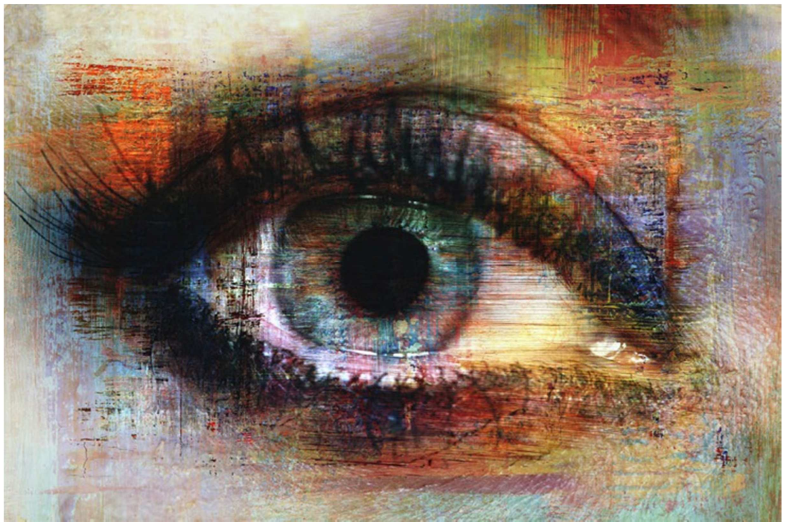
Let's talk color; but first, how do we see color? The human eye gives us the sense of sight; from which, we can interpret colors, shapes and dimensions of the world around us by processing light reflecting or emitting from an object. We can see in bright light or dim light, but not in the absence of light. The eye focuses light from our surroundings by refraction through the cornea then the pupil through the lens to the retina at the back of the eye. The iris or colored part of the eye regulates the size of the pupil which in turn controls the amount of light passing through it. The retina is where photons of light are converted into electrical neural signals to be sent along the optic nerve into the brain for interpretation. Distributed within the layers of the retina are tiny photoreceptive nerve cells known as rods and cones. These work alone or together to adjust our visual system. Within the rods and cones are protein pigment molecules called opsins, which absorb a photon of light and transmit the signal through transduction into electrical impulses. Rhodopsin is for light reception in rods and photopsin is for reception of colors of light in cones. The brain can detect as little as one photon of light. There is a third type, melanopsin not thought to be involved in conscious vision, which mediates the pupil reflex and is involved in setting the body's biological clock controlling circadian rhythms.

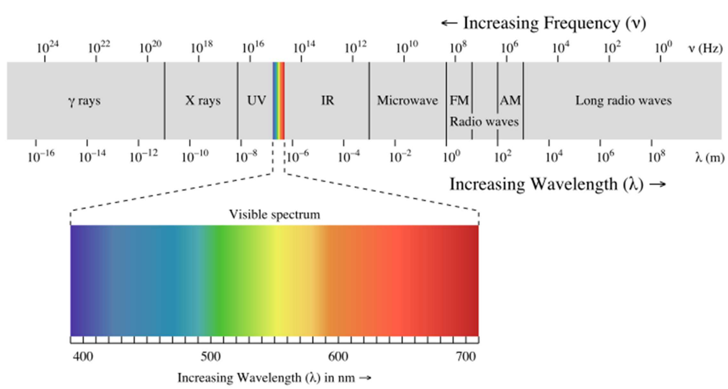


a. Rods contain only one type of light-sensing pigment making them monochromatic. They function best in dim light and enable night vision. There are approximately 90 to 100 million rods mainly concentrated toward the outer edge of the retina, providing our peripheral vision. Rods outnumber cones and are much more sensitive to a single photon of light; however, they are slower to respond than cones. Multiple rod cells must converge, collecting and amplifying a signal to be sent to a single interneuron making visual acuity less than that of a cone. The "collective information" is not as distinct as if coming from an individual rod cell like cones can provide.

i. For night or scotopic vision to occur, the eye must go through a process of adaptation. It takes 20-30 minutes for full adaptation from bright sunlight to complete darkness. Both rods and cones must make chemical changes to the visual pigment opsin and retinal. Since rods are more sensitive to light, they take longer to regenerate the photoreceptors reaching their maximum sensitivity in ~30 minutes; however, they improve greatly after 5-10 minutes. The perception of color also changes as light levels rise or fall. This shift is sometimes called Purkinje shift and the effect introduces a difference in color contrast under differing levels of illumination. As light levels fall, the eye shifts towards the blue-green end of the color spectrum as the rods take over. Once the rods are in full control, humans are basically color-blind since rods can only provide essentially black and white vision at maximum absorption of rhodopsin ~500 nanometers (nm). Another interesting fact about rhodopsin, within a normal human rod, it is insensitive to the longer wavelength of red. Using a red light at night will help preserve your night vision.

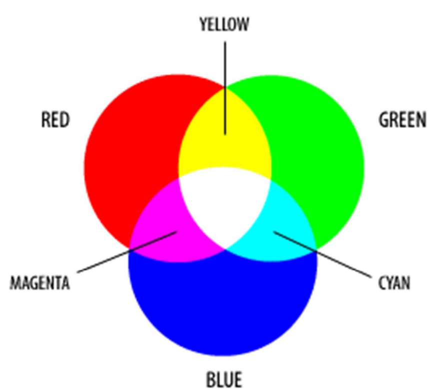
b. Cones detect or perceive color and provide fine details. They function best in bright light and are less sensitive to light than rods. Six to seven million cones are in the human eye, densely packed in the central portion of the retina called the macula lutea becoming sparse toward the periphery of the retina. The center of the macula, referred to as the fovea centralis, is the highest concentration of cones. The fovea is where the sharpest, most acute, vision occurs. However, in this rod free area, detection of small dim objects in the dark is impossible to see if you look directly at them. If you look to the side of the object, the light falls outside the macula where numerous rods cells can detect dim light and movement.

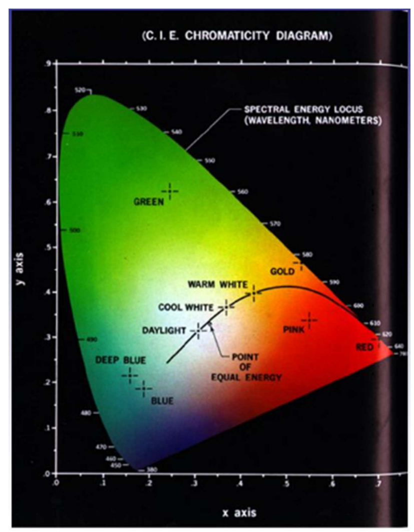
i. In the daytime we see color, referred to as photopic vision as the cones dominate. They are most sensitive to green light at ~555nm. There are three different cones types referred to by the maximum spectral sensitivity in wavelengths; short (S cones), medium (M cones) and long (L cones) making our trichromatic color vision. In lighting conditions average to high-brightness, short cones register from 420-440nm, medium cones 530-540nm and long cones 560-580nm wavelengths. Each has a different response curve to variation in color and allows the brain to perceive a continuous range of color, ~10 million. Not all invertebrates have just three types of cones. For example, some insects, fish and birds have a fourth or even a fifth cone to pick up energy of other wavelengths including ultraviolet. In fact, humans are pretty low in the amount of perceived colors as compared to say a pigeon or butterfly, which in some species can perceive into the billions ~10 billion.



To further explain the spectral sensitivities in the human eye, we must explore color in the visible spectrum. Color models or spaces were created early on to bring standards to colorimetry. The following are a few color models and their descriptions in layman terms.

a. CIE 1931 color spaces. Commission Internationale de Eclairage (CIE) was founded in 1913 to do just that and to bring about standards for all things lighting related. In 1931, the CIE RGB color space referenced the first defined link between physically pure colors or wavelengths in the visual spectrum and physiologically perceived colors in human vision. To create the RGB color space, the CIE would have an observer look through an aperture at a split screen. One half of the screen was lit with a test lamp of pure spectral color and the other half was lit with three lamps one each of the primary colors, red, green and blue. The observer would use the three lamps to match the color on the test lamp.



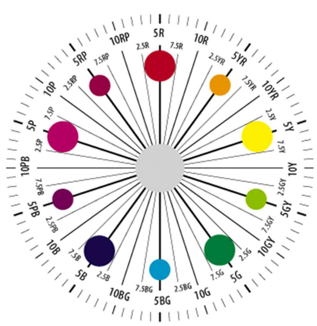


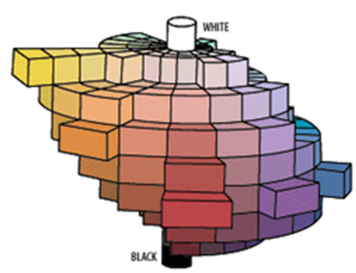
From this, the tristimulus values were obtained; however, it did not convey all colors in the visible light spectrum, CIE XYZ would try to do this. The XYZ values were mathematically obtained by formulating in the curve of the human eye's response to the luminance of a color. The Y value would be on a scale of 0-100, where 0 would show the fullest or saturated color and 100 would be the highest or lightest a color could get ending in white.

b. The Munsell color system was developed by an American artist Albert Henry Munsell. In 1898, he began working his model for defining color in a rational way although it did not see publication until 1905. He created a 2-D disk with five principal colors:

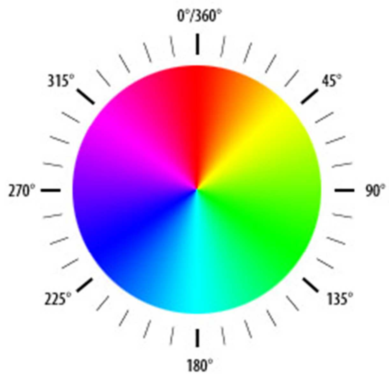
red, yellow, green, blue and purple and five intermediate colors: yellow-red, green-yellow, blue-green, purple-blue, and red-purple calling these Hues. At the center or axis would be the grey level of each color and he called this the Value. The disk became more 3-D to create an orb with the Value running from 0 or black at the bottom up the grey scale to 10 or white at the top. From the axis value running in a right angle, he designated the color's Chroma, the quality of a color distinguished from grey to the purest hue. As he discovered, not all chroma is uniform and each hue reaches full chroma at a different place on the color orb. Reds, purples and blues have stronger hues averaging higher chroma values at full saturation. Yellows average a much shorter chroma axis, thus rendering the envisioned orb or sphere into an asymmetric "tree".

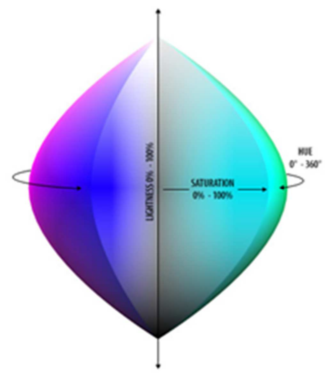
(Munsell color tree) Color solid. (From Preise Color Communication: Color Control from Feeling to Instrumentation. P9: courtesy of Minolta Camera Company., Ltd. Japan.)





c. To bring color into the digital world, Munsell's system was adapted and can be found in Adobe products. The HSB/HLS color models are two variations of defining colors in desktop graphics programs and closely match the way we perceive color. Somewhat similar to Munsell's system, HSB uses Hue to define a color in degrees (0-360º) where the top of the circle at 0/360° is red, running around to the left purple (315º), blue, green, yellow, back to red or running around to the right, yellow (45º), green, blue, purple, back to red. Saturation to indicate the percentage to which the hue differs from neutral gray (0%) at the center to full color saturation (100%) up the axis and Brightness/Lightness to indicate the level of illumination where the lightness is a color range from no light (0%) or black to the lightest (100%), in which the illumination washes out the color or appears white.

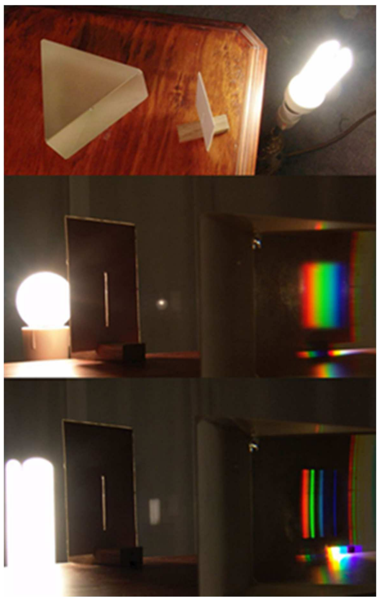


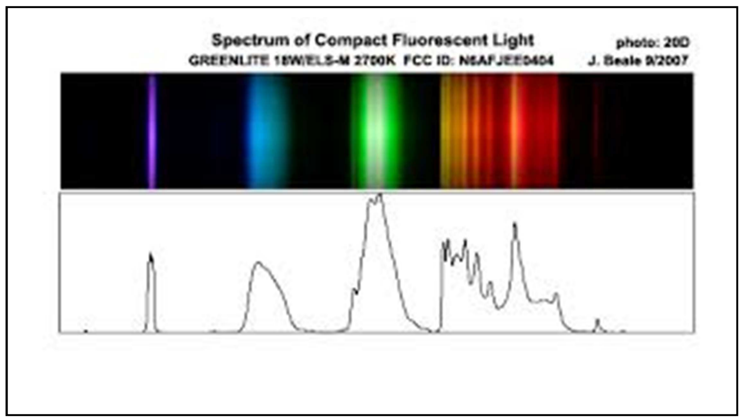


The mathematical relationships defined by these color spaces are essential for color management of things like ink, dyes, cameras, art and even lighting in the areas around us. Now that we have discussed how we see color, the next step in this article will be how we know the color we see is represented accurately.

(CRI) Color rendering index is a scale measuring of the ability of a given light source to illuminate or reveal the colors of various objects accurately in comparison with an ideal or standardized reference light source. Lighting in general, as with any product, is becoming more standardized. Whether it's with LEDs or other sources of light a part of the standardization is labeling our products so we can make comparative decisions. To rate light sources in a significant way that will affect our lives other than in the pocket book, like comparing watts for energy savings or lumens for total light output, you might have noticed a new number listed next to a word like CRI or color accuracy. Scientists around the world wanted to learn how accurately artificial light could reproduce colors when compared to daylight emitting from the sun. This too was defined by the International Commission on Illumination (CIE) and properly called the CIE Ra value. Daylight (D) became the ideal light source or as phrased by CIE, the standard illuminant since it displays the whole visual spectrum of colors. The higher the CRI numerically, from 0 to 100 being the highest, the truer in color the object appears to us. The CRI value does not give the apparent color of a light source; this is obtained by the correlated color temperature (CCT) in degrees Kelvin (K). The CRI value is determined by the emitted visual spectrum from the light source. The standard illuminant (D) is used to calculate the CRI for any test source with a CCT above 5000K. Below 5000K, the light source is compared to a perfect source or a blackbody; an object which absorbs all incoming light and reflects none – appearing black at room temperature and is defined as having a CRI of 100. If the light source gives off a continuous spectrum of light, the higher the CRI value. As opposed to a banded or discrete line spectrum where it looks like there are black spaces in between each color, representing low or near zero relative power for viewing those colors. Lighting has a huge impact on how we see certain objects. I myself have put on makeup by incandescent light in my home only to find I look washed out under the fluorescent lights in the office. The spectrum of fluorescent light is not complete, some colors in this light don't register high enough relative power to view and this explains why I would look washed out under them.

(Incandescent vs fluorescent) https://en.wikipedia.org/wiki/Color_rendering_index





Referencing the images above, incandescent vs fluorescent, you can see the full emitted visual spectrum from the incandescent making it almost a blackbody radiator and having a CRI of 100. Fluorescent lights range from ~50-89 CRI for the best tri-phosphor types. LEDs typically have ~80-90 CRI and some claim 98 CRI. The good thing is CRI is very easy to understand. A light source with a CRI of 70 or below is not great and colors may look yellow or washed out and could even change the hue of objects. 80 CRI is above good and a source with 90 CRI or above would be very good. For those of us who want to know the exact measurement of CRI, you would need to borrow or buy a spectrometer to measure spectra wavelengths. For the rest of us, we can view the accepted chart below.

https://en.wikipedia.org/wiki/Color_rendering_index

Light source	CCT (K)	CRI
Low-pressure sodium-vapor	1800	-44
Clear mercury-vapor	6410	17
High-pressure sodium-vapor	2100	24
Coated mercury-vapor	3600	49
Halophosphate warm-white fluorescent	2940	51
Halophosphate cool-white fluorescent	4230	64
Tri-phosphor warm-white fluorescent	2940	73
Halophosphate cool-daylight fluorescent	6430	76
"White" sodium-vapor	2700	82
Standard LED Lamp*[23]	2700-5000	83
Quartz metal halide	4200	85
Tri-phosphor cool-white fluorescent	4080	89
High CRI LED Lamp (Blue LED)*[24]	2700-5000	95
Ceramic discharge metal-halide lamp	5400	96
Ultra High CRI LED Lamp (Violet LED)*[25]	2700-5000	98
Incandescent/halogen bulb	3200	100

*HIGH CRI LED LIGHTING. yujiintl.com. Retrieved on March 28, 2017.

As with most products, a higher price tag comes along with higher CRI, better quality light sources. So, knowing when to be concerned about CRI and paying a higher price matters.

A high CRI is necessary in color-critical situations. For example, babies in Neonatal units are highly observed for color changes indicating their oxygen levels, blue bad to red good, or any jaundice which gives a yellow coloring. Art restoration would require correctness in color. You wouldn't want to betray the original coloration of a Picasso or a Michelangelo. Your bathroom vanity or closets would need to be 90 CRI or above, if you want to know the true color of your cloths or makeup. Matching a black top with black pants could be a nightmare if you didn't notice the slight hue change. Makeup, as I talked about before, is important if you want to look healthy and restored. Retail displays would want 80+ CRI to invite the consumer to buy. Photographers are in the need-to-know when selecting the correct light source to render the desired photographic look. Which tray of food would you pick to eat?

When would a high CRI value not be necessary? Take your home for example; the living room and bedrooms don't need to be as high in CRI as compared to the closets or vanities. Home security or pathway lighting can be minimal. Warehouses, where color coding isn't important, can be lit with lower cost, lower CRI light sources. Parking lots or roadway illumination has been of lower quality such as sodium or mercury vapor lighting; however, with the world moving more towards higher efficiency and natural lighting effects these types of bulbs might be on their way out. I personally would love it if all lights were high in CRI value, everything would look natural. Good thing there are many products out there to satisfy one's own preference and now you can better choose the lighting in your life.