatic Adaptation

Chromatic adaptation refers to the human visual system's ability to adjust to the color of overall illumination, rather than the absolute levels of the illumination. This is perhaps best explained with a common example. Consider a white object, such as a piece of paper. This paper can be viewed under a variety of light sources, such as daylight, incandescent, and fluorescent. Despite the large change in the color of these sources (ranging from blue to orange), the paper will always retain an approximate white appearance. Chromatic adaptation is often thought to be a result of independent gain control mechanisms on the three types of cone photoreceptors, as illustrated in Figure 12. This is similar to the receptor gain control functions of light and dark adaptation, though those can also be explained with a single gain control function for all photoreceptors.

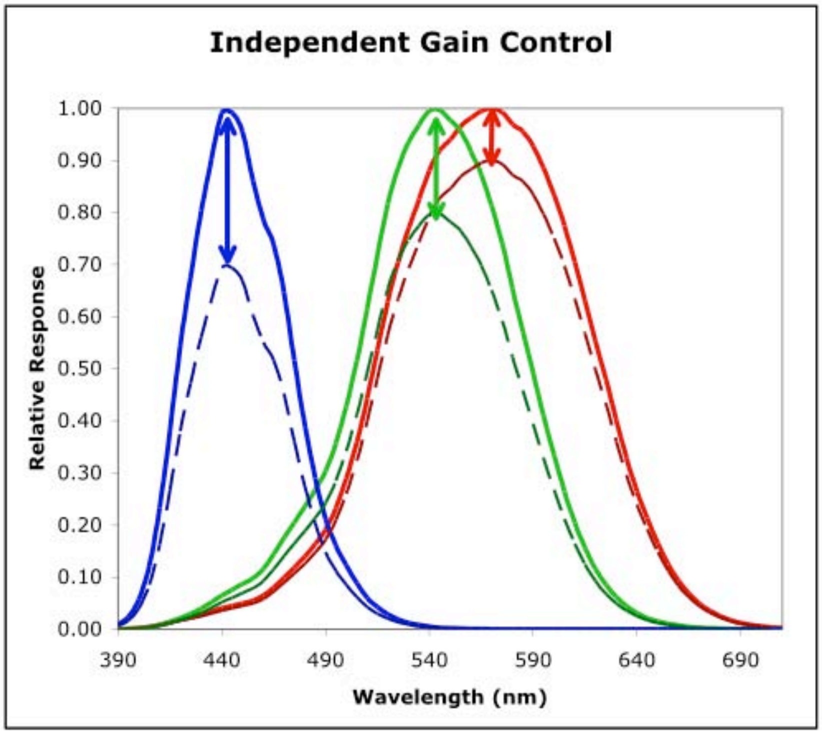

Figure 12. Iconic concept of independent cone gain control.

While this is certainly a valid hypothesis, there is no evidence that the gain control mechanisms do not also occur at other stages of visual processing. The theory of independent photoreceptor gain control was first published 100 years ago, in a seminal paper by von Kries.[40],[41] In that paper, translated by MacAdam, he wrote:

> *…the individual components present in the organ of vision are completely independent of one another and each is fatigued or adapted exclusively according to its own function.*[40,41]

This insight, though now we know it is not entirely correct, provided an excellent starting point on the theory of chromatic adaptation.

The receptor gain control idea of chromatic adaptation is very similar in principle to an automatic white balance in a digital camera or camcorder. Those devices adjust the sensitivities of their detectors such that the "brightest" object in the scene appears white. This is accomplished by normalizing all the detectors with the strongest detector signal. This type of adaptation is classified as a *sensory* mechanism. A sensory mechanism is a mechanism that responds automatically to the stimulus energy. If chromatic adaptation were entirely a sensory mechanism, it would be much easier to understand and model. Unfortunately, (at least from a modeling standpoint) chromatic adaptation is a combination of sensory and *cognitive* mechanisms. A cognitive mechanism responds to a stimulus based upon an observer's knowledge of scene content.

Some cognitive mechanisms have been discussed in previous sections. Examples include discounting-the-illuminant and color constancy. Another interesting cognitive mechanism is memory color. Memory color is the phenomenon that recognizable objects often have a "known" color that is associated with them. Typical memory colors might be green grass, blue sky, skin tones, and the red apple example given above. Figure 13 illustrates the idea of cognitive mechanisms and perhaps memory color for a yellow banana. The image on the left of Figure 13 has a green filter placed over the entire image, while the image on the right has the filter only on the banana. The banana retains its yellow color when the entire image is filtered, while the identically colored banana looks greenish when it is the only object filtered.

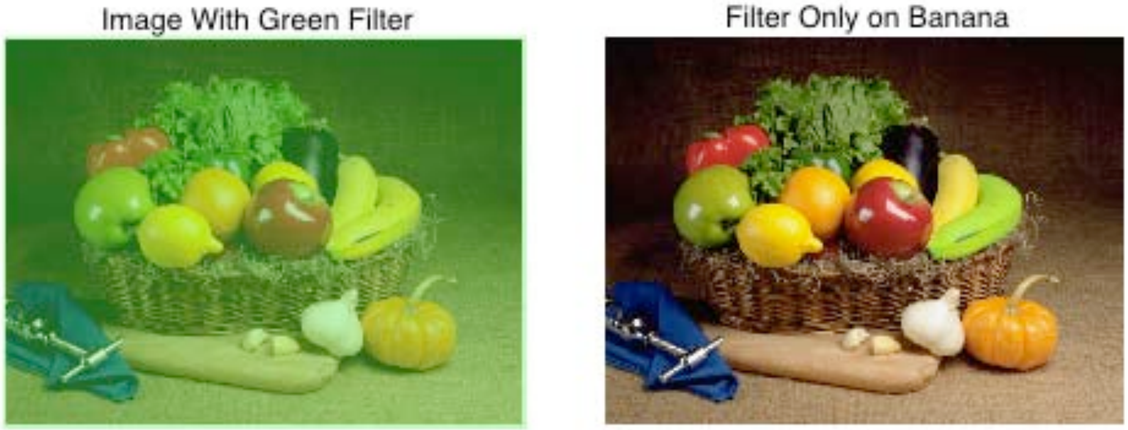

Image With Green Filter

Filter Only on Banana

Figure 13. An example of cognitive mechanisms of chromatic adaptation. The image on the left is covered with a green filter. The image on the right has the same green filter placed only on the banana. The color of the banana is the same for both images, though it retains its yellow appearance in the left image and looks green in the right.

When asked to produce memory colors in an experiment, using techniques such as the method of adjustment, observers are generally able perform that task with relative ease. An interesting note is that memory colors often are remembered differently than the actual object. For instance when asked to produce a grass green, observers typically make a green that is much more saturated than actual grass.[42] Perhaps this is an indication of observer preference blending into memory color. Cognitive mechanisms of color appearance are discussed in much greater detail in works by Evans[43], Jameson and Hurvich[39], Davidoff[44], and Fairchild[1].

Chromatic Adaptation Models

Models of chromatic adaptation are the first step toward the creation of a color appearance model. Chromatic adaptation models extend the function of basic tristimulus colorimetry. Basic colorimetry was designed to predict appearance matches between stimuli within a single, constant viewing condition. The color appearance phenomena described in the sections above illustrated areas where basic colorimetry fails. Chromatic adaptation enables visual matches to persist through wide ranges of viewing conditions. Two stimuli that are viewed in different conditions, yet appear to match are called *corresponding colors*. For example, one stimulus might be viewed under daylight simulators, while another is viewed under a tungsten light bulb. The two stimuli might have different XYZ tristimulus values, but because of chromatic adaptation to the illuminating light sources, they might appear to match.

Basic colorimetry is not designed to predict matches across different viewing conditions. In order to predict these matches, we need a model of chromatic adaptation. The general form of a chromatic adaptation was first described by von Kries, as discussed above.[40] He described a simple hypothesis for a model of chromatic adaptation, based upon cone photoreceptor normalization. There are two general misconceptions regarding von Kries' ideas for chromatic adaptation. Although many chromatic adaptation models claim to utilize a von Kries transformation, often called a von Kries coefficient or proportionality law, the equations used in these types of models were never actually proposed by von Kries. Rather, he simply proposed his idea for independent cone adaptation. This idea was meant to serve as an interim solution, or a stepping-stone for more advanced research. Little did he know that one hundred years later his simple hypothesis would still be in widespread use.

von Kries Model

Though von Kries himself didn’t formulate equations for chromatic adaptation, his hypothesis has been used to create a simple chromatic adaptation model. Many chromatic adaptation models are designed to work in conjunction with CIE colorimetry. The hypothesis laid out by von Kries suggested that the cone photoreceptors adapted independently of one another. To model this, in a meaningful physiological manner, it is necessary to transform from CIE XYZ tristimulus values into LMS cone responses (sometimes referred to as RGB, or ργβ responses). The LMS cone responses can be calculated fairly accurately using a linear transform of CIE tristimulus values. An example transformation, referred to as the Hunt-Pointer-Estevez transformation (normalized to illuminant D65), is described in Equation 7.[45]

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.4002 & 0.7076 & -0.0808 \\ -0.2263 & 1.1653 & 0.0457 \\ 0.0 & 0.0 & 0.9182 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (7)$$

These LMS cone responsivities are then used in a modern interpretation of a chromatic adaptation model, known as a coefficient model. This interpretation is shown in Equations 8-10:

$$L_{adapted} = \alpha_{\mathrm{L}} \cdot L \qquad (8)$$

$$M_{adapted} = \alpha_{\mathrm{M}} \cdot M \qquad (9)$$

$$S_{adapted} = \alpha_{\mathrm{S}} \cdot S \tag{10}$$

In these equations, LMS represent the initial cone responses to a given stimulus, and $\mathrm{LMS}_{\mathrm{adapted}}$ are the post-adaptation cone signals. To obtain the adapted cone signals, each LMS response is scaled using the independent gain control coefficients: α_{L}, α_{M}, α_{S}. How these gain control coefficients are calculated is the key aspect to most chromatic adaptation models. For the typical von Kries model, those coefficients are described to be the inverse of the maximum LMS response in the scene. The maximum LMS response is typically the scene white, so a von Kries adaptation is often referred to as a "white-point normalization." Equations 11-13 illustrate the idea of a white point adaptation:

$$\alpha_{\mathrm{L}} = 1/L_{\max} \quad \text{or} \quad \alpha_{\mathrm{L}} = 1/L_{white} \tag{11}$$

$$\alpha_{\mathrm{M}} = 1/M_{\max} \quad \text{or} \quad \alpha_{\mathrm{M}} = 1/M_{white} \tag{12}$$

$$\alpha_{\mathrm{S}} = 1/S_{\max} \quad \text{or} \quad \alpha_{\mathrm{S}} = 1/S_{white} \tag{13}$$

Often times it is convenient to express the chromatic adaptation model as a linear matrix transform. This is especially useful for concatenating transforms, as well as when programming models. The above interpretation of the von Kries type chromatic adaptation model is shown in Equation 14:

$$\begin{bmatrix} L_{adapted} \\ M_{adapted} \\ S_{adapted} \end{bmatrix} = \begin{bmatrix} 1/L_{white} & 0.0 & 0.0 \\ 0.0 & 1/M_{white} & 0.0 \\ 0.0 & 0.0 & 1/S_{white} \end{bmatrix} \cdot \begin{bmatrix} L \\ M \\ S \end{bmatrix} \tag{14}$$

By expressing the chromatic adaptation transform as a matrix transformation, we can generate adapted CIE XYZ tristimulus values with a single 3x3 transformation. This is shown in Equation 15.

$$\begin{bmatrix} X_{adapted} \\ Y_{adapted} \\ Z_{adapted} \end{bmatrix} = \mathbf{M}^{-1} \cdot \begin{bmatrix} 1/L_{white} & 0.0 & 0.0 \\ 0.0 & 1/M_{white} & 0.0 \\ 0.0 & 0.0 & 1/S_{white} \end{bmatrix} \cdot \mathbf{M} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{15}$$

M and $\mathbf{M}^{-1}$ represent the Hunt-Pointer-Estevez transformation, and inverse transformation as illustrated in Equation 7. While it is useful to obtain the adapted CIE XYZ tristimulus values for a given stimulus, often times it is more useful to obtain corresponding colors data. Recall that corresponding colors are two stimuli that appear to match when viewed under disparate conditions. A model that can calculate the tristimulus values necessary to obtain this perceptual match across different viewing conditions is known as a chromatic adaptation transform, or CAT.

von Kries Transform

Once a chromatic adaptation model is available, it is very easy to extend it with the ability to "transform" CIE XYZ tristimulus values from one viewing condition to another. The general form of this transformation is shown in Equations 16-18:

$$L_2 = (L_1 / L_{white}) \cdot L_{white2} \tag{16}$$

$$M_2 = (M_1 / M_{white}) \cdot M_{white2} \tag{17}$$

$$S_2 = (S_1 / S_{white}) \cdot S_{white2} \tag{18}$$

L_2,M_2, and S_2 are the predicted cone responses of the perceptual match for the original LMS responses, though under the second viewing conditions. L_{white}, M_{white}, and S_{white} are the cone responses of the white point in the original viewing condition, while L_{white2}, M_{white2}, and S_{white2} are cone responses of the white point in the new viewing conditions. These equations are essentially calculating the post adaptation signals from the first viewing condition, designated LMS, and setting those signals equal to the post adaptation signal from the second viewing condition. The chromatic adaptation model is then inverted, to calculate the pre-adaptation response necessary to elicit that equal signal. The corresponding CIE XYZ tristimulus values can be found by concatenating Equation 15 with Equations 16-18. This is illustrated in Equation 19:

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \mathbf{M}^{-1} \cdot \begin{bmatrix} L_{white2} & & \\ & M_{white2} & \\ & & S_{white2} \end{bmatrix} \cdot \begin{bmatrix} 1/L_{white} & 0.0 & 0.0 \\ 0.0 & 1/M_{white} & 0.0 \\ 0.0 & 0.0 & 1/S_{white} \end{bmatrix} \cdot \mathbf{M} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{19}$$

Nayatani's Model

The von Kries model of chromatic adaptation is a relatively straightforward linear scaling of fundamental cone responsivities. This model was enhanced by Nayatani *et al.* to include a nonlinear term, in addition to the linear gain control.[46,47] The nonlinear model was extended from a nonlinear model first proposed by MacAdam.[48] The Nayatani model is essentially a von Kries type gain adjustment, followed by a power function that has a variable exponent. The exponent of the power function is determined by the overall luminance of the adapting field. In addition to the power function, the Nayatani model adds in a noise term, and a coefficient for forcing complete color constancy of non-selective (gray) samples of the same luminance as the adapting field. The power function enables the Nayatani model of chromatic adaptation to predict luminance appearance phenomena, such as the Hunt and Stevens effect. The noise term aids in the prediction of threshold data. Equations 20-22 show the generalized expressions of this nonlinear model:

$$L_{adapted} = a_{\mathrm{L}} \cdot \left(\frac{L + L_n}{L_{white} + L_n} \right)^{\beta_L} \tag{20}$$

$$M_{adapted} = a_{\mathrm{M}} \cdot \left(\frac{M + M_n}{M_{white} + M_n} \right)^{\beta_M} \tag{21}$$

$$S_{adapted} = a_{\mathrm{S}} \cdot \left(\frac{S + S_n}{S_{white} + S_n} \right)^{\beta_S} \tag{22}$$

$L_{adapted}$, $M_{adapted}$, and $S_{adapted}$ are the adapted cone response signals; LMS are the input cone response signals; L_{white}, M_{white}, and S_{white} are the cone responses of the adapting condition; L_n, M_n, and S_n are the additive noise terms; β_L, β_M, and β_S are the exponent terms for the power function, and are based on the adapting luminance level. In addition to these terms, a_L, a_M, and a_S are coefficients determined to produce color constancy for medium gray stimuli.

The Nayatani model illustrates that a simple extension of a von Kries type chromatic adaptation model was capable of predicting many complicated color appearance phenomena. This model has served the basis for many of the other chromatic adaptation, and color appearance, models that were to follow. More information on this chromatic adaptation model and several of its enhancements can be found in publications by Nayatani et al.[49], and Fairchild.[1]

Fairchild Model

The original nonlinear Nayatani model suffered slightly from over predicting the degree of adaptation. That is to say, it predicted more complete adaptation than what was witnessed experimentally. Despite many claims that the human visual system is "color constant," often there are situations where chromatic adaptation is less than 100 percent complete.[50] This prompted a series of experiments attempting to measure the degree of adaptation for many different forms of adapting stimuli, including both hard and soft copy.[51] These experiments helped derive a linear chromatic adaptation model that accounted for luminance effects, discounting-the-illuminant, and incomplete adaptation.[52,53]

This model, like the von Kries and Nayatani models before it, is based on a relatively simple extension to basic CIE colorimetry. The general form of this model is identical similar to the von Kries model, as shown in Equation 23:

$$\begin{bmatrix} L_{adapted} \\ M_{adapted} \\ S_{adapted} \end{bmatrix} = \begin{bmatrix} a_L & 0.0 & 0.0 \\ 0.0 & a_M & 0.0 \\ 0.0 & 0.0 & a_S \end{bmatrix} \cdot \begin{bmatrix} L \\ M \\ S \end{bmatrix} \tag{23}$$

Where a_L, a_M, and a_S are the adapting gain control coefficients. These gain control coefficients are calculated in a slightly more complex manner than the typical von Kries manner. Equations 24-26 illustrate the calculations for the L cone coefficients. The M and S cone coefficients are calculated in a similar form.

$$a_L = \frac{p_L}{L_n} \tag{24}$$

$$p_L = \frac{\left(1 + Y_n^{1/3} + l_E\right)}{\left(1 + Y_n^{1/3} + 1/l_E\right)} \tag{25}$$

$$l_E = \frac{3\left(L_n / L_E\right)}{L_n / L_E + M_n / M_E + S_n / S_E} \tag{26}$$

While daunting at first, these equations really are essentially a modified von Kries transformation. The Y_n term refers to the adapting luminance in cd/m^2. Any term with an n subscript refers to the adapting stimulus, while terms with an E subscript refer to the equal-energy illuminant. Equation 24 simplifies to a complete von Kries adaptation term, as p approaches 1. On the other hand, Equation 24 can also simplify to zero adaptation, as p approaches the adapting cone response value. Any value in-between represents a degree of incomplete adaptation. The amount of adaptation is a function of both overall luminance level as well as deviation from the equal-energy illuminant. Essentially, as the luminance level increases so too does the degree of adaptation, and the further the adapting illuminant is from the equal-energy illuminant the less adaptation.

The original Fairchild model also included a luminance-dependent interaction among the three cone types. This was subsequently removed, when it was determined to produce an overall increase in lightness predictions.[54] Corresponding color data can be calculated using this model by cascading Equation 23 with the Hunt-Pointer-Estevez primaries. The cascaded equation reduces to a simple 3x3 matrix multiplication, allowing for quick calculations for large data sets. For this reason, the Fairchild chromatic adaptation transform, and the color appearance model that was based on it, are useful for processing image data.

Spectrally Sharpened Chromatic Adaptation Models

Much chromatic adaptation research focus of late has been on the topic of "spectrally sharpened" cone fundamentals.[55,56;57,58] The research has been a convergence of two rather distinct fields, color science and computational color constancy. The first chromatic adaptation transform to use spectral sharpened cone fundamentals was the Bradford transform.[55] The Bradford transform is also a modified von Kries gain control model, with a nonlinear term similar to Nayatani's model on the short wavelength cone signal. The calculations in this model begin with a transform from CIE XYZ tristimulus values into normalized cone responses. These calculations are shown in Equations 27 and 28.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M} \cdot \begin{bmatrix} X/Y \\ Y/Y \\ Z/Y \end{bmatrix} \tag{27}$$

$$\mathbf{M} = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \tag{28}$$

There are several interesting features of this transform. The XYZ tristimulus values are all normalized by dividing by the Y. This is in effect luminance normalization, as all stimuli with identical chromaticity coordinates will have identical "cone" responses. The cone responses, RGB, do not represent physiologically plausible cone responses. Instead, they represent spectrally sharpened cone responses. What that means is that "cones" themselves have narrower support, as well as negative responsivity at some wavelengths. Figure Z.x illustrates the principle of sharpened sensors. The sharpened responsivities tend to preserve saturation, as well as color constancy. The Bradford responsivities are not the only spectrally sharpened cones that can be used in a chromatic adaptation transform. More details can be found in publications by Finlayson[57] and Calabria.[58]

The remainder of the Bradford transform is relatively straightforward. With the addition of terms for incomplete adaptation this is the chromatic adaptation model used in the CIECAM97s color appearance model, so further details are given below.

COLOR APPEARANCE MODELS

CIE tristimulus colorimetry was designed with a single purpose, for which it has enjoyed good success. This purpose is to predict when two simple stimuli will match, for the average observer, under a single viewing condition. We have already seen the limitations of basic colorimetry with some of the color appearance phenomena described above. Chromatic adaptation transforms, as described in the previous section, extend basic colorimetry so that it is possible to predict matches across disparate viewing conditions. Chromatic adaptation transforms are still limited, in that they do not help describe the actual color appearance of a stimulus.

To accurately describe the color appearance of a stimulus, we must use the color terminology described in an earlier section. These terms include the relative terms of lightness, hue, saturation, and chroma as well as the absolute terms of brightness, colorfulness and hue (again). Even with a chromatic adaptation transform, CIE tristimulus colorimetry is not able to describe any of these appearance terms. In order to do that, it is necessary to use a color appearance model.

So what is a color appearance model, exactly? The CIE Technical Committee TC1-34, *Testing Colour Appearance Models*, came up with a definition of what constitutes a color appearance model.[59] The definition agreed upon is as follows: A color appearance model is any model that includes predictors of at least the relative color-appearance attributes of lightness, chroma, and hue. This is a relatively lenient definition of what constitutes a color appearance model, though it does require some form of a chromatic adaptation transform at the very least. Models that are more complicated are capable of predicting absolute attributes, such as brightness and colorfulness, as well as luminance-dependent effects such as the Hunt and Stevens effect. Spatially structured phenomena, such as crispening and simultaneous contrast require both models of spatial vision as well as color appearance.

There are many color appearance models available, each designed with specific goals in mind. Among those models are CIELAB, Hunt, Nayatani, ATD, RLAB, LLAB, ZLAB, and CIECAM97s. This section will describe CIELAB as a rudimentary color appearance model, as well as CIECAM97s, which is the CIE recommended model. Fairchild[1] has presented a very thorough review of all of these models.

CIELAB as a Color Appearance Model

Although designed as a uniform color space for expressing color differences, rather than a color appearance model, CIELAB does have predictors of lightness, chroma, and hue. These predictors allow CIELAB to be labeled as a color appearance model. We will use it here as a simple model to illustrate the design of more complicated color appearance models.

CIELAB calculations require a pair of CIE XYZ tristimulus values, those of the stimulus itself, as well as those of the reference white point. The reference white point values are used in a von Kries-type chromatic adaptation transform. The adaptation transform is followed by a compressive cube-root nonlinearity, and an opponent-color transformation. The exact calculations are shown in Equations 29-32.

$$L^* = 116 f(Y/Y_n) - 16 \tag{29}$$

$$a^* = 500\left[f(X/X_n) - f(Y/Y_n)\right] \tag{30}$$

$$b^* = 200\left[f(Y/Y_n) - f(Z/Z_n)\right] \tag{31}$$

$$f(x) = \begin{cases} (x)^{1/3} & \text{if } x > 0.008856 \\ 7.787(x) + 16/116 & \text{if } x \le 0.008856 \end{cases} \tag{32}$$

XYZ are the tristimulus values of the stimulus, while X_n, Y_n, and Z_n are the tristimulus values of the adapting white. There are several points that need to be emphasized. The white point normalization, or chromatic adaptation, is not performed in a physiological cone space. Rather it is performed in XYZ tristimulus space. This transform is sometimes referred to as a “wrong von Kries” chromatic adaptation transform.[60] The effects of performing the chromatic adaptation in XYZ tristimulus space, rather than cone space, are most noticeable in the hue predictions, often causing inaccurate hue shifts.

The cube root power functions attempt to model the compressive relationship between physical measurements and psychological perceptions. These compressive results were first discussed above in regard to Fechner and Stevens’ laws. The cube root function is replaced by a linear function, for very dark stimuli, as shown in Equation 32.

The CIELAB L* coordinate, as expressed in Equation 29, is a correlate to perceived lightness. It can range between 0.0 for absolute black stimuli, to 100.0 for diffuse white stimuli. The a* and b* coordinates approximate respectively the red-green and yellow-blue of an opponent color space. A positive a* value approximates red, while a negative approximates green. Similarly a positive b* correlates to yellow, while negative values correlate to blue. Achromatic stimuli, such as whites, grays, and blacks, have values of 0.0 for both a* and b*.

The definition of a color appearance model requires a minimum of predictions for lightness, chroma, and hue. CIELAB L* provides a lightness prediction, but a* and b* do not fully predict correlates of chroma and hue. These correlates can be calculated by transforming the Cartesian coordinates of a* and b* into cylindrical coordinates of C^*_{ab} and h_{ab}, where C^*_{ab} represents chroma, and h_{ab} represents hue angle. Equations 33 and 34 illustrate those transformations.

$$C^*_{ab} = \sqrt{\left(a^{*2} + b^{*2}\right)} \tag{33}$$

$$h_{ab} = \tan^{-1}\left(b^*/a^*\right) \tag{34}$$

With the cylindrical coordinates of chroma and hue angle, we now have enough information to predict the color appearance of a stimulus. There are several caveats, however. The wrong von Kries transform is clearly a source of color appearance errors. CIELAB is also incapable of predicting many of the color appearance phenomena described above. These include all luminance, surround, background, and discounting-the-illuminant effects. CIELAB also assumes 100% adaptation to the white point. Since CIELAB was only designed to predict small color differences between similar objects, under a single viewing condition, it is impressive that it can be used as a color appearance model at all. The CIELAB space is also known to hue non-uniformities, especially in the blue region.[61,62,63] This becomes important in certain image processing techniques, such as gamut mapping, where it is desirable to follow lines of constant perceptual hue. Clearly, it is important to have a color appearance model that was designed specifically for the use.

The Genesis of Color Appearance Models

Color appearance research over the course of many years has resulted in the formulation of many different color appearance models, each with different goals and methods. Until recently, it was often difficult to decide model to use for any given task. This changed in 1997, with the formulation of the CIE recommended CIECAM97s color appearance model.[59] The CIECAM97s model was designed to work as least as good as, if not better than, all of the previous models, for the color appearance phenomena it predicts. Thus, it is essentially a hybrid of the best parts of many different models. It is important to understand the pedigree of CIECAM97s in order to understand why it takes the form it does. This pedigree stems from the Hunt, Nayatani, RLAB, and LLAB models.[59] The interested reader is encouraged to delve into this rich history of color appearance research. The texts by Hunt[36] and Fairchild[1] provide many references to the development of these models.

The *Hunt* model is a very sophisticated model designed to predict many color appearance phenomena. It has undergone relentless development over the course of more than 2 decades.[36] The high degree of sophistication in the model comes at the price of a high degree of complexity. Perhaps the model is better described as a model of the human visual system response. This model was designed to predict a large range of appearance phenomena, including changes in background, surround, luminance level, and viewing modes. Many of the features, including the underlying color space, found in CIECAM97s are direct descendents of the Hunt model of color appearance.

The *Nayatani* model of color appearance is another model that is capable of predicting a wide range of appearance phenomena. The Nayatani model evolved directly from the nonlinear chromatic adaptation transform discussed in the previous section. This model has also undergone many revisions over the years. The most recent revisions, as well as a thorough summary, were described by Nayatani *et al*. in 1995.[64] This model was originally designed as a model for predicting the appearance of objects under various illuminants from an illumination engineering perspective. The ultimate goal of predicting the color rendering properties of light sources is quite different than some of the other color appearance models and therefore the Nayatani model predicts some phenomena differently than other models, such as those designed with a goal of accurate color image reproduction.

One such model designed with color image reproduction in mind is the *RLAB* color appearance model.[65] The RLAB model was developed as a simple color appearance model designed for practical applications. It is based on the Fairchild incomplete chromatic adaptation transform, and is thus capable of predicting many significant color appearance phenomena. The RLAB model was specifically targeted at cross-media image reproduction, such as a CRT to print system, and was built to extend upon CIE colorimetry. Because of its simplicity in design, it is incapable of predicting certain appearance correlates such as brightness and lightness. It is also not designed for use across wide luminance levels, and does not predict luminance effects such as the Hunt and Stevens effect.

Another similarly designed model is the *LLAB* color appearance model.[66] This model was designed as a model of color appearance specification, color difference calculation, and color match prediction. Like RLAB, it is designed to extend CIE colorimetry and CIELAB. Built upon the Bradford chromatic adaptation, the LLAB model calculates predictions of lightness, chroma, colorfulness, saturation, and hue. It is capable of predicting many appearance phenomena, such as surround and background changes, discounting-the-illuminant, and the Hunt-effect. This model also has a specified color difference equation. It is incapable of predicting the Stevens effect, or incomplete chromatic adaptation. The LLAB model is relatively simple, lying between RLAB and the Hunt model in complexity.

CIECAM97s

That there are many different color appearance models, each derived with different goals and techniques, has led to confusion in both industry and research. Traditionally it has been difficult to choose which model to use for any given situation and thus industry acceptance of color appearance models was tenuous at best. The CIE recognized this problem, and created TC1-34 with the task of creating a single color appearance model. The goal was to create uniformity of practice with compatibility with modern color imaging systems in mind.[59] TC1-34 was successful in their task with the formulation of the CIE 1997 Interim Color Appearance Model (simple version), CIECAM97s. CIECAM97s is the amalgamation of the research efforts of many people over many years.[59]

CIECAM97s model requires certain input data. These data include the luminance of the adapting field, expressed in cd/m^2. This is normally taken to be 20% of the luminance of white in the adapting filed, and is designated L_a. The CIE tristimulus values of the stimulus in the source conditions, designated XYZ, as well as the source itself, X_w, Y_w, Z_w are also necessary. Additional inputs include the relative luminance of the source background, designated, Y_b, also in the source conditions.

In addition to the above model inputs, there are also several constants that need to be selected. These constants include: the impact of surround, *c*, a chromatic induction factor, N_c, a lightness contrast factor, F_{LL}, and a factor determining the degree of chromatic adaptation, F. These constants can be selected using the following chart:

Viewing Condition	c	N_c	F_{LL}	F
Average Surround, Samples Subtending> 4°	0.69	1.0	0.0	1.0
Average Surround	0.69	1.0	1.0	1.0
Dim Surround	0.59	1.1	1.0	0.9
Dark Surround	0.525	0.8	1.0	0.9
Cut-Sheet Transparencies (on a viewing box)	0.41	0.8	1.0	0.9

Chromatic Adaptation

The first step is to transform the stimulus from the source viewing conditions into the conditions of the equal-energy illuminant. This chromatic adaptation transform uses the spectrally sharpened cone responses, RGB, of the Bradford transform given above. Equations 35 and 36 illustrate the transformation into the cone primaries, as well as the inverse transform.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M} \cdot \begin{bmatrix} X/Y \\ Y/Y \\ Z/Y \end{bmatrix} \tag{35}$$

$$\mathbf{M}_B = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \qquad \mathbf{M}_B^{-1} = \begin{bmatrix} 0.9870 & -0.1471 & 0.1600 \\ 0.4323 & 0.5184 & 0.0493 \\ -0.0085 & 0.0400 & 0.9685 \end{bmatrix} \tag{36}$$

The chromatic adaptation transform itself is a modified von Kries-type transformation, with a nonlinear power function on the short-wavelength. The degree of adaptation is determined using the variable, D. The degree of adaptation is set to 1.0 for complete adaptation or complete discounting-the-illuminant, as is generally the case for reflecting materials. D is set to 0.0 for no adaptation, and can take on intermediate values for various other degrees of adaptation. These values can be manually determined, against existing data, or can be calculated using Equation 41. This calculation is based upon luminance levels, as well as surround equations.

$$R_c = \left[D(1.0/R_w) + 1 - D\right]R \tag{37}$$

$$\mathrm{G_c} = \left[\mathrm{D}(1.0/\mathrm{G_w}) + 1 - \mathrm{D}\right]\mathrm{G} \tag{38}$$

$$B_c = \left[D(1.0/B_w^p) + 1 - D\right] \left|B\right|^p \tag{39}$$

$$\mathrm{p} = (\mathrm{B_w}/1.0)^{0.0834} \tag{40}$$

$$\mathrm{D} = \mathrm{F} - \mathrm{F}\Big/\left[1 + 2(\mathrm{L_A^{1/4}}) + (\mathrm{L_A^2})\Big/300\right] \tag{41}$$

If B happens to be negative, then B_c also must be set to be negative. The above calculations must also be performed for the source white, as they are required in later calculations. Before further calculations can be performed, various other factors must be determined. These factors include the background induction factor, n, the brightness and chromatic induction factors, N_{bb} and N_{cb}, and the base exponential linearity, z. These factors are calculated using Equations 42-46.

$$\mathrm{k} = 1/(5\mathrm{L_A} + 1) \tag{42}$$

$$\mathrm{F_L} = 0.2\mathrm{k}^4(5\mathrm{L_A}) + 0.1(1 - \mathrm{k}^4)^2(5\mathrm{L_A})^{1/3} \tag{43}$$

$$n = Y_b / Y_w \tag{44}$$

$$N_{bb} = N_{cb} = 0.725(1/n)^{0.2} \tag{45}$$

$$z = 1 + F_{LL} n^{1/2} \tag{46}$$

The post-adapted signals for both the sample, as well as the source white point, must then be transformed back from the sharpened cone responses into physiological cone responses. This is accomplished using the inverse of the Bradford transform, $\mathbf{M_B}^{-1}$ given in Equation 36, and the Hunt-Pointer-Estevez transformation. The complete transformation is given in Equations 47 and 48.

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \mathbf{M}_H \mathbf{M}_B^{-1} \begin{bmatrix} R_c Y \\ G_c Y \\ B_c Y \end{bmatrix} \tag{47}$$

$$\mathbf{M}_H = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00 & 0.00 & 1.00 \end{bmatrix} \quad \mathbf{M}_H^{-1} = \begin{bmatrix} 1.9102 & -1.1121 & 0.2019 \\ 0.3710 & 0.6291 & 0.00 \\ 0.00 & 0.00 & 1.00 \end{bmatrix} \tag{48}$$

The signals are then processed through a nonlinear response compression, to get post-adaptation cone responses. This is done for both the stimulus, and the adapting white. Equations 49-51 illustrate this calculation.

$$R'_a = \frac{40(F_L R'/100)^{0.73}}{\left[(F_L R'/100)^{0.73} + 2\right]} + 1 \tag{49}$$

$$G'_a = \frac{40(F_L G'/100)^{0.73}}{\left[(F_L G'/100)^{0.73} + 2\right]} + 1 \tag{50}$$

$$B'_a = \frac{40(F_L B'/100)^{0.73}}{\left[(F_L B'/100)^{0.73} + 2\right]} + 1 \tag{51}$$

Appearance Correlates

The adapted cone-responses are then used to determine correlates of appearance. The first step is to calculate preliminary red-green and yellow-blue opponent dimensions. This is accomplished using Equations 52 and 53.

$$a = R'_a - 12G'_a/11 + B'_a/11 \tag{52}$$

$$b = (1/9)(R'_a + G'_a - 2B'_a) \tag{53}$$

The hue angle, *h*, is calculated in a similar manner as the CIELAB hue angle. This calculation is done using Equation 54.

$$h = \tan^{-1}(b/a) \tag{54}$$

Often times it is desirable to have the hue correlates for the four unique hues (red, green, yellow, and blue) lie opposite each other in a color space. This is known as the Hue quadrature. Each of the unique hues have different weights in regards to the perceptual colorization of neutral colors, and this is known as the hue's eccentricity factor. Hue quadrature, H, and eccentricity factors, e, are calculated from the following unique hue data via linear interpolation between the following values for the unique hues:

Red: h = 20.14, e = 0.8, H = 0 or 400,
Yellow: h = 90.00, e = 0.7, H = 100,
Green: h = 164.25, e = 1.0, H = 200,
Blue: h = 237.53, e = 1.2. H = 300

An example of the linear interpolation used to calculate hue quadrature and eccentricity values for any given hue angle is shown using Equations 55 and 56.

$$e = e_1 + (e_2 - e_1)(h - h_1) / (h_2 - h_1) \tag{55}$$

$$H = H_1 + \frac{100(h - h_1) / e_1}{(h - h_1)/e_1 + (h_2 - h)/e_2} \tag{56}$$

The achromatic response is then calculated, using Equation 57. This response is used to calculate brightness and lightness, so the calculations must be performed for both the stimulus and the adapting white.

$$A = \left[2R'_a + G'_a + (1/20)B'_a - 2.05\right]N_{bb} \tag{57}$$

Lightness, J, is then calculated from the achromatic response to both the stimulus and the adapting white. This is shown in Equation 58.

$$J = 100\left(A / A_w\right)^{cz} \tag{58}$$

Brightness is calculated using the lightness value, and the achromatic response for the adapting white. Brightness is designated Q, and is calculated using Equation 59.

$$Q = (1.24 / c)(J / 100)^{0.67}(A_w + 3)^{0.9} \tag{59}$$

Thus we now have correlates of hue, brightness, and lightness. From these values, we can calculate correlates of saturation, chroma, and colorfulness, designated *s, c,* and *M* respectively. Equations 60-62 illustrate these calculations.

$$s = \frac{50\left(a^2 + b^2\right)^{1/2} 100e(10/13)N_c N_{cb}}{R'_a + G'_a + (21/20)B'_a} \tag{60}$$

$$C = 2.44s^{0.69}\left(J/100\right)^{0.67n}\left(1.64 - 0.29^n\right) \tag{61}$$

$$M = CF_L^{0.15} \tag{62}$$

Using the Model

As can be seen, the CIECAM97s model is rather complicated. In addition to the complexity of the equations themselves, several constants need to be determined prior to utilizing this model. All these choices can be quite daunting to the casual user. To help alleviate these situations, Moroney has provided usage guideline for CIECAM97s.[67]

Often it is necessary to invert a color appearance model, in order to predict how a stimulus in one viewing condition might appear when viewed in a different situation. In order to calculate these colors, it is necessary to invert the model. The nonlinearities in the chromatic adaptation transform mean that CIECAM97s can only be inverted using analytical models. Details on this inversion process can be found in the CIE publication[59], or in the text by Fairchild[1].

Future Directions

The CIE designated name for CIECAM97s has great significance, as it is called the *Interim* color appearance model. While it is considered the best of what was available at the time of formulation, this does not mean that further development has ceased altogether. Already the CIE has formulated another technical committee, TC8-01, that is charged with considering potential revisions to CIECAM97s. Fairchild has published a list of proposed changes, as well as implementation details of those changes.[68]. These changes are designed to simplify the model, fix errors, and add accuracy. Among the proposed changes are:

1. Linearize the chromatic adaptation transform, to facilitate inversion.
2. Fix surround compensation errors.
3. Fix lightness of perfect black.
4. Fix chroma scale expansion for low chroma colors.
5. Add continuously variable surround compensation.

It is expected that a new color appearance model, incorporating these and other changes, will be approved for testing by the CIE in 2002.

Research on color appearance models will not end with the work of TC8-01, either. Already research is being conducted on the next generation of color appearance models. Models of spatial and color vision are already appearing, such as the spatial extensions of CIELAB proposed by Zhang and Wandell[69] as well as Johnson and Fairchild.[70] Spatial models of vision and color appearance, such as the multi-scale model proposed by Pattanaik[71] *et al.* will allow for the prediction of the spatially structured appearance phenomena described above. Spatial information is thought to be crucial when dealing with the appearance of digital color images. The future is indeed bright for color appearance research.

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