Product Document

Published by
ams OSRAM Group

TAOS Inc.

is now

ams AG

The technical content of this TAOS document is still valid.

Contact information:

Headquarters:
ams AG
Tobelbader Strasse 30
8141 Premstaetten, Austria
Tel: +43 (0) 3136 500 0
e-Mail: ams_sales@ams.com

Please visit our website at **www.ams.com**

White Paper TAOS TEXAS ADVANCED OPTOELECTRONIC SOLUTIONS®

TAOS Colorimetry Tutorial

"The Science of Color"

contributed by Todd Bishop and Glenn Lee
February 28, 2006

ABSTRACT

The purpose of this paper is to give a brief overview of colorimetry. Colorimetry is the science of measuring color and color appearance. The main focus of colorimetry has been the development of methods for predicting perceptual matches on the basis of physical measurements. This topic is much too broad to be covered by one document, so a general coverage of the subject will be introduced.

COLOR AND LIGHT

The question of what is color would seem to be an easy one at face value. If a child was asked what color an apple was, they would say red. But what does red really mean? Most people have been asked the riddle, "if a tree falls in the forest and no one is there to hear it, does it make a sound?" The answer is it makes a sound wave, but it is not a sound until a brain interprets the sound wave. The same can be said if the riddle asks, "what color is a tree if no one is there to see it?" A 'color' is an interaction between a very small range of electromagnetic waves and the eyes and brain of a person. What people call red, green, or blue are just ways of categorizing what their brain experiences.

The spectrum of light the eye can see is called the visible region as can be seen in Figure 1. Light is a type of energy, which makes up a small portion of the electromagnetic spectrum, as does radio and TV signals. Electromagnetic waves that are used for radio and TV are generally discussed in terms of frequency. Visible light could be expressed as a frequency, but the magnitude is so large people generally express the wavelength of light in units of nanometers (10^{-9} meters) to describe light. The speed, frequency, and wavelength of light are related by equation (1).

$$c = f*\lambda \qquad (1)$$

Where c is the speed of light that is approximately 3×10^{8} m/s in a vacuum, f is frequency given in Hz, and λ is the wavelength in units of meter.

The region of visible light consists of light with a wavelength between approximately 380 nm to 780 nm. The visible colors and their corresponding range of wavelengths can be found in Table 1.

Table 1. Color vs. Wavelength Range

Color	Wavelength Range (nm)
Violet	380~410
Indigo	410~450
Blue	450~510
Green	510~560
Yellow	560~600
Orange	600~630
Red	630~780

There are many wavelengths in the electromagnetic spectrum the eye cannot see. Wavelengths that are just shorter than blue region are called ultraviolet. This is the light that causes sun burns. Wavelengths that are just longer than red are called infrared. These are the wavelengths that produce heat. White light is a mixture of all the colors of the entire visible spectrum. Black is a total absence of light.

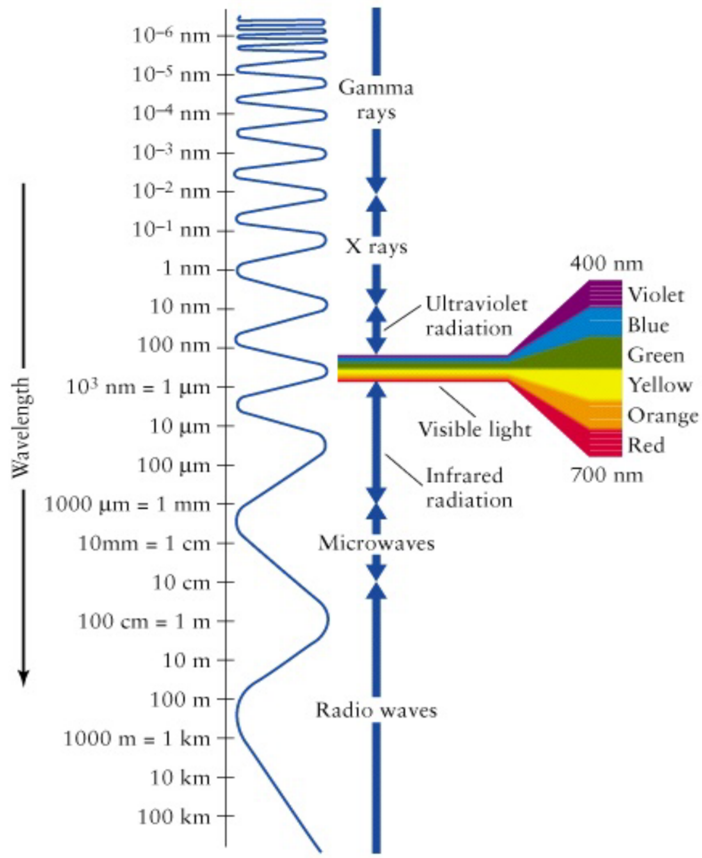

Figure 1. Electromagnetic radiation

THE WORKINGS OF THE HUMAN EYE

Light enters the front of the eye through a lens and is focused on the retina in the back of the eye. The human retina has rods and cones located on it. The rods and cones contain pigments. Pigments absorb light with absorption sensitivities that are wavelength dependent. The pigments allow the rods and cones to react to light in the visible region and pass that information to the optic nerve. Each eye has around 120 million rods, which are concentrated around the edges of the retina. See Figure 2 for a drawing of the inner eye.

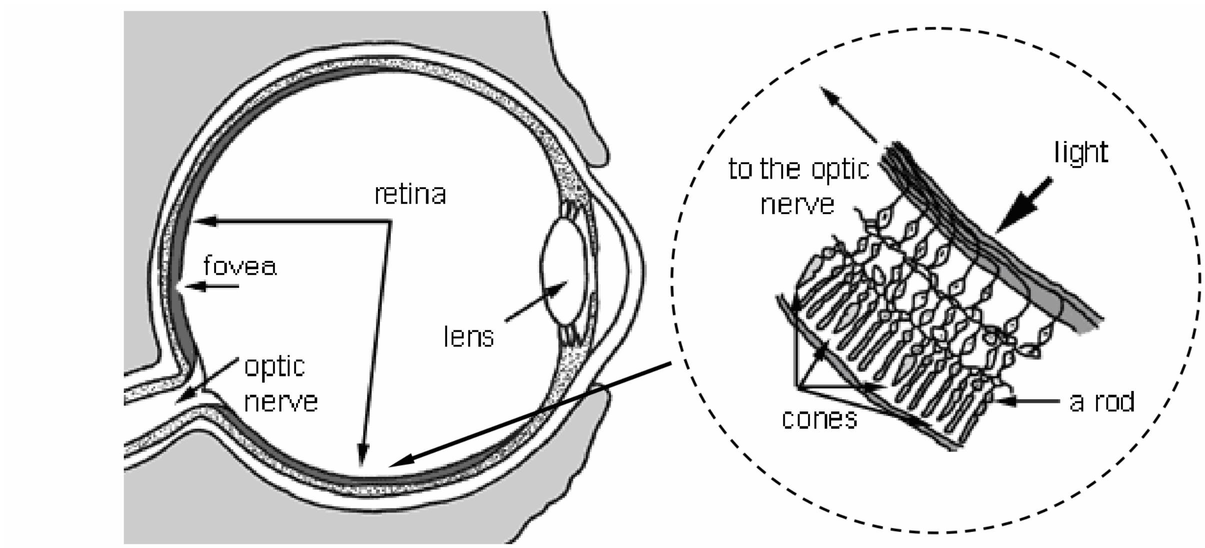

Figure 2. Human Eye and Retina

Rods are optimal at low light levels (**scotopic** vision), such as night vision, and provide the brain with information about light and dark which is good for seeing motion at night. At luminance levels below approximately 0.034 cd/m^2, vision is classified as scotopic and is completely lacking in color. The rods have a peak reponsivity to light around 510 nm in the blue-green region, and have little to no effect on color vision. See Figures 4 and 5.

The cones are what give humans the ability to distinguish colors at higher light levels (**photopic** vision). At luminance levels above approximately 3.4 cd/m^2, vision is classified as photopic. There are around 6 million cones in each eye. The cones are mainly located in the center of the retina, called the Fovea Centralis. The Fovea Centralis is a tiny dimple on the retina where light is focused. Photopic vision has a peak response around 555 nm in the green region of the visible spectrum. The cones contain photo pigments that react to light in certain areas of the visible region. There are three types of cones which are classified as long (L), medium (M), and short (S) relative to their peak wavelength sensitivity in the visible spectrum. The three pigments have maximum absorptions at about 430, 530, and 560 nm. The cones are often associated with red, green or blue response because these are the primary colors within each band. However, the spectral bands they detect are wider than any one perceived color and overlap each other. See Figure 5 for the cones spectral response. The L and M cones add together, with a scaling factor, to create the photopic curve which represents luminance detection in Figure 4. The S cones do not contribute to luminance detection, but are very important for hue and saturation perception, especially for yellow to blue discrimination. See Figures 4 and 5.

There is a region of vision between low light levels (scotopic) and high light levels (photopic) called **mesopic** where both rods and cones contribute to vision. An example of mesopic vision is when the sun starts to set. During this time, reddish colors fade to grey shades, followed by greens, and finally blues. Mesopic vision is not fully understood and is still a subject of much research. See Figure 3 for the three levels of vision and corresponding luminance levels of common sources.

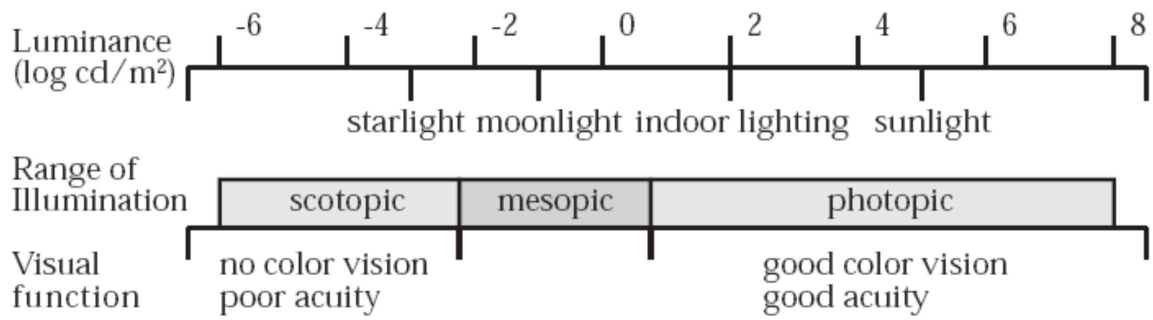

Figure 3. Types of Vision

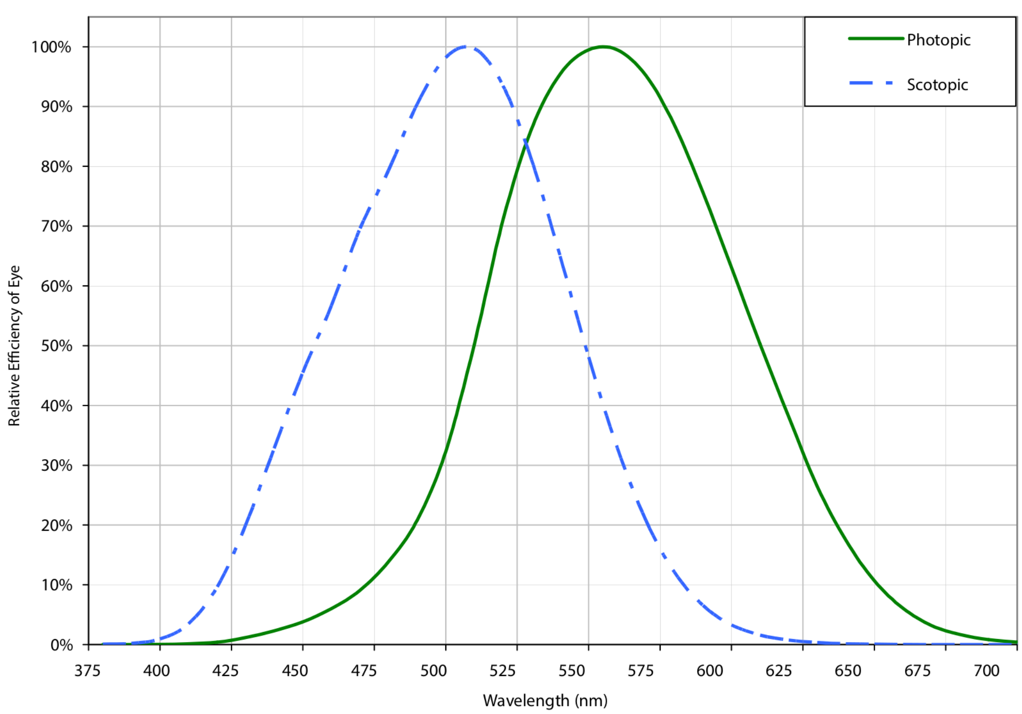

Figure 4. Scotopic and Photopic Vision

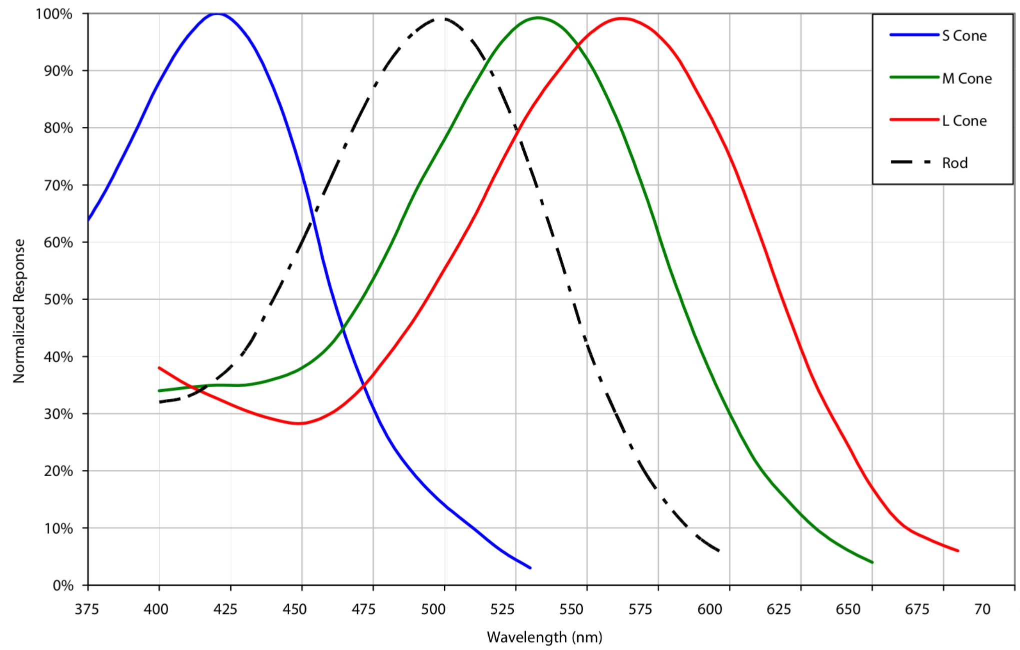

Figure 5. Eye Cones and Rod Response

The brain is ultimately the deciding factor in how people categorize a color, but the color information is processed based on the spectrum of light that reaches our retina. This spectrum of light is determined by the light source that produces the light and the adsorption and transmission characteristics of all the materials that interact with the light. A 'white' object reflects all or most of the light that falls upon it, while a 'black' object absorbs all or most of the light. Plants appear green because they have pigments which absorb wavelengths from the red and blue parts of the visible spectrum and only allow the 'green' wavelengths to be reflected back to the eye. This process of absorbing parts of the spectrum not only happens when light is reflected off of surfaces, but also when it is transmitted through substances. A bluish glass, for example, will absorb many of the longer green and red wavelengths entering the glass and pass through more of the shorter 'blue' wavelengths. An important concept to understand is that light sources and objects may appear to have the same color but have different spectral power densities, absorption, and transmission properties. Most of the colors people see are able to be replicated by mixing Red, Green and Blue (RGB) or Cyan, Magenta and Yellow (CMY).

Colors can be created in one of two ways. One method to produce color is called the **Subtractive** color process. This is accomplished by absorbing certain wavelengths which are subtracted from the full spectrum of visible light. The resulting wavelengths which reflect off a surface make up the color people see. The colors seen in everyday life are often a result of the Subtractive color process. The subtractive method is also used in the printing and film photography business.

The other method to produce color is the **Additive** color process. In this method, narrow bands of visible light are added together to produce a combination of light that is a different color. This is the method many light sources use to produce colored light. Monitors used for televisions and computers use the Additive color process by using the primary colors of Red, Green, and Blue to produce white and other colors.

To reproduce the colors seen in nature, people have worked with both the additive and subtractive processes to create colors. When reproducing color, it is more efficient and economical to use as few colors as possible. Within the additive color process, red, green and blue primaries are the best choice for producing the largest color set. In a subtractive color process like printing, red, green and blue are not the best choice of primary colors because these colors subtract too much light. Imagine a blue dot on a page, with a red dot printed over the top of it. Light would hit the red dot and almost all of the green and blue light waves would be absorbed, leaving red waves to pass on. The blue dot would then subtract the red light waves and leave little of the remaining green light to be reflected off the page. With a subtractive system of color reproduction; Red, Green and Blue are incapable of producing the full range of colors people can see. The best choices are Cyan, Magenta and Yellow. This choice is not arbitrary: these colors have a special, 'complimentary,' relationship with red, green and blue. For an example of additive and subtractive color mixing see Figure 6.

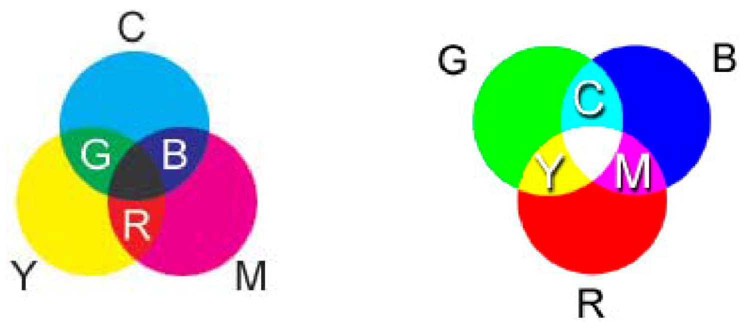

Figure 6. Subtractive Color process (left); Additive Color process (right)

LIGHT SOURCES

Since the light source that illuminates an object can greatly alter how the color appears to a viewer, a few common light sources will be discussed. **Incandescent** light is the oldest and most common form of illumination. Incandescence is a solid or liquid heated to the point that it emits light. The sun, a campfire, and a tungsten bulb are examples of this type of light source. A second type of light source is a gas discharge lamp that creates light by running an electric current through a gas. An example would be a mercury or neon light. A third type of light is photoluminescence which transmits energy to phosphors which reemit light. A fluorescent bulb is a combination of a gas discharge mercury lamp with photoluminescence created by a coating of phosphors on the bulb.

COLOR TEMPERATURE

Color temperature is a measurement system for the color of 'white' light. The units of color temperature are **kelvin (K)**. The kelvin temperature scale starts at 0K at absolute zero which is minus 273 degrees Celsius. The color temperature is the perceived color of light a perfect blackbody radiator would appear when heated to a particular kelvin temperature. Planck determined that the Spectral Power Density **(SPD)** radiated from a hot object, referred to as a blackbody radiator, is a function of the temperature to which the object is heated. The SPD of a light source is a measurement of all the spectral wavelengths that make up an objects radiated energy.

A blackbody radiator, also referred to as a Planckian radiator, is a theoretical object with zero reflectance. Its spectral radiant distribution is determined by Planck's radiation law in equation (2):

$$M(\lambda, T) = c_1 \lambda^{-5} \left(\exp(c_2 / \lambda T) - 1\right)^{-1} \tag{2}$$

where:

$c1 = 3.74183 \times 10^{-16}$ W m^2
$c2 = 1.4388 \times 10^{-2}$ m K

Where λ is the wavelength in meters and T is the blackbody temperature in kelvin. The spectral radiant distribution $M(\lambda, T)$ is directly proportional to λ and a given temperature T.

Incandescent light sources can be modeled by blackbodies, so it is often useful to characterize an illuminant by specifying the temperature (in units of kelvin, K) of a blackbody radiator that appears to have the same hue. The kelvin scale itself was determined by progressively heating a black object until it appeared red, followed by white and finally blue. A low color temperature looks red (~2400K), and a high color temperature appears bluish (~9300K). Color temperature is counterintuitive to most people's perception of temperature and color. For example, a cool color temperature has as a reddish glow which people associate with heat, and a warm color temperature appears as a bluish shade.

Human vision adapts to 'white' in the person's field of view. An image viewed in isolation, such as a slide projected in a dark room, creates its own white reference, and a viewer will likely not notice errors in the white point. If the same image is viewed relative to another white reference or a second image, then differences in white point can create an image with poor quality representation. Complete adaptation for white reference seems to be in to the range of 5000K to 5500K color temperature. For most people, 6500K has a little hint of blue. Tungsten illumination, at about 3200K, always appears somewhat yellow. The color temperature of a light source will affect the appearance of objects illuminated by it. When compared to the human eye and brain's ability to compensate for a varying white point, a less sophisticated device such as a low-end camera will often produce photographs with an off-white appearance. Table 2 list color temperatures for various standard light sources.

Table 2. Blackbody Radiator Temperature Approximation of Various Illuminants.

Light Source	Color Temperature (K)
Candle flame	1900
Sunlight at sunset	2000
Tungsten bulb--60 watt	2800
Tungsten bulb--200 watt	2900
Tungsten/halogen lamp	3300
Carbon arc lamp	3780
Sunlight plus skylight	5500
Xenon strobe light	6000
Overcast sky	6500
North sky light	10000

For broadband light sources that do not produce light from a heated element, their color temperature can be characterized by **Correlated Color Temperature (CCT)** and is measured in kelvin. Most fluorescent and metal halide lamps designed for architectural applications exhibit chromaticities that are close to, but not necessarily coincident with, the Planckian locus. The **Planckian locus,** shown in Figure 9, represents all possible color temperatures. CCT was introduced to address broadband light sources that are not modeled by a blackbody radiator. CCT is defined as the temperature of a Planckian radiator whose chromaticity point is closest to that of non-planckian light source on a color space diagram. Correlated color temperature is basically a shorthand description of whether the light is bluish-white, neutral, or reddish white.

There is no CIE-approved or even recommended method for determining CCT, but various photometric laboratories have adopted different algorithms. Testing by the Council for Optical Radiation Measurement (CORM) found agreement to within ±2 kelvin at lower CCTs and ±10 kelvin at higher CCTs between these algorithms. The differences were less than one mirek (reciprocal microkelvin). The mirek is calculated by multiplying 10^6 times the reciprocal of the color temperatures, also known as the mired (micro-reciprocal-degree). A difference of one mired is representative of the perceptible difference in color to an observer, under the most favorable conditions. So a color temperature of 2000K is 500 mireds. Color correcting filters can be purchased with positive or negative mired values which will, when added to the mired value of any thermal source, give the mired value of the filtered light. For example, a -100 mired filter will change a 2000K (500 mired) source to a 2500K (400 mired) source.

EFFECT OF LUMINOSITY

A person's perception of color has been related to light intensity and color temperature of a light source. The color experience of a given light mixture may also vary with absolute luminosity, because both rods and cones are active at once in the eye as light levels drop below photopic into mesopic vision. This happens because rods take over gradually for cones as the brightness is reduced to scotopic vision. In 1941, A.A. Kruithof published data that showed a relationship between color temperature and intensity of a light source. He determined that as intensity is increased there is an increasing range of color temperature that produces a 'pleasant' quality of light for a user. For example an object that appears white with 6000K light at 1000 LUX may appear grey with only 200 LUX of light applied. This data formed what is referred to as the 'Kruithof curve' as can be seen in Figure 7.

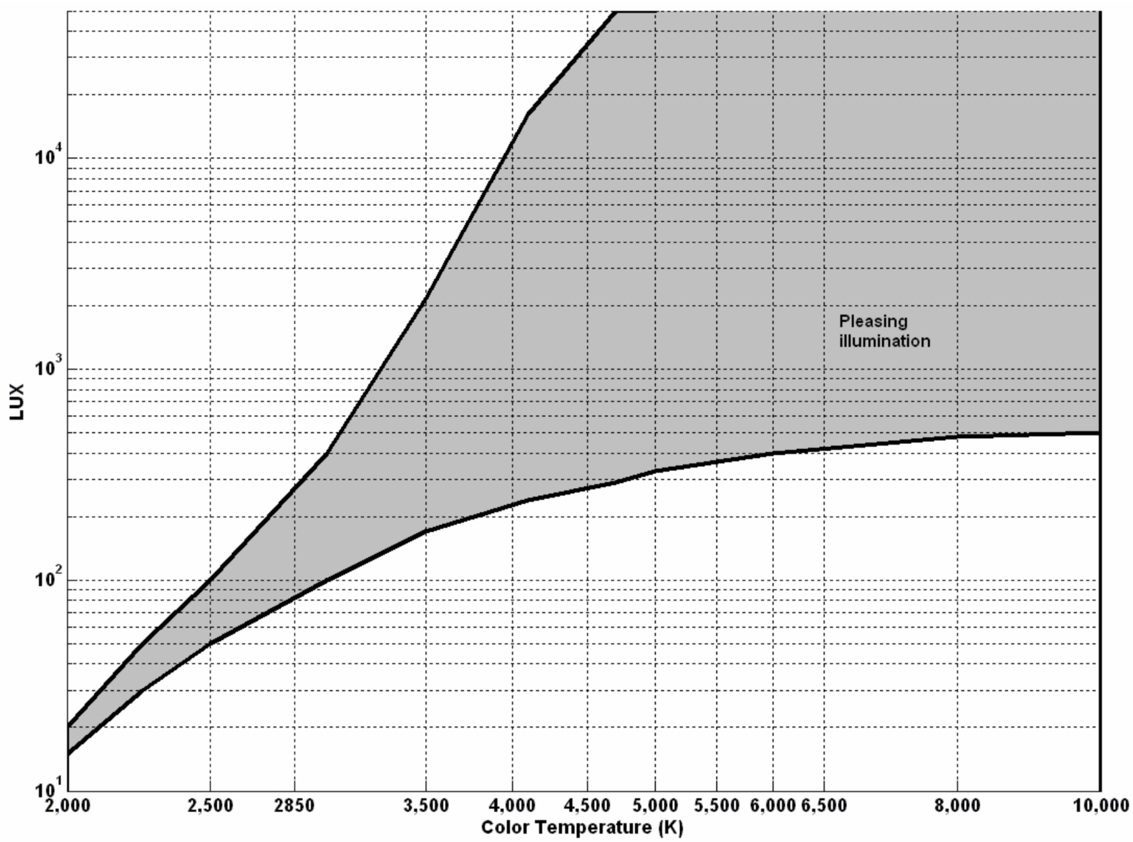

Figure 7. Kruithof Curve

SPECIFICATIONS BEYOND COLOR TEMPERATURE

Although an illuminant can be specified informally by its color temperature, a more complete specification is provided by the chromaticity coordinates of the SPD of the source. However, light sources can also be characterized by the quality of their light. Two light sources can have the same color temperature but be very different in the composition of wavelengths. One source might consist of a fairly even distribution of wavelengths, while the other source might have a very discontinuous distribution of wavelengths. Although these two sources will give the same overall color cast to a scene, the one with the very uneven spectral distribution is likely to strike particular 'colored' objects in odd and unpredictable ways. Some colors may appear washed out, and others overemphasized. A light source's quality is rated using the **Color Rendering Index (CRI)**, which has a scale of 0-100. The closer to 100 a light source's CRI is, the more even the distribution of wavelengths and more 'natural' the light appears. The CRI of a test source is compared to a 'perfect' source within 100K of each other. If the source's color temperature is between 2000K and 5000K the perfect source is considered a blackbody radiator. A standard incandescent bulb has a very good CRI rating because it models a blackbody radiator very well. Fluorescent bulbs typically have lower CRI rating because their SPD are less uniform. For test sources with color temperatures greater than 5000K, an agreed on type of daylight, such as D65, is used as the perfect source. A CRI rating difference of less than 3 between two light sources of the same color temperature are not large enough to be perceptible.

CIE AND COLOR STANDARDS

The CIE is the main international organization concerned with color and color measurement. CIE is short for Commission Internationale de l'Eclairage which is the French title for the International Commission on Illumination. In order to form a color standard the CIE conducted a series of experiments with about a dozen people in 1931. This data was taken for a 2 degree field of view of the fovea. Since there are three types of color photoreceptors in the eye, the numerical system to measure color also has 3 elements. The CIE named these elements the XYZ primaries. This work formed what is known as the CIE 1931 Standard Observer for a 2 degree field of view. Subsequent data was taken in 1964 with about 50 people and is known as the CIE 1964 Standard Observer for 10 degree field of view. The 1964 standard is recommended if more than a 4 degree of view is required.

The CIE standard is based on 3 imaginary primaries that can be additively mixed to form any color. This means that the XYZ values represent the relative amount of these fictional primaries that would be required to match a monochromatic light source of a particular wavelength. The primaries are imaginary because it is impossible to take three real primaries and additively mix them to produce all possible colors. Because of this limitation, any real system that uses additive mixing to produce colors, such as a monitor, has a reduced number of colors that it can produce when compared to what a person is capable of seeing. The range of colors a device can produce is known as its color **gamut**. The 1931 imaginary primaries where chosen with several restrictions. Because of the computational power available at the time, it was decided that the tristimulus values XYZ would always produce positive values for any real color stimulus. The Y tristimulus value was chosen to be proportional to luminance. Luminance is the perception of light brightness on an area, which has been normalized back to the human eye efficiency which peaks at 555 nm. The values were also determined to be equal to each other for an equal-energy SPD source. The CIE specified illuminant E as an equal energy source across the visible spectrum of wavelengths.

The CIE created a table for the color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ so that the tristimulus values X, Y, and Z can be calculated. The magnitudes of the XYZ components are proportional to the ratiometeric energy, but their spectral composition corresponds to the color matching characteristics of human vision. The graph of the color matching functions is shown in Figure 8. Applying the CIE color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ of the CIE standard colorimetric observer determines the CIE tristimulus values X, Y, and Z from equation (3):

$$\begin{aligned} X &= k\sum_{\lambda} \Phi(\lambda)\bar{x}(\lambda)\Delta\lambda \\ Y &= k\sum_{\lambda} \Phi(\lambda)\bar{y}(\lambda)\Delta\lambda \\ Z &= k\sum_{\lambda} \Phi(\lambda)\bar{z}(\lambda)\Delta\lambda \end{aligned} \tag{3}$$

Where $\Phi(\lambda)$ is the spectral power distribution of the source to be measured, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the 1931 CIE color-matching functions and k is a normalization factor. The equations to calculate XYZ state that the tristimulus values are equal to the sum of the spectral power of a light source multiplied by the color matching function for each wavelength in the visible region.

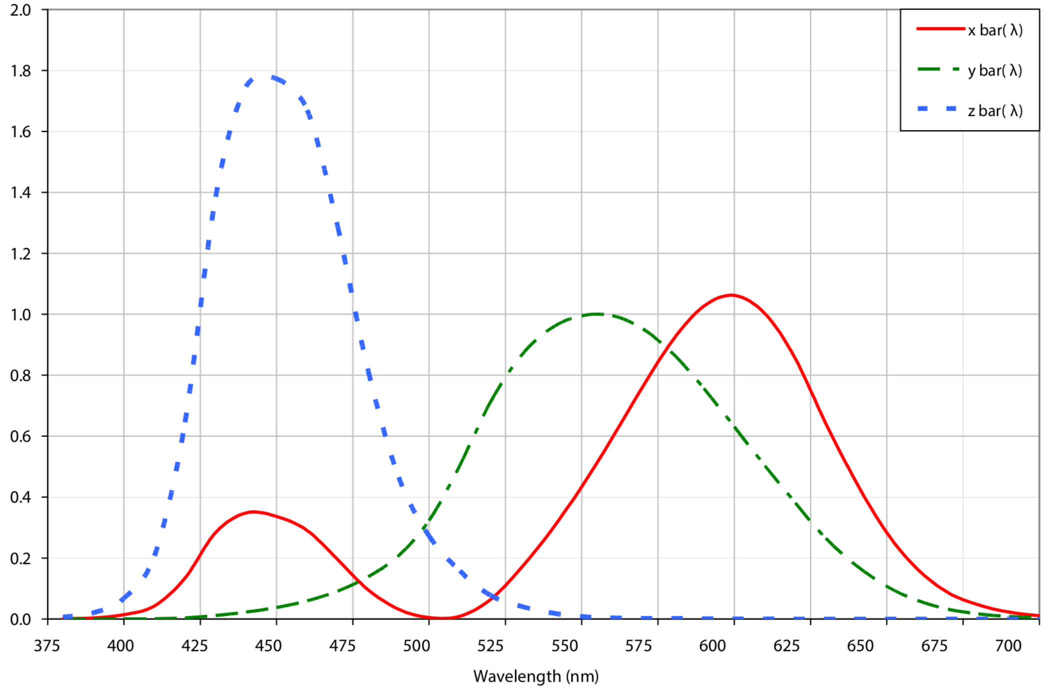

Figure 8. CIE Standard Observer Color matching Functions $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$.

Once the values X, Y, and Z have been determined, the CIE 1931 chromaticity diagram coordinates x and y can be calculated using equation (4):

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z} \qquad (4)$$
$$z = \frac{Z}{X+Y+Z}$$

$$x + y + z = \frac{X+Y+Z}{X+Y+Z} = 1$$

$$z = 1 - x - y$$

A color can be specified by its chromaticity and luminance, in the form of a xyY triple. To recover X and Z from chromaticities and luminance, equation (5) is used:

$$X = \frac{x}{y}Y$$
$$Z = \frac{1-x-y}{y}Y \qquad (5)$$

Y will provide an absolute photometric quantity which has a maximum response of 683 lumens per watt at 555 nm.

Chromaticity coordinates are usually given as x and y only, because z is redundant. If a light source was monochromatic (one wavelength), then X would equal $\bar{x}(\lambda)$ times some multiple, and the same would be said for Y and $\bar{y}(\lambda)$, and Z and $\bar{z}(\lambda)$. The color matching functions and corresponding chromaticity coordinates (x,y) for wavelengths between 380nm to 780nm in increments of 10nm can be found in Table 3.

On the CIE chromaticity diagram, pure spectral (monochromatic) colors lie on the curved border of the 'horseshoe' or 'shark fin' shape of the chromaticity diagram. The color range of purple on the lower portion of the chromaticity diagram connecting 380 nm to 700 nm cannot be reproduced with a single wavelength. To produce purple, a mixture of long (reddish) and short (bluish) wavelengths are required.

All possible sets of tristimulus values can be represented in a two-dimensional plot of x and y chromaticity coordinates. Figure 9 is referred to as a chromaticity diagram. This does not mean that the plot represents three-dimensional data though. Two points may have the same chromaticity point and have unequal luminance (Y). Take for example the chromaticity point x=0.33 y=0.33. This point represents black through white. At Y=0 the color would be black, and as Y is increased the color would change to grey, until at a normalized value of 1 the color white would be reached. **Hue**, which is one or more colors mixed together, travels clockwise around the diagram. **Saturation**, which is perceived as a change in a color between a neutral grey to a pure color, is the movement from the boundary of the chromaticity diagram to the white point of x=0.33 and y=0.33 (See Figure 10). On the chromaticity diagram, Y travels in the 3rd dimension out of the page as can be shown in Figure 11. As the luminosity is increased, the possible color gamut is decreased towards white at a normalized Y value of 100%.

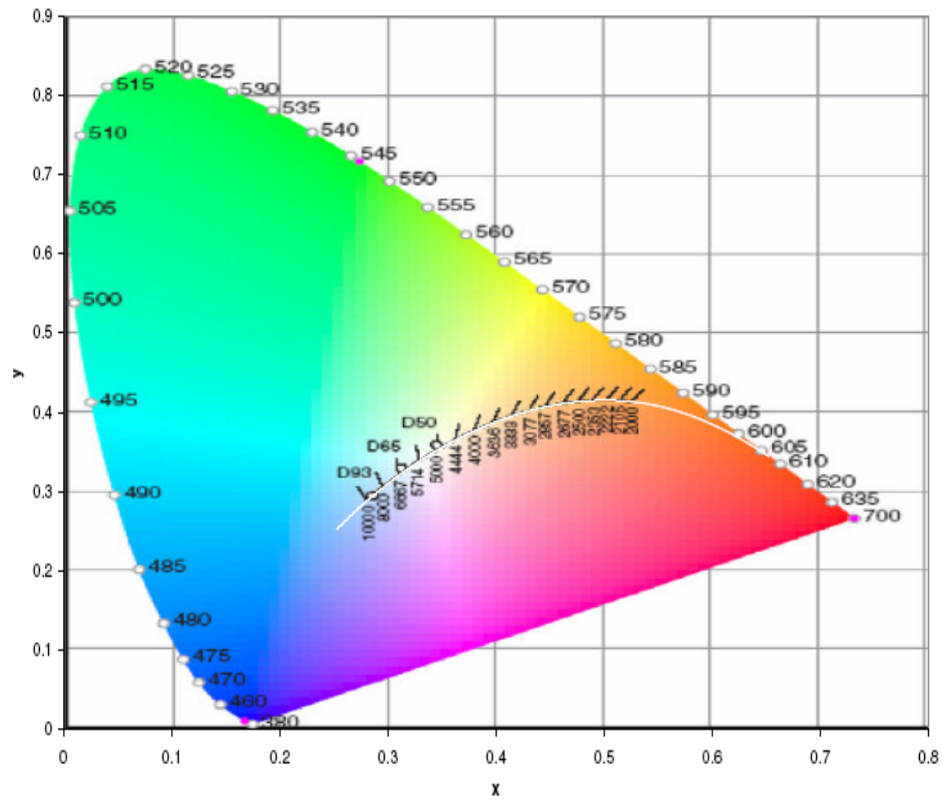

Figure 9. CIE 1931 Diagram

Table 3. CIE 1931: 2 Degree Field View 380 nm to 780 nm

λ (nm)	$\bar{x}$	$\bar{y}$	$\bar{z}$	x	y
380	0.00137	0.00004	0.00645	0.1743	0.0051
390	0.00424	0.00012	0.02005	0.1737	0.0049
400	0.01431	0.00040	0.06785	0.1733	0.0048
410	0.04351	0.00121	0.20740	0.1726	0.0048
420	0.13438	0.00400	0.64560	0.1714	0.0051
430	0.28390	0.01160	1.38560	0.1689	0.0069
440	0.34828	0.02300	1.74706	0.1644	0.0109
450	0.33620	0.03800	1.77211	0.1566	0.0177
460	0.29080	0.06000	1.66920	0.1440	0.0297
470	0.19536	0.09098	1.28764	0.1241	0.0578
480	0.09564	0.13902	0.81295	0.0913	0.1327
490	0.03201	0.20802	0.46518	0.0454	0.2950
500	0.00490	0.32300	0.27200	0.0082	0.5384
510	0.00930	0.50300	0.15820	0.0139	0.7502
520	0.06327	0.71000	0.07825	0.0743	0.8338
530	0.16550	0.86200	0.04216	0.1547	0.8059
540	0.29040	0.95400	0.02030	0.2296	0.7543
550	0.43345	0.99495	0.00875	0.3016	0.6923
560	0.59450	0.99500	0.00390	0.3731	0.6245
570	0.76210	0.95200	0.00210	0.4441	0.5547
580	0.91630	0.87000	0.00165	0.5125	0.4866
590	1.02630	0.75700	0.00110	0.5752	0.4242
600	1.06220	0.63100	0.00080	0.6270	0.3725
610	1.00260	0.50300	0.00034	0.6658	0.3340
620	0.85445	0.38100	0.00019	0.6915	0.3083
630	0.64240	0.26500	0.00005	0.7079	0.2920
640	0.44790	0.17500	0.00002	0.7190	0.2809
650	0.28350	0.10700	0.00000	0.7260	0.2740
660	0.16490	0.06100	0.00000	0.7300	0.2700
670	0.08740	0.03200	0.00000	0.7320	0.2680
680	0.04677	0.01700	0.00000	0.7334	0.2666
690	0.02270	0.00821	0.00000	0.7344	0.2656
700	0.01136	0.00410	0.00000	0.7348	0.2652
710	0.00579	0.00209	0.00000	0.7348	0.2652
720	0.00290	0.00105	0.00000	0.7342	0.2658
730	0.00144	0.00052	0.00000	0.7347	0.2653
740	0.00069	0.00025	0.00000	0.7340	0.2660
750	0.00033	0.00012	0.00000	0.7345	0.2655
760	0.00017	0.00006	0.00000	0.7345	0.2655
770	0.00008	0.00003	0.00000	0.7345	0.2655
780	0.00004	0.00002	0.00000	0.7345	0.2655

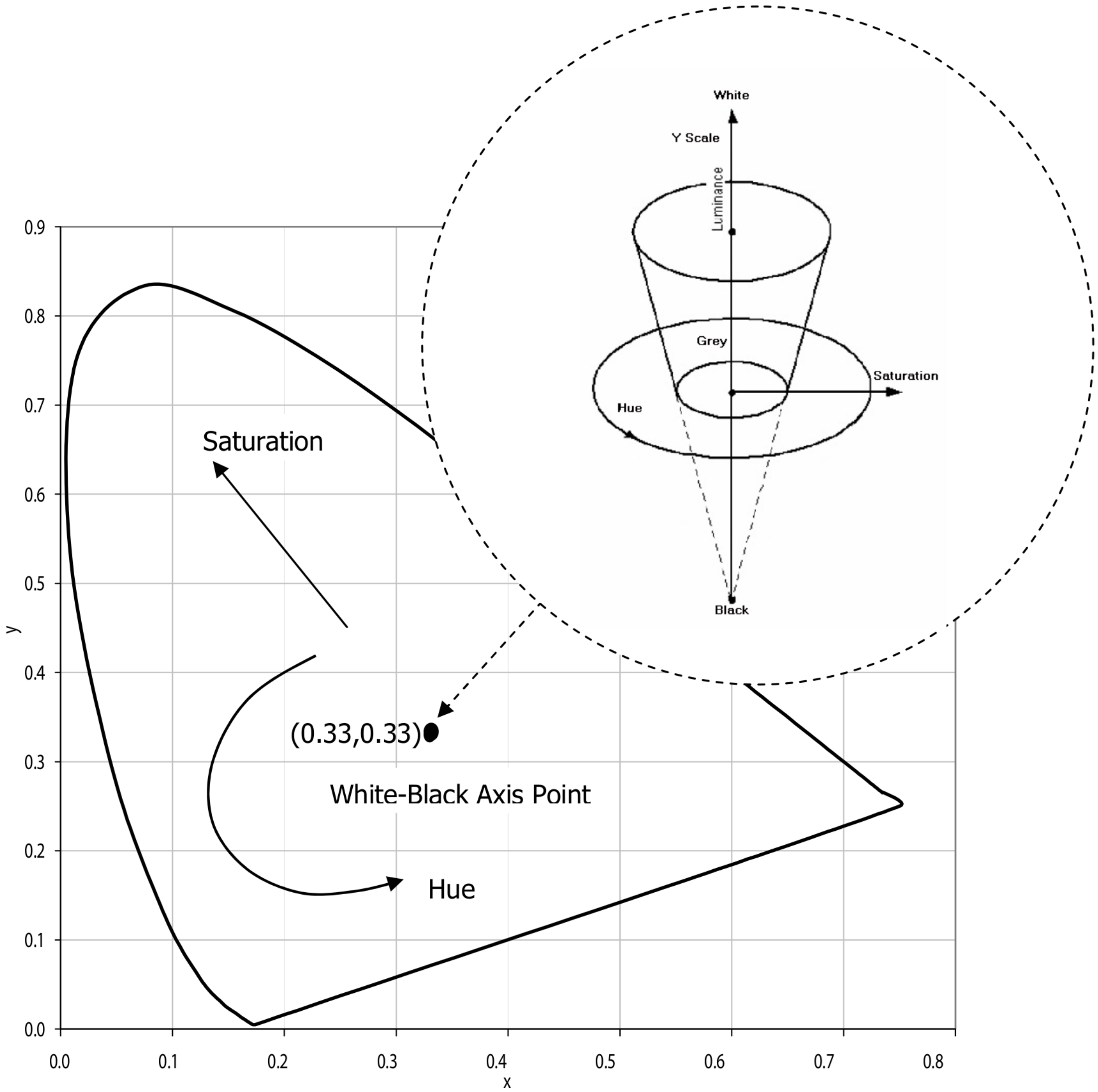

Figure 10. Hue, Saturation, and Luminance

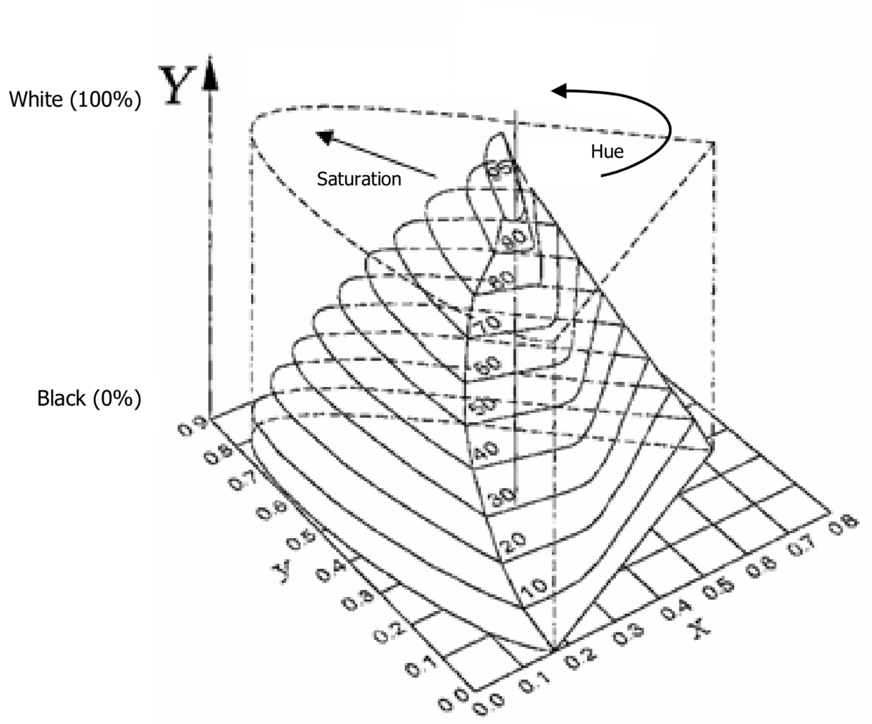

Figure 11. Three-Dimensional CIE Diagram

The relationship between color temperature and chromaticity is highly nonlinear. For instance, the difference in chromaticity for a one degree difference at 2,000K corresponds to a difference of 100 degrees at 20,000K. This makes it impractical to compare chromaticity differences on the basis of differences in color temperature.

McCamy (1992) proposed equation (6) for calculating the CCT of a light source:

$$n = (x - x_e)/(y_e - y) \tag{6}$$

Where x_e = 0.3320 and y_e = 0.1858.

$$CCT = 449.0 * n^3 + 3525.0 * n^2 + 6823.3 * n + 5520.33$$

McCamy's method claims to have a maximum absolute error of less than 2 kelvin for color temperatures ranging from 2,856K to 6,500K (corresponding to CIE illuminants A through D65). In the absence of CIE recommendations for a particular method, this method may prove useful for implementation in real-time CCT measurement systems.

One limitation of CCT is the precision of the measurement. Various sources have recommended that CCTs for light sources should not be reported with any greater precision than is currently used for fluorescent lamps. Thus, errors in measurement of ±300K are likely acceptable for a low cost CCT meter. For example, ANSLG (2001) specifies CCTs of 2,700K, 3,000K, 3,500K, 4,000K, 5,000K and 6,500K and their corresponding chromaticities for fluorescent lamps.

A second limitation of the CCT as a metric is that there are no constraints on the distance from the Planckian locus a CCT number is valid. Plotting the chromaticity coordinates of a blackbody elevated from 2000K to 10,000K on the CIE 1931 chromaticity diagram in Figure 9 yields the Planckian locus. A given color temperature therefore has a unique color that is defined by its chromaticity coordinates (x,y). The color temperature of a non-blackbody illuminant becomes increasingly difficult to determine as the chromaticity coordinates deviate from the Planckian locus. It has been suggested that a CIE (x,y) chromaticity difference on the order of ±0.02 from the locus would be an acceptable maximum for determining CCT. See Table 4 for the chromaticity coordinates and color temperature of several common light sources.

Table 4. Standard White Points: Chromaticity and Color Temperature

Source	Description	*x*	*y*	CCT
Direct Sunlight	Sun	0.3360	0.3500	5335
Overcast Sky	Sky	0.3130	0.3270	6500
North Sky	Sky	0.2770	0.2930	10000
Illuminant A	Incandescent	0.4476	0.4074	2856
Illuminant B	Direct Sunlight	0.3484	0.3516	4874
Illuminant C	Average Daylight	0.3101	0.3162	6774
Illuminant E	Equal Spectrum	0.3330	0.3330	5400
Illuminant D50	Daylight	0.3457	0.3585	5000
Illuminant D55	Cloudy Daylight	0.3324	0.3475	5503
Illuminant D65	Daylight	0.3127	0.3290	6504
Illuminant D75	Daylight	0.2990	0.3149	7500
F1	Standard Fluorescent	0.3131	0.3371	6430
F2	Standard Fluorescent	0.3721	0.3751	4230
F3	Standard Fluorescent	0.4091	0.3941	3450
F4	Standard Fluorescent	0.4402	0.4031	2940
F5	Standard Fluorescent	0.3138	0.3452	6350
F6	Standard Fluorescent	0.3779	0.3882	4150
F7	Broadband Fluorescent	0.3129	0.3291	6500
F8	Broadband Fluorescent	0.3458	0.3586	5000
F9	Broadband Fluorescent	0.3741	0.3727	4150
FA10	Tri-phosphor Fluorescent	0.3458	0.3588	5000
FA11	Tri-phosphor Fluorescent	0.3805	0.3769	4000
FA12	Tri-phosphor Fluorescent	0.4370	0.4042	3000

OTHER COLOR SPACES

An issue with the chromaticity diagrams is that it is not perceptually uniform. Perceptually uniform means that a small change in the chromaticity coordinates produces an equal change in visual perception across the whole color space diagram. There is no uniform color space, although many different transformations have been computed which are more uniform than the original x,y chromaticity diagram. CIE standardized two systems, L*u*v* and L*a*b*, sometimes written CIELUV and CIELAB to improve perceptual uniformity. Both L*u*v* and L*a*b* improve the 80:1 or so perceptual non-uniformity of XYZ to about 6:1. Computation of CIE L*u*v* involves intermediate u' and v ' quantities from equation (7), where the prime denotes the successor to the obsolete 1960 CIE u and v system. See Figure 12 for the u'v' color space diagram. There are many other color spaces that have been developed that are beyond the scope of this paper. For information on those color spaces and more in-depth knowledge of topics briefly introduced in this tutorial there are many very good color reference books available such as *Color Vision and Colorimetry Theory and Applications* by Malacara.

$$u' = \frac{4X}{X + 15Y + 3Z} \qquad v' = \frac{9Y}{X + 15Y + 3Z} \tag{7}$$

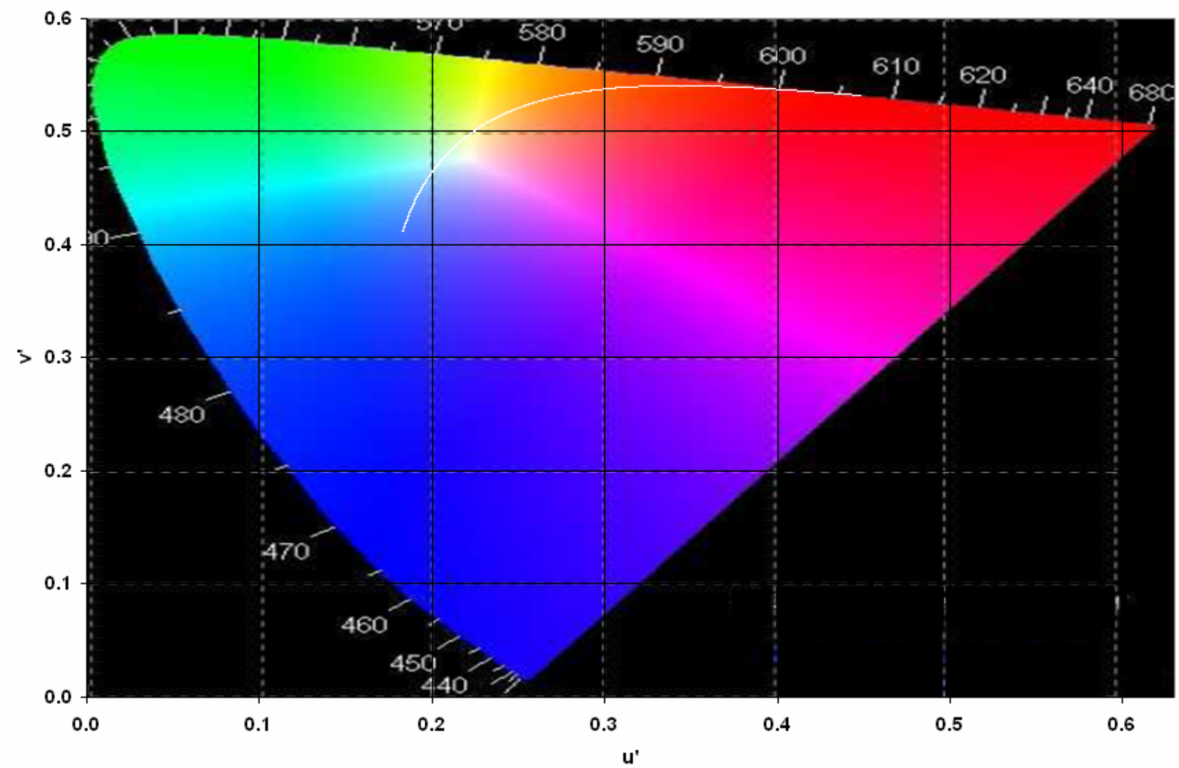

Figure 12. CIE u'v' Diagram

CONCLUSION

This paper has attempted to give a brief description of how the human eye perceives color. In an attempt to model the human eye and brain's perception of color, the CIE group was formed with the goal of forming standardization for the science of color. There have been many color standards formed over the years as people gain a better understanding of color vision. The first recognized standard was the CIE 1931 standard observer and it is still used today for many color systems. For more information on sensor applications involving color and photopic response, please visit www.taosinc.com.

REFERENCES

ANSLG. 2001. Specifications for the Chromaticity of Fluorescent Lamps, ANSI C78.376-2001. Rosslyn, VA: American National Standards Lighting Group – National Electrical Manufacturers Association

Borbély, A., A. Sámson, and J. Schanda. 2001. *The Concept of Correlated Color Temperature Revisited*, Color Research & Application 26(6):450–457

CIE, 1986. Colorimetry, Second Edition. Technical Report CIE 15.2-1986. Vienna, Austria: CIE Central Bureau

Ferwerda, James A., *Fundamentals of Spatial Vision*,
Internet http://www.graphics.cornell.edu/~jaf/publications/notes_final.pdf

Malacara, Daniel*, Color Vision and Colorimetry Theory and Applications,* SPIE Press, Bellingham WA, 2002

McCamy, C. S. 1992. *Correlated Color Temperature as an Explicit Function of Chromaticity Coordinates*, Color Research & Application 17:142–144

McGuire*,* Kevin "Daylight: Is it in the eye of the beholder?",
Internet http://www.solux.net/edu13.htm

Poynton, Charles, "The Color FAQ", Internet www.poynton.com/ColorFAQ.html

Walker, John, "Color Rendering of Spectra",
Internet http://www.fourmilab.ch/documents/specrend/