LIGHT EMITTING DIODE COLOR RENDITION PROPERTIES

by

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Abstract

This paper discusses the color rendition capabilities of light emitting diodes (LEDs) and their relationship with the current standard for color rendition quality. The current standard for judging light source color rendering properties, known as the color rendering index (CRI), has come under heavy scrutiny in recent years with the introduction of LED in commercial lighting applications. LEDs, depending on construction type, have highly structured spectral distributions which do not scale well under the color rendering index; moreover, CRI for LEDs has become disjointed with the subjective measurement of human color preference. Unfortunately, given the multidimensional nature of color, an all-encompassing scale with a single rated value for color rendition capabilities of a light source has proven difficult to establish.

An analysis on the human visual system is first discussed, establishing how the visual system first detects color in the eye and subsequently encodes that color information through a color-opponent process, formulating conscious color appearance. The formation of color appearance leads into a discussion on human color vision and the creation of three dimensional color space, which is subsequently used for the measurement of color fidelity (CRI) of consumer light sources. An overview of how LED lamps create light and color is then discussed, showing that the highly structured spectral distribution of LED lamps is often the cause of discrepancy within the CRI system. Existing alternatives to the CRI system are then compared and contrasted to each other, and the existing CRI system.

A final color preference study was conducted where four LED lamps where compared to a reference lamp of equal correlated color temperature. Observers were asked to rate the various test lamps against the reference lamp in terms of vividness, naturalness, overall preference, and individual color preference. It was found that no significant difference was found between the first three dimensions measured but significant trend lines existed for the preference of individual colors when illuminated by either LED lamps or the reference source. Recommendations are then made for how the lighting industry could move forward in terms of color metrics.

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All survey participants

Dedication

To Will, because you made the world a much more colorful place.

Chapter 1 - Introduction

The lighting industry in recent years has seen a technological shift when it comes to the standard use light source, where lamps are used in residential and commercial applications. The common incandescent lamp is on the verge of being completely replaced by newer and more efficient light sources such as compact fluorescent lamps (CFLs) and light emitting diodes (LEDs). These newer technologies come with promises of greater energy efficiency, longer lifetimes, and better payback than their incandescent predecessors. Yet one performance category that these newer technologies have had a hard time matching, or even surpassing (especially LEDs), has been the color rendering provided by an incandescent source.

Color rendition is best thought of as a light source's ability to accurately represent an object's "true" color. In the lighting industry, a light source's color rendering ability is rated on a 0 to 100 scale called the color rendering index (CRI). The CRI system is unfortunately quite dated, being established in 1948 (Wyszecki & Stiles, 1982), and its inadequacies have become more pronounced with new technologies being introduced into common practice. LEDs in particular have demonstrated the limitations of the CRI system and the need for a new standard in color rendition quality (CIE 177:2007, 2007).

The trouble with rating accurate color rendering is that the appearance of color is subjective by nature. A light source, the medium through which light moves, and the individual viewer are but three of the factors which affect final color appearance; so many additional multidimensional factors play into an object's final color that it becomes extremely hard to quantify with a single numerical value a source's color rendering ability. Nonetheless, work has been, and is currently, being done to set a new color rendering standard which better represents a lamp's color properties. This paper will discuss the specific troubles related to color rating properties of LED lamps and how they are being addressed.

This paper will first discuss the psychology of human color perception and its relationship to the color rating system. By understanding the fundamental psychology behind how the human brain perceives color the exact nature of color can be established as well as how humans interact with it. Once the basics behind color have been set, the color rendition index and how light sources are currently rated will be discussed. Next, the various types of light emitting diodes and how their physical construction and light emitting properties influences color quality are examined. Afterwards, this paper will describe how and why LEDs commonly rank poorly on the CRI and what alternatives there may be to color quality scaling.

Chapter 2 - Perception of Color

Color perception is a product of our visual system which adds a dynamic dimension to the visible world. Color is an evolutionary tool that has developed to give humans a greater understanding of the physical world. Interestingly enough, color as humans understand and perceive it is not a physical property of nature; that is to say, there is no discrete physical quantization for color encoded in the natural world. If color were to be a unique property found in nature then all organisms with the physical ability to detect and perceive optical radiation would see color equally, however this is not case (Gregory, 1997).

The creation of color stems from the presence of optical radiation (a partial portion of what is referred to as the electromagnetic spectrum) which enters into the eye. The electromagnetic spectrum is wave-like in nature and contains a wide range of radiation. Light that is perceived by the visual system, and subsequently color, is only a small portion of wavelengths which exists within the electromagnetic spectrum (Wolfe, Kluender, & Levi, 2012).

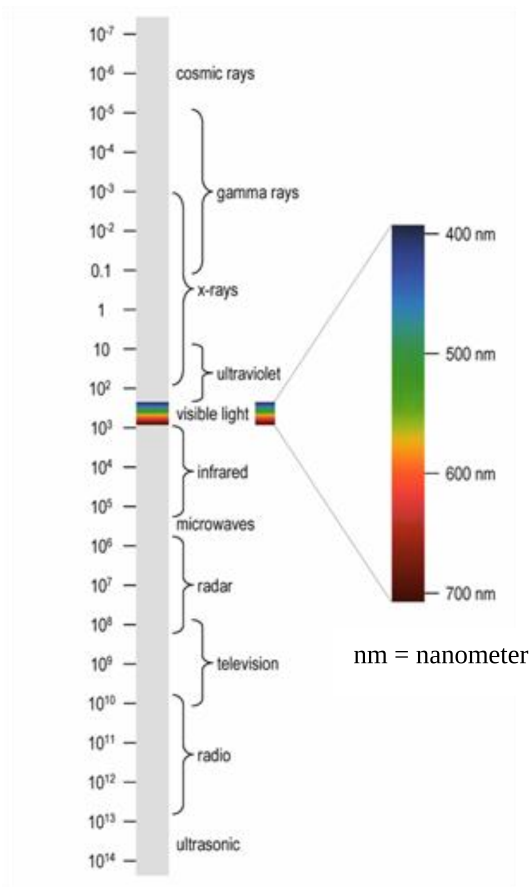


Figure 2.1: Electromagnetic Spectrum (Discover Lighting, 2011)

What is important to note is that the perception of color is a particular response to the presence of certain (or combination of) wavelengths of light. So while color is not a physical property in nature, it is the derivative of one. To understand how color is derived from the greater electromagnetic spectrum it is important to recognize the brain's neurological process in optical perception. This process explains how light is transformed from a physical stimulant to a perceptual experience.

Color Detection

The gateway to which the world is seen and perceived is none other than the human eye. Light enters the eye through the cornea and into the pupil and it is subsequently refracted though the vitreous humor via the lens, where it ultimately reaches the retina. Once light reaches the retina it is absorbed by photoreceptors which are responsible for converting physical stimulation into neurological information that the brain can process (Wolfe, Kluender, & Levi, 2012). Photoreceptors are broken down into two major subcategories which perform different functions in the visual perception process.

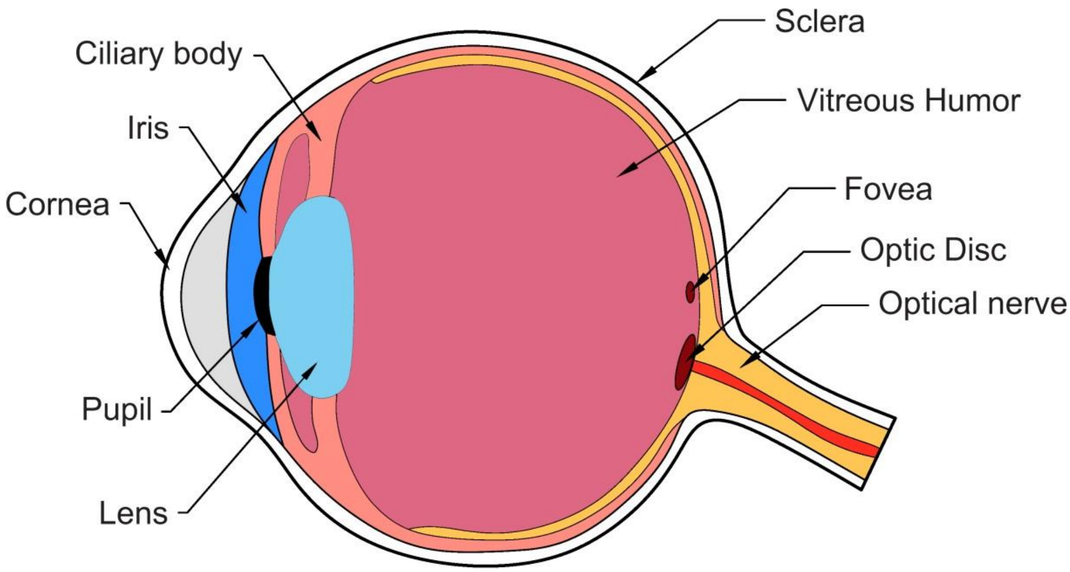


Figure 2.2: Human Eye Diagram

The first photoreceptor is referred to as a rod type that is mainly responsible for seeing during low lighting conditions where the eye is operating in what is called scotopic vision. Interestingly enough, rods are achromatic (they cannot detect difference in color) but are important to color vision because of their ability to discern luminance (an indicator of how bright a surface is) values of light. Rods play a more dominant role in motion detection for the human visual system and are more common in the peripheral region of the eye, this leads to humans having poor color vision in the peripheral fields of view (Livingstone, 2002).

The second photoreceptor, and the one mainly responsible for color vision, is known as a cone type. Cone type photoreceptors can be broken down further into three subcategories known as S, M, and L cones which each respond most heavily to blue, green, and red regions of the electromagnetic spectrum, respectively. How each cone type is broken down is best represented by their individual spectral response curves, seen in Figure 2.3. These three cone photoreceptors are found almost exclusively within the central region of the retina known as the fovea which is why human color vision is most acute in the center of the visual field (Gregory, 1997). These photoreceptors function most effectively with daylight levels of luminance, thus during low light level scenarios the human visual system becomes essentially color blind because it must rely on the luminous input of rod photoreceptors for visual information. It has been well established that cone photoreceptor density reaches a maximum within the fovea and then exponentially deteriorates with increasing eccentricity from the fovea (Curicio, Kenneth, Packer, Hendrickson, & Kalina, 1987). Thus cones, being the mechanisms for beginning color perception, contribute to the high level of color acuity in central vision. This high color acuity in the fovea can also be contributed to the one-to-one relationship that fovea cones share with corresponding retinal ganglion cells (Hansen, Pracejus, & Gegenfurtner, 2009). With a higher amount of pathways originating from the fovea, the visual system is able to have better color sensitivity and discrimination as compared to the peripheral region (Nagy, Sanchez, & Hughes, 1995).

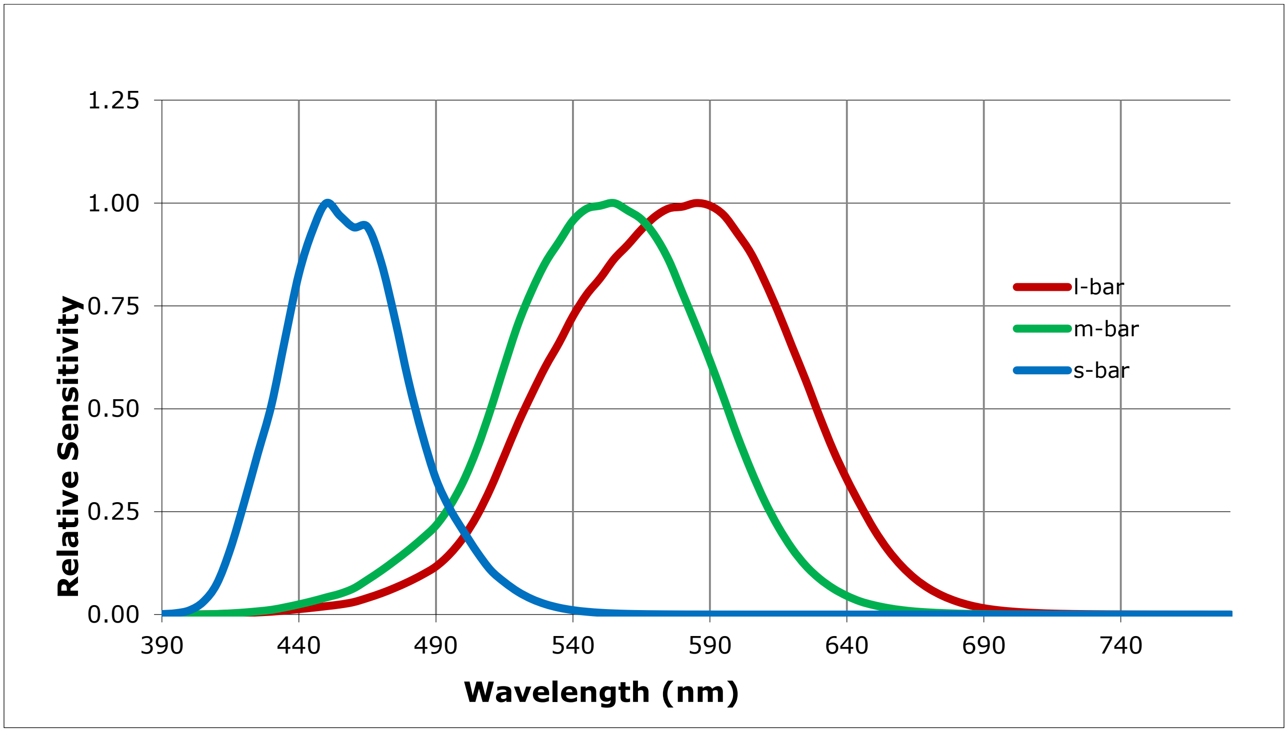


Figure 2.3: Cone Spectral Response Curves

While photoreceptors are essential to the color vision process they do not actually "see" color. Photoreceptors are fundamentally a means to an end of the color process. The tristimulus responses from the three cone type photoreceptors and the luminance values from rod type photoreceptors are used in a later visual progression known as color-opponent processing.

Color Processing

There have been many theories throughout the centuries for how humans process color, yet today two conjunctive theories have been generally accepted: trichromatic theory and color-opponent theory (Livingstone, 2002). Trichromatic theory is related to the discussion earlier about color detection through conic photoreceptors in the eye. Photoreceptors located in back of the retina are the first step towards color processing, yet alone each photoreceptor cannot distinguish the difference between one color and another. It takes the combined input of all photoreceptors to discriminate individual colors for the brain to process a color. These combined responses are based on each photoreceptor's disposition towards a certain wavelength and combined they are known as the tristimulus response values.

The tristimulus response values from the retinal cones are used by their corresponding ganglion cells to form the basis of the color-opponent theory in color vision by forming receptive color fields that are biased to the presence or absence of certain color wavelengths. There are two different types of color-opponent ganglion cells, the blue/yellow opponent cell and the red/green opponent cell. Blue/yellow opponent cells are comprised of input from all three color photoreceptors and can be mathematically expressed as [S-(L+M)]; conversely, the red/green opponent cells are comprised of inputs from two color photoreceptors and can be represented as [L-M] (Wolfe, Kluender, & Levi, 2012). Colors are thus constructed by subtracting the different cone responses and luminance is constructed by summing the different cone and rod responses (Livingstone, 2002).

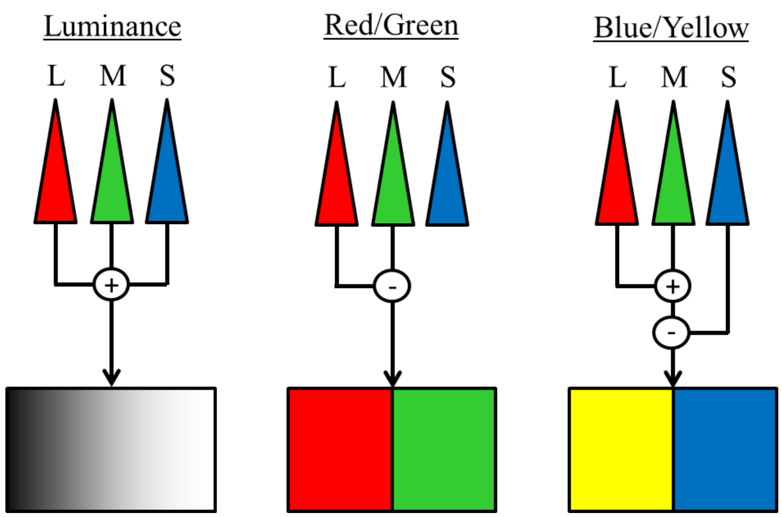


Figure 2.4: Color Opponent System

One benefit to color opponency is that the individual pairs actually neutralize each other to create an intermediate color (red and green combine to make yellow while blue and yellow combine to make white). This is an especially useful property to color perception. By processing for color in an antagonistic methodology, the visual system is able to interpret millions of colors with only three different photoreceptors. This is a much more efficient way for the encoding of color information than having a unique photoreceptor for every single color (Livingstone, 2002). LEDs take advantage of this visual process when attempting to create the imitation of white for our visual system, which will be discussed later on.

Opponent signals are compared and contrasted within the visual cortex of the brain where they are deciphered into a specific color. This process (in an ideal form) can be illustrated by a Hering color wheel in Figure 2.5. While not completely representative of the visual system, the color wheel shows how colors are seamlessly created and transitioned from four “primary colors”. The exterior ring shows colors which are considered color-opponent (red/green and blue/yellow) and the center ring represents colors which are created by various amounts of color opponent responses.

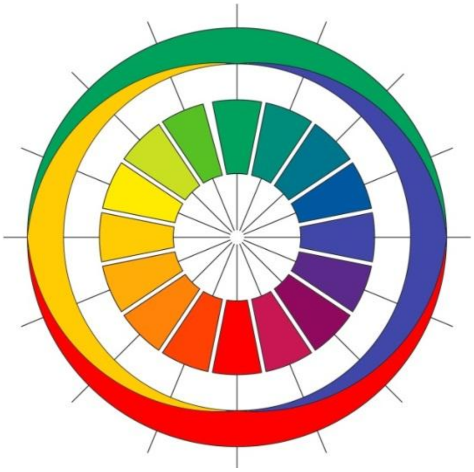


Figure 2.5: Hering Opponent-Colors Diagram

While the color wheel shown does a decent job at showing how colors are created in pairs, it does not accurately demonstrate the actual range in which humans see. The normalized versions of human conic photoreceptors in central vision are seen in Figure 2.6. These distributions represent how sensitive each cone is to a certain wavelength in the two degree viewing range. The two degree viewing range is the range of vision which falls upon the fovea (region with the most cone photoreceptors) located within the eye. The three curves form the basis for the tristimulus values for color vision. For example, a unique blue of 450nm would elect a large neural response from S-type photoreceptors, a small response from L-type receptors, and a negligible response from M-type receptors. From first glance it would seem that colors in the blue range would be the most dominant color that we see yet this is not the case. Humans have a predisposition towards green region of color in the central viewing field due to the density of medium and long cone photoreceptors in the fovea of the retina. The combined responses of these photoreceptors form what is commonly referred to as color space with each photoreceptor curve representing a different three dimensional axis. How color space is derived from the tristimulus response curves of cone photoreceptors is discussed in the next chapter.

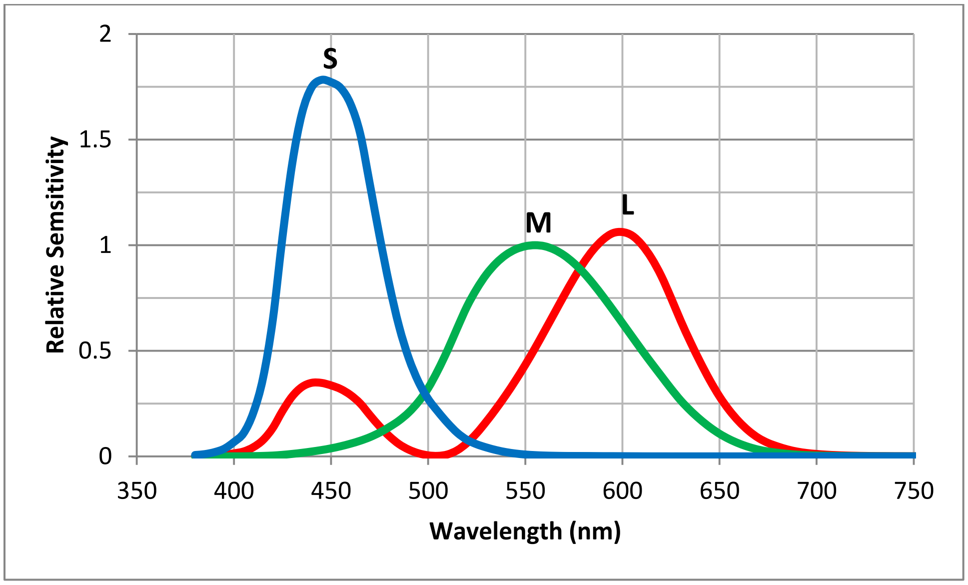


Figure 2.6: CIE 1932 2° Standard Observer

The tristimulus response curves shown in Figure 2.6 can be used to derive the actual color opponent range for which colors are processed (Figure 2.7 and Figure 2.8) with the relative sensitivity axis representing photoreceptors affinity towards the presences of certain wavelengths of light. The response curves are independent of each other in terms of relative sensitivity to a discrete wavelength of color; therefore, there is no way to interpolate what colors are created solely from the color response curves. That is to say, if two separate photoreceptors are excited by two different wavelengths of light at the same time, it is difficult to determine what color is perceptually created by looking solely at the graphs in Figure 2.6. This problem is addressed by the creation of three dimension color space discussed in Chapter 3. Higher order visual processes occurring in the lateral geniculate nucleus (LGN) of the brain take the opponent color appearances to begin the first stages of conscious color processing which is then relayed to the primary visual cortex. Double-opponent and single-opponent visual cells respond to the presence of either red and green or blue and yellow to create the visual perception of a field of color (Wolfe, Kluender, & Levi, 2012).

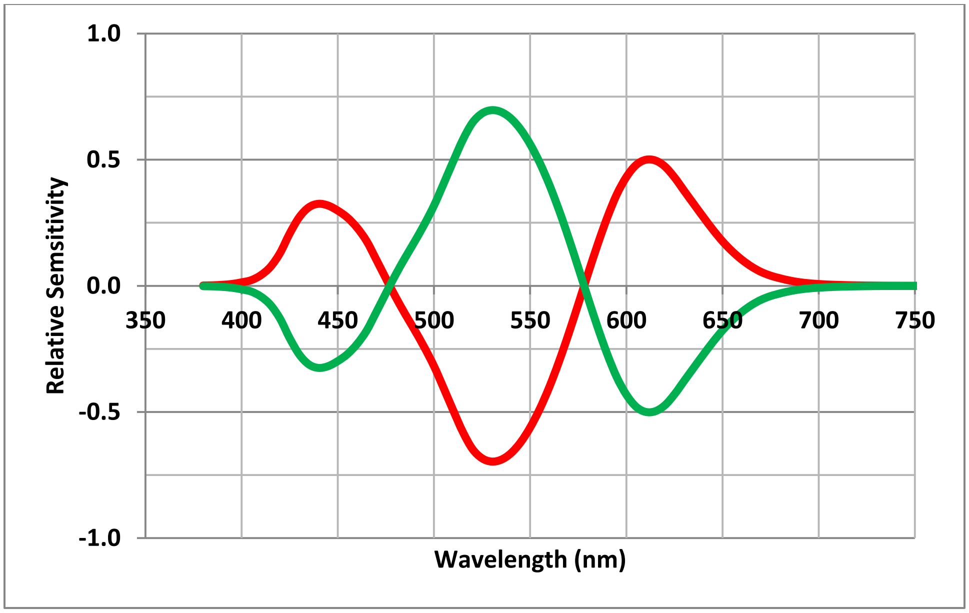


Figure 2.7: Red/Green Opponent Response Curves

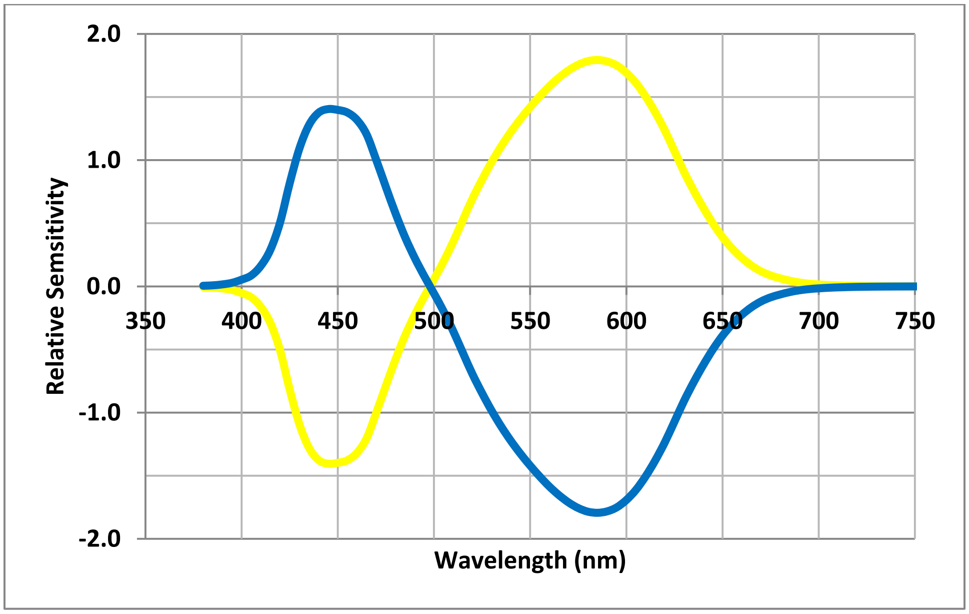


Figure 2.8: Blue/Yellow Opponent Response Curves

Chapter 3 - Color-Rendering Index

There are three distinct features which describe a lamp when it comes to color quality; the ability to create accurate color representation, the ability to create visually appealing colors, and the ability to create a certain level of differentiation between unique hues. These three qualities are represented as color fidelity, appeal, and discrimination, respectively (LED Color Characteristics, 2012). Today's set standard for color measurement quality of commercial illuminants is known as the color-rendering index (CRI), though it is only metric for color fidelity. CRI, as it is measured, is based upon the International Commission on Illumination (CIE) chromaticity diagram, seen in Figure 3.2, and is the only internationally accepted color metric (Davis & Ohno, 2005). Color rendition is defined by the CIE as the "Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant" (CIE 177:2007, 2007).The CRI system has been in place for well over fifty years and has been argued by most to be outdated, yet the system still remains the industry standard (Davis & Ohno, Toward an improved color rendering metric, 2005). The CIE color specification system is used for all colorimetric measurements for light sources as it is a singular reference point for color measurements.

CIE Chromaticity Diagram

The CIE chromaticity diagram is a graphical representation of all visible color. The color distribution is based on the conic tristimulus values from Figure 2.6. One of the shortcomings of viewing the cone responses graphically as in Figure 2.6 is that it is not immediately clear how they interrelate in terms of color creation. The CIE chromaticity chart overcomes this difficulty by creating a planer projection of the three dimensional data of cone responses; moreover, the cone responses are recalculated into ratios of each other for discrete wavelengths. These ratios are presented in Color Science Section 3.3.8 as follows:

$$\boldsymbol{x} = \boldsymbol{X}/(\boldsymbol{X}+\boldsymbol{Y}+\boldsymbol{Z})$$ **Equation 3.1**

$$\boldsymbol{y} = \boldsymbol{Y}/(\boldsymbol{X}+\boldsymbol{Y}+\boldsymbol{Z})$$ **Equation 3.2**

$$z = Z/(X + Y + Z) \qquad \textbf{Equation 3.3}$$

where,

X= L-cone spectral response

Y= M-cone spectral response

Z= S-cone spectral response

The three ratios from Equations 3.1-3 each represent a three dimensional coordinate which can be graphed to represent color space as seen in Figure 3.1. The boundary layer shown represents pure spectral hues that require no color mixing to create; indeed, the boundary layer may look familiar as it is an extension of the electromagnetic spectrum from Figure 2.1 with respect to individual cone responses. An important note is that Figure 3.1 is only a visual aid tool to demonstrate the formation of two dimensional color space and should not be used to record color information such as color coordinates. The green and cyan regions of the graphs are not proportionally correct. A final representation of the CIE Chromaticity Diagram is seen in Figure 3.2 where pure chromatic wave lengths are marked along the border of the diagram and the internal area represents all possible mixed colors.

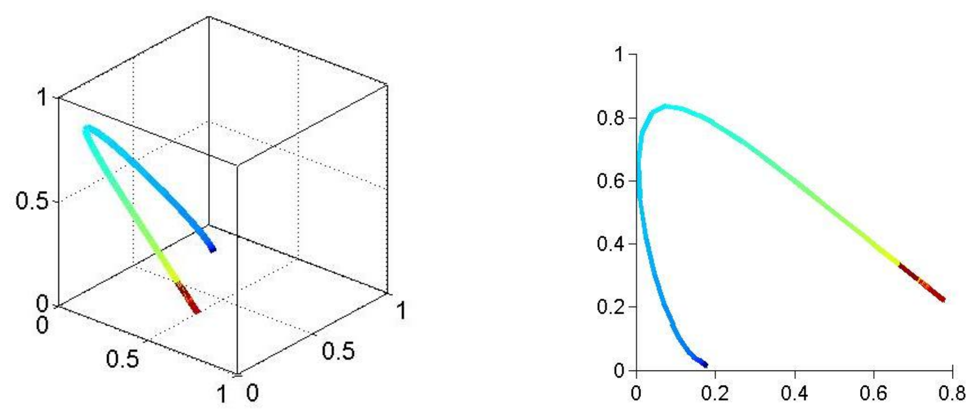


Figure 3.1: Three Dimensional Cone Responses and x-y Planar Section

In order to put the three dimensional data into a useful form the CIE takes the planar projection of the graph along the x and y axis. By converting the three dimensional data into a planar form some information is inherently lost. This information is in the form of luminance, or intensity, which is a measurement of black to white saturation in color. Information which is maintained in the CIE chromaticity diagram includes hue and saturation. Hue is the unique color appearance of a light source or object (blue, red, green, etc.) and saturation is the relative purity of a single hue (colors towards the boundary line have the greatest saturation).

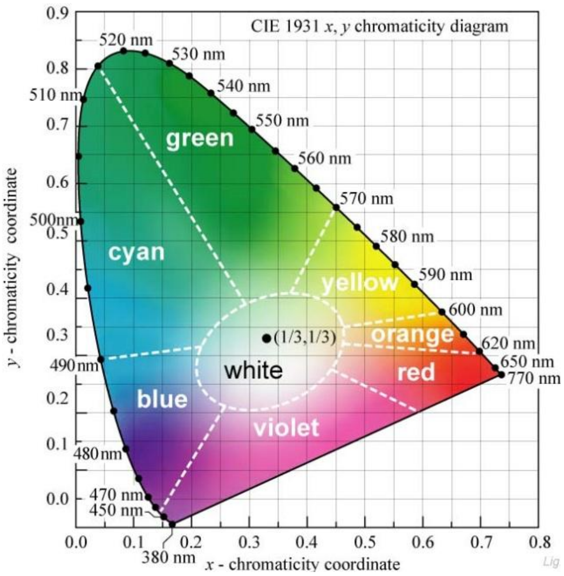
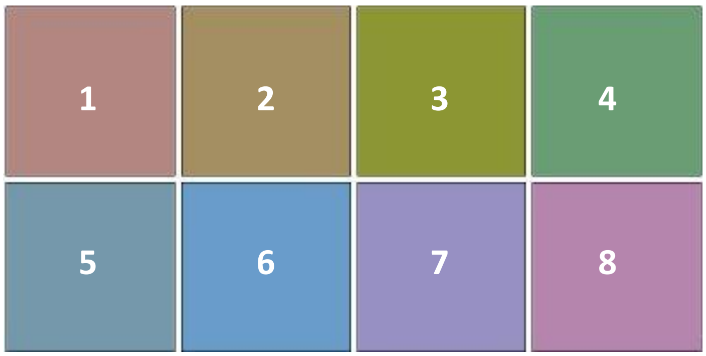


Figure 3.2: CIE 1931 x,y Chromaticity Diagram

One special property of the chromaticity diagram, that becomes useful for color rendering and appearance, is that by picking any two points within the color space, all the colors that may be created by the combination of those two colors represented by a line in-between them. This property of the diagram makes sense based on the discussion earlier on color perception and is particularly useful for LED light sources, which utilize blue-yellow color mixing to create white light. As mentioned in earlier, blue and yellow are to color opposites in the visual system which together create white light.

CRI Measurement

CRI rates lamps by measuring the resultant color shift of a test color swatch of eight preselected colors, seen in Figure 3.3, as compared to a standard reference illuminant of the same or similar correlated color temperature (DiLaura, Houser, Misrtrick, & Steffy, 2011). These test-color samples are used because of their moderate saturation and intensities under daylighting conditions; moreover, each of the color samples are approximately equally spaced in the CIE chromaticity diagram. The eight samples shown in Figure 3.3 are representative samples only which are not completely accurate and should not be used for actual scientific measurements because the original colors cannot be acuaralty reproduced through print or digital media.



Swatch	Name	Appr. Munsell
1	TCS01	7, 5 R 6/4
2	TCS02	5 Y 6/4
3	TCS03	5 GY 6/8
4	TCS04	2, 5 G 6/6
5	TCS05	10 BG 6/4
6	TCS06	5 PB 6/8
7	TCS07	2, 5 P 6/8
8	TCS08	10 P 6/8

Figure 3.3: CRI Munsell Reference Colors (Approximate)

One of the first major points that must be understood about the CRI scale is that it is relative in measurement. The reference point to which a lamp is rated is dependent on the correlated color temperature (CCT) of the lamp to be measured. For lamps below 5000K the reference source is a Planckian black body radiator with a predetermined CRI of 100 and a CCT of matching intensity to the measured lamp. An actual blackbody radiator is actually physically impossible to produce; thus, the blackbody radiator in a CRI calculation is substituted with an incandescent type lamp. Lamps exceeding a CCT of 5000K use the spectral distribution curve of daylight to measure relative CRI (Wyszecki & Stiles, 1982). The reasoning behind the broken distribution of lamp measurement is that reference black body radiators in the lower ranges of CCT do not have the ability to produce adequate spectral power in the shorter wave lengths (violets and blues).

Calculation of CRI

As stated earlier, CRI is measured by the resultant color shift of eight color samples under a tested illuminant. The eight color samples, when illuminated by a reference lamp with a CRI of 100, will occupy specific points in color space. These points in color space are considered reference points for a test lamp to be measured against. The eight color swatches will subsequently occupy different points in color space when they are illuminated by a test lamp. This change in points is considered a chromaticity shift and is the basis for how CRI is calculated. By measuring the distance between the original color point and the test point, CRI can be determined. The individual chromaticity shift of each Munsell reference color is referred to as a special color rendering index and is calculated by the following equations found in Color Science Section 3.3.11:

$$\mathbf{R_i = 100 - 4.6(\Delta E)_i} \qquad \textbf{Equation 3.4}$$

where,

R_i= Special color rendering index

ΔE = Euclidian distance between coordinates

The general color rendering index specifies the arithmetic mean of all eight special color rendering indices to create a singular value for color rendition.

$$\mathbf{R_a = \frac{1}{8}\sum_{i=1}^{8} R_i} \qquad \textbf{Equation 3.5}$$

where,

R_a= General Color Rendering Index

While the CRI has been utilized for a number of years as the set standard for color fidelity, it is apparent that the system is not without its flaws. The next section will discuss these limitations in detail.

CRI Limitations

The CRI system is far from perfect, yet it is the most commonly used system to measure lamp color redition today. The use of a relative rating, colors measured, and calculation method are few of the shortcomings of which the system is subject to. The problem with the use of a relative scale is two-fold. First, lamps of varying CCT cannot be compared to each other in terms of color quality because they have a dissimilar reference point on the CIE chromaticity diagram. This inability to compare lamps in terms of color quality creates a common complaint among lighting designers in industry. Moreover, having various light sources of differing CCT as reference source creates an ambiguity concerning how a color should actually appear. A reference lamp with a CCT of 2700K and 100 CRI has a different spectral power distribution from a reference lamp that has a CCT of 4100K and 100 CRI and both lamps will render a single color differently, yet both are rated as completely correct in color appearance because of their differing spectral distributions. Therefore, it is unclear what “true” color appearance actually is when colors are allowed to vary in appearance.

Next, the CRI system measures chromatic shifts of the eight unique Munsell reference colors discussed previously, and seen in Figure 3.3. The use of only eight colors does not accurately represent the entire range to which human color vision can perceive; moreover, the color space in which the eight color samples are equally spaced is viewed as outdated (Davis & Ohno, 2005). All eight color samples have relatively low saturations which have been harmful to the rating of newer lighting technologies, LED light sources are one lighting technology which has been particularly hurt by CRI due to the structure of their spectral distributions, which have highly structured spectra. Highly structured spectra have the tendency to render vivid and saturated hues particularly well, which can be subjectively viewed as better color rendering.

Because the calculation method for CRI uses a simple averaging method of the eight chromatic shifts to determine the general color quality, it is subject to skewing and misrepresentation of color data. By only averaging the chromatic shifts, lamps which score poorly for only one or two colors still receive positive color ratings. A chromatic shift of a sample color is when a color moves its position in color space when illuminated by different light sources, seen in Figure 3.4. This calculation method is rather inadequate because it may be easily manipulated by special tuning spectral distributions to render the original eight color samples well while leaving other colors neglected. In theory, a lamp with a spectrum that rendered only the eight color samples relatively well would score higher than a lamp which had a broad spectral rendering curve.

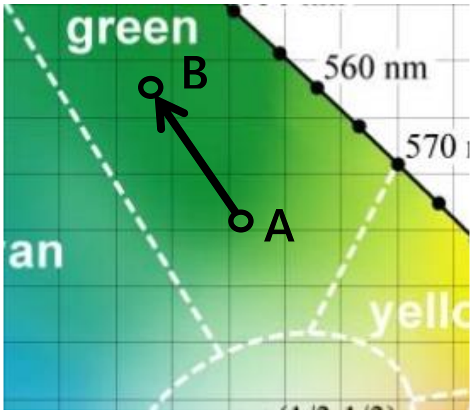


Figure 3.4: Sample Chromatic Shift

Chapter 4 - Light Emitting Diodes

Light emitting diodes, commonly referred to as LEDs, are one of the newer lamp technologies to emerge into the commercial building lighting industry. Their high efficacy (lumens per watt) has been one of the greatest drivers of their development and implementation into the building industry. Interestingly, LEDs have been around in minimal form for a while, but it is only within the past decade that they have become serious contenders for the top illumination source in the commercial lighting industry.

A Brief Overview

LEDs were first introduced in commercial application in the 1960s where they were dominantly used as status indicators and numerical displays (Chang, Das, Verde, & Pecht, 2011). The first visible LEDs passed an electric current over a gallium arsenide phosphide in order to produce a red light. These first diodes were not extremely bright and were particularly expensive to manufacture so they did not catch on as lighting alternatives until the 1990s, with the development of ultra-bright electroluminescent compounds. What has been particularly useful for the adaptation and implementation of LEDs is the expansion of spectral wavelengths that they are able to produce. Over the years new fluorescent compounds have been invented to be used for solid state lighting to produce new colors in the electromagnetic spectrum, including ultraviolet light. By expanding the wavelength range which can be produced, LEDs have become a viable commercial option for lighting.

An LED package is mounted on a printed circuit board (PCB) and contains the individual semiconductor diode (the light producing engine of an LED), a heat sink, protective capsule, and metal housing, as seen in Figure 4.1. One of the greatest selling points to LED is their theoretical lamp life. Many manufacturers claim that their LED products have rated lifetimes of 50,000 to 70,000 hours (Chang, Das, Verde, & Pecht, 2011). The rated lifetime of an LED is measured differently from that of typical lighting technologies because LEDs rarely ever completely stop working from normal operation. Rated lifetime for typical light sources is measured as the time it takes for the light source to cease operation and fails to create light. LEDs after an extended period succumb to lumen depreciation. Lumen depreciation is the lowering of light output of a lamp over its lifetime. LEDs eventually become too dim to be considered useful (about 70% of their initial light output) and at that point are considered to be at the end of their rated life (Lifetime of White LEDs, 2009). While the advertised lifetime is a major selling point for LEDs, the light source still has barriers to overcome, particularly cost, if they are to become the standard lighting technology utilized. One of the largest technical challenges the LEDs face is their degradation when exposed to heat. When an LED is exposed to heat beyond its intended design conditions for an extended period time, lamp life, lumen output, and original color all deteriorate towards the point of lamp failure.

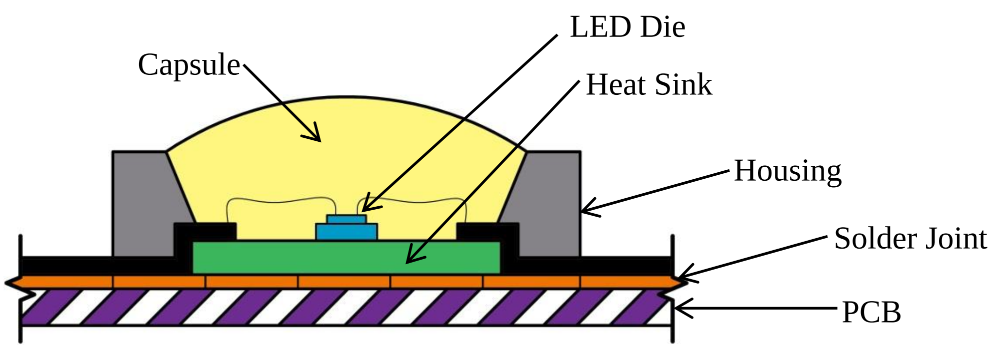


Figure 4.1: Typical LED Package Cross Section

Operation

LEDs are a form of solid state lighting, which is short for solid state electroluminescence. Individual LEDs rely on what is referred to as a p-n junction to generate light. A p-n junction is a type of diode where two semiconductors with oppositely charged ions (the p side contains positively charged “holes” and the n side contains negatively charged electrons) are conjoined. The semiconductors used in a p-n junction are typically poor conductors which have impurities added to them in the process called doping. Because the two semiconductors within a p-n junction are oppositely charged, a potential difference is created between the two sides of the junction where in negative electrons begin to move towards positive holes in the center of the junction. The region which is created by movement of charged particles into an equilibrium state in the center of the diode is referred to as the depletion zone. To overcome the potential difference that is created within a p-n junction an electrical current must be applied across the diode in order to energize electrons to a higher energy state (referred to as the bandgap). It is this elevation of electron energy states that causes the creation of ultraviolet and visible light.

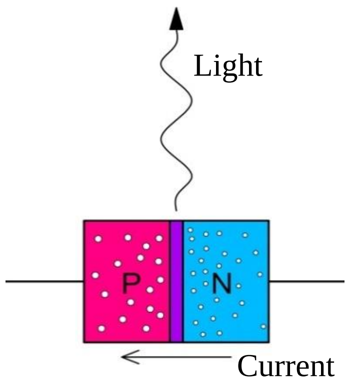


Figure 4.2: P-N Junction

When an electron moves across the diode and is paired with positively a charged hole, an ion which is an electron acceptor, it moves to a lower energy state. Because the electron is moving to a lower energy state it must release its excess energy in the form of a small massless particle called a photon. It is the photon which causes the perception of light. Electrons move up and down energy states in discrete quantum levels (known as valance electron energy states) where a greater energy drop corresponds with a higher natural frequency of the photon (a more energized photon). The natural frequency with which photons move through space is considered a light's wavelength in the electromagnetic spectrum. This frequency is what is perceived as a color to a human observer. Light is often described as a dichotomy between wave and particle form as the particles of light, photons, which have a frequency, or wavelength, at which they travel. It can be recalled that from Figure 2.1 that specific colors correspond to varies wavelengths of light. LEDs are capable of producing many wavelengths of light based upon the type of p-n junction compounds which are utilize in construction.

Color Properties

Because electrons fall into lower bandgap energy levels in discrete intervals, the photons that they emit resonate at specific frequencies. These specific frequencies thus correspond to the spectral distribution patterns of LED lights. These structured spectra often peak at the high energy intensities for the monochromatic wavelength for which they correspond to (LED Color Characteristics, 2012). In other words, the specific colors that are created by LEDs tend to be saturated in appearance. When the spectral power distribution curves of LED lights are modeled they tend to have narrow tall peaks at various intervals, such as the example in Figure 4.3.

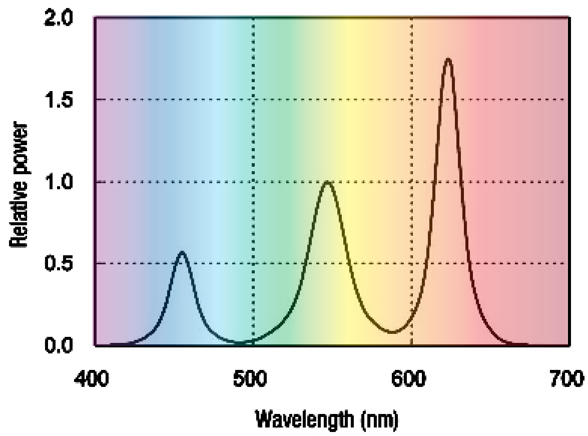


Figure 4.3: Example SPD of an LED

LED Types

There are two main categories of LED types in use for general lighting purposes: white LEDs and RGB LEDs. Each LED type uses a different color creation method in order to arrive at the same end, approximate white light. White light LEDs utilize red, green, blue, orange, and/or yellow phosphors with a blue LED diode in order to produce white light (Chang, Das, Verde, & Pecht, 2011). The phosphors are coated on the LED encapsulate and are activated to fluoresce (illuminate) when hit by the high energy wavelengths of the blue LED diode, referred to as down conversion LED. This down conversion process is similar to that used by common commercial fluorescent lamps. Phosphor particles are part of a silicon matrix material which absorbs blue light emitted from an LED die and reemits the energy as yellow light (Hu, Luo, Feng, & Liu, 2012). This method of producing white light is more common in commercial applications because it broadens the spectral power distribution of the LED source. LEDs which utilize phosphor based lighting tend to have peaks in the blue and yellow ranges allowing them to produce the perceptual experience of cool white light. The perception of white light is created because blue and yellow are color opponents in the visual system (refer back to Chapter 2). These types of LEDs have seen a larger portion of the commercial market growth due to the lower cost associated with manufacturing. White LEDs only require a single diode type for effective operation (Chen, Chu, & Liu, 2011).

Figure 4.4: Example Phosphor Based White LED Lamp (A-Shape LED, 2013)

RGB (Red-Green-Blue) LEDs utilize the three primary additive colors in order to create white light. By combining the wavelength of all three diodes white light is easily created for viewing. Recall from the CIE Chromaticity Diagram that if any two colors of light are used in conjunction, that any color point lying between the two can be created. This rule is compounded by adding a third point to the diagram (in the form of three LEDs) which creates an effective area of colors. RGB LEDs are thus very versatile when it comes to color creation and can be used for a number of color sensitive applications. Individual diodes can be adjusted in intensity in order to create various colors across the lamps respective gamut area.

Some of the most basic problems have plagued RGB LEDs and prevented them from becoming more common in general lighting applications. Efficiency of individual color diodes varies by color which makes it difficult to balance the diodes in order to maintain a constant white light output. Moreover, the individual diode's efficiencies change at dissimilar rates which means that a color shift of the entire LED lamp can occur over its lifetime. Disassociation of individual diode efficiencies becomes increasingly more problematic when few diodes are used for an LED lamp. This discontinuity between lifetime decay rates cause the need for more sophisticated optical properties of the entire lamp in order to create uniform color appearance (LED Color Characteristics, 2012). Finally, because three different colors are required, the price of RGB LEDs usually exceed that of phosphor based LEDs, although RGB based LEDs have greater color changing abilities (Chen, Chu, & Liu, 2011).

Figure 4.5: Example RGB Type Fixture (Lumenbeam Large Color Changing, 2012)

Chapter 5 - LEDs and CRI

LEDs have developed quickly over the past decade in terms of efficacy, cost, and reliability, yet one topic that remains controversial for LEDs is CRI. LEDs have often been rated low on the color rendering scale even though they create the perceptual experience of cool white light and natural color appearance. Often LEDs have contradicting ratings between visual preference and technical rating (CIE 177:2007, 2007). So what causes this disassociation? The problem is multifaceted.

The first problem lies within the CRI system itself. As mentioned in Chapter 3 the color rendering index takes samples of eight reference colors to judge color quality. These samples (Figure 3.3) are muted in color and take only a small range of hues to be sampled. LEDs have highly structured spectral distributions which may or may not correspond to these colors, which causes discrepancies for select color samples. The CIE has acknowledged this issue and states the following:

> …different order of magnitude of the colour differences occurring if the reflective samples are illuminated by a white LED light source and by other light sources, due to the peculiar spectral power distributions of the white LED light sources 'interacting' with the spectral reflectance of the test-colour samples (CIE 177:2007, 2007).

If one or two colors do not appear close to their reference counterpart because the LEDs spectra differ then the error is compounded by the CRI calculation method. Calculation of an average value color rendering across all eight color samples penalizes LEDs heavily because all the colors are equally weighted, even though their visual perception in color space is not equal. Consequently LEDs may produce a perfectly acceptable palette of color in terms of visual performance, yet because a couple of the eight color samples appear skewed, the calculated CRI may be poor.

Another problem that has caused LEDs to perform poorly in CRI is that they may actually render colors "too well." As described in Chapter 4, LEDs have very narrow spectral distributions which tend to peak at relatively high intensities when shown on a spectral distribution curve. The peaks translate perceptually into high saturated chroma which can be equated to the color property vividness (the CRI system only measures fidelity). This creates an interesting conflict between LEDs appearance and the CRI system. When ranked visually among observers, saturated chroma are seen as more appealing, yet when rated by the CRI system saturated chroma are ranked negatively because they skew test samples chromaticites (Color Rendering Index and LEDs, 2008). It is interesting to note that many fluorescent type light fixtures have spectral distributions that are similar in shape to LED lamps yet have reasonably high CRI ratings. Over the past forty years fluorescent lamp manufacturers have fine-tuned which phosphors are coated on their lamps in order to render the eight color samples used by the CRI system.

Because of the discontinuity between CRI and LEDs the International Commission on Illumination has released an official response in the form of CIE Technical Report 177:2007, *Color Rendering of White LED Light Sources*, where it recommends not using CRI for white LED sources. CIE 177:2007 states the following:

> Visual experience has shown that the current CRI based ranking of a set of light sources containing white LED light sources contradicts the visual ranking….The conclusion of the Technical Committee is that the CIE CRI is generally not applicable to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in this test….The Committee recommends the development of a new colour rendering index (or set of new colour rendering indices).

The report cites several studies where color rendition and visual ranking where weighted against each other. In each case the same relative conclusion occurred. CRI is not an appropriate metric for measuring color ranking and a new metric should be derived and adopted.

Chapter 6 - CRI Alternatives

While it is apparent that CRI has numerous flaws, it is still the industry standard. There has been abundant amount of alternative color metrics proposed throughout the years to address the flaws of CRI. A few of the most popular alternatives and supplements to CRI are discussed below.

Color Quality Scale

One recently developed alternative to the CRI system by researchers at the National Institute of Standards and Technology (NIST) is the Color Quality Scale (CQS). CQS differs from the CRI systems in that it is not simply a measurement of color fidelity but rather a total measurement of quality. Some of the factors which CQS accounts for that differentiate it from CRI include: an updated color space, color saturation, color temperature, additional color samples, and an improved calculation method (Davis & Ohno, 2005).

The color space which the CRI system bases its chromatic measurements on has been outdated for an extended period of time, yet it remains the standard method of color measurement. The CQS system uses an updated version of the color space called CIELAB which better represents the uniform distribution of perceived colors because the original CIE color space diagram does to give proper weighting to certain color regions (CIE 177:2007, 2007).

A problem with the CRI system is the unfavorable rating of sources with peaked spectral distributions which tend to saturate colors (increase of chromaticity). The irony to this is that an increase in saturation is often seen as favorable by the standard observer. Often a standard observer perceives an increase in chromaticity as an increase in brightness and distinguishability (Davis & Ohno, 2005). In order to address this issue, in particular when it comes to LEDs, the CQS applies a saturation factor to the overall color quality of the lamp.

As mentioned earlier all lamps tested under the CRI system are tested against a reference lamp of corresponding CCT. This method of measurement has a discontinuity to it as lamps in the extreme ends of color temperature (where color quality becomes distorted) are given equal value to those color temperatures in the median of the color temperature range (where colors appear appropriately). The CQS begins penalizing reference sources towards the extreme color temperature where color appearance becomes distorted.

It has been well accepted that the eight color samples used for the CRI rating system are not an accurate sampling of the entire color space which humans can perceive; moreover, the colors are muted in appearance and do not appear favorable to many viewers. The CQS system replaces the original eight samples with 15 new colors which have a higher saturation and are taken from a wider range that encompasses more color space.

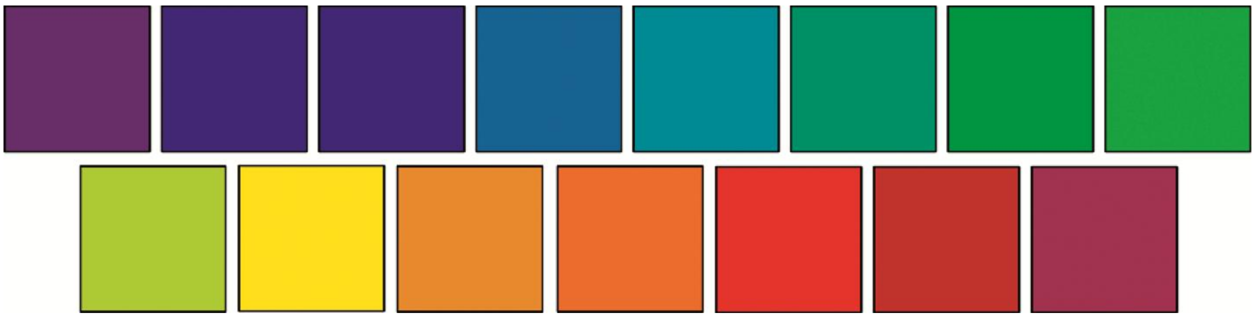


Figure 6.1: Color Quality Scale Color Samples (Approximate)

One of the last major changes which CQS implements is the method of calculation for color difference between a test lamp and reference lamp. Recall from $\mathbf{R_a} = \frac{1}{8}\sum_{i=1}^{8} \mathbf{R_i}$ Equation 3.5 that the color differences in the CRI system were averaged amongst each other. Averaging of the color shifts can cause large color shifts to go unnoticed by the final CRI value. To mitigate this issue the CQS take the root-mean-square (RMS) of all the color differences in color space (Davis & Ohno, Developement of a Color Quality Scale). This equation is seen in Development of a Color Quality Scale as:

$$\Delta E_{RMS} = \sqrt{\frac{1}{15}\sum_{i=1}^{15} \Delta E_i^2} \qquad \textbf{Equation 6.1}$$

where,

ΔE_{RMS}= RMS of the color differences

ΔE_i = Color difference for individual color samples

The main intent of CQS is not to completely replace the CRI system method but to supplement it with more information pertaining to the light sources and colors being rendered. Instead of rating the color properties of a lamp with a single value (CRI), two values (CRI and CQS) are used to give a more well-rounded representation to a lamp's color quality. The system has yet to be universally accepted by any set of standards despite initial support from the academic community (LED Color Characteristics, 2012).

Color Gamut Area Index

Not necessarily a replacement for the CRI system but rather an enhancement to it, the gamut area index (GAI) can be a useful predictor of color quality that offsets the shortcomings of CRI (Rea & Freyssinier-Nova, 2007). As mentioned in earlier chapters, CRI is only a measurement of color fidelity and not a predictor of "vividness" which is typically associated with saturation and visual preference. To offset this limitation GAI was introduced to measure the vividness of a light source. GAI is a measurement of area enclosed by a polygon of colors which are able to be created by a light source in CIE color space. Recall from Figure 3.2 that the boundary line of CIE color space represents pure monochromatic wavelengths of light which are the more saturated hues. If a light source has a larger polygonal area within color space it is able to create more saturated hues which are associated with vividness. Consequently, GAI can be used as a supplemental predictor to CRI to account for color vividness of a light source.

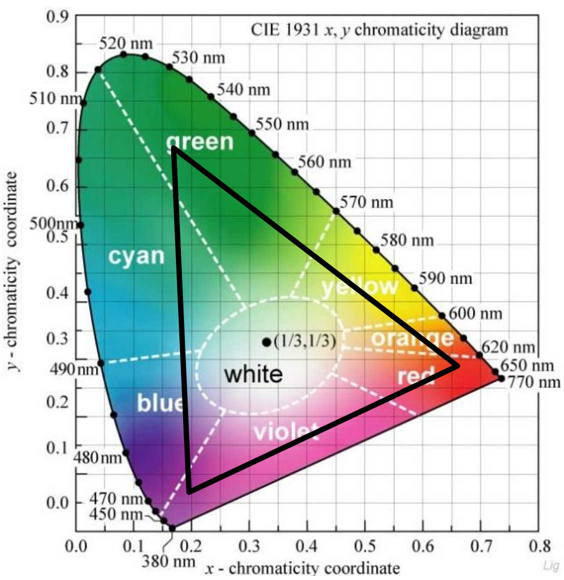


Figure 6.2: Example Gamut Area

Color Discrimination Index

Similar to GAI, the color discrimination index (CDI) uses the enclosed area within color space to predict color measurement. Unlike CRI and GAI, CDI measures the third tenet of color rendition which is a viewer's ability to distinguish unique hues from each other based on a lamp source. CDI is argued to be an absolute color metric which can be used to compare light sources of different color temperatures and spectral distributions unlike the CRI system (Thornton, 1972). Recent studies conducted have shown that RGB LEDs with a relatively high CDI rating actually perform poorly when tested by a Farnsworth Munsell 100 Hue color discrimination test (Royer, Houser, & Wilkerson, 2012).

Chapter 7 - LED Color Preference Study

To investigate the relationship between CRI and LEDs, a preferential study was conducted between a sample of four LED lamps of equal CCT and an incandescent lamp of corresponding CCT. An incandescent lamp was chosen because it is the standard source used when trying to imitate a pure black body radiator. A survey was created to judge a direct comparison between the LED light sources and the incandescent light source.

Experimental Equipment

A double compartment illumination box was constructed where on one side an incandescent lamp was mounted on a light shelf which indirectly illuminated an observation portal which viewers observed from a distance of two feet. On the second portion of the illumination box a series of four test LED lamps were placed in a similar light shelf configuration where they were able to illuminate an observation portal concurrently with the reference portal.

The illumination box was constructed with a combination of 3/4" plywood and 1/8" white matte foam core board. Plywood was used on the base and side of the box to give it rigidity and stability; additionally, plywood was used to construct electrical chases within the box to conceal electrical boxes and wiring. White matte foam core was used as a substitute for 3/4" plywood to limit the weight of the illumination box and to allow for easy access to lamps for changing and modification purposes. Foam core pieces were attached to the plywood structure via adhesive white Velcro strips. All plywood surfaces which faced the interior of the illumination box were painted with three coats of matte white paint to reflect indirect light from the reference and test light sources. Dimensional characteristics and graphical diagrams for the construction of the illumination box can be seen in Appendix F.

Electrical wiring consisted of #12 AWG THHN solid copper wire and all lamps were connected in a parallel configuration so that each lamp could be switched on independently. A simplified graphical wiring diagram of the illumination box can be seen in Appendix E. All lamps utilized were 120V single phase E26 screw base lamps.

The lamps used for the experiment came from five separate manufacturers in order to diversify data sampling. Each lamp's technical specification can be seen in Table 7.1. Each of the lamps used were phosphor based LED lamps. In addition to the test lamps used was a single halogen reference lamp of 3000K and 100 CRI which all test lamps were rated against. The reference lamp had a higher initial lumen output (1490 lumens) than that of the test lamps. To address the luminance difference, diffusers were utilized on the reference lamp to lower the illuminance falling on the viewing plane of the reference portal to match the illuminance of the test lamps viewing plane. The use of lamps with the same CCT made comparison of their CRI ratings possible; additionally, multiple lamps were used to create trending results for LED lamps in general.

Lamp	Manufacturer	CRI	CCT	Lumens
1	Feit Electric	80	3000K	450
2	Lighting Science	82	3000K	450
3	Phillips	80	3000K	380
4	Sylvania	80	3000K	400
Reference	TCP	100	3000K	1490

Table 7.1: Experiment Lamps

Experiment Procedure

Forty observers, six females and thirty-four males, with an average age of 23 years and normal color vision were asked a series of questions pertaining to color appearance and preference when introduced to a series of color swatches illuminated by the four test lamps and the reference lamp. The color swatches used were of moderate saturation and included the following: red, orange, yellow, green, blue, and violet. The swatches used and their respective RGB values can be found in Appendix N. The color swatches used are spaced evenly in color space and represent the standard primary and secondary colors which human color vision may identify. Observers were asked to perform a series of four surveys asking the personal preferences on certain qualities of the color swatches appearance.

Participants were asked to rate the test lamps on a -5 to 5 scale with -5 representing a test lamp with a much worse color quality than the reference lamp and 5 having a much better color quality than the reference light. The -5 to 5 scale was utilized to minimize confusion on rating lamps for observers and its easier implementation into a Gaussian distribution of the sample population taken. In order to minimize participant bias towards any one lamp during the experiment, each test lamp was turned on in a randomized order between participants. The reference lamp remained on through the entirety of the experiment.

The first test asked the observer to compare the vividness (or saturation) of the color swatches in the test light viewing portal to that of the reference light viewing portal. The second and third tests performed asked observers to rate the color swatches in a similar manner but in terms of naturalness and overall preference, respectively. The last test performed differed from the first three by asking participants to choose their preference for each individual color under either the reference light source or the test light source. If the participant could not distinguish between the color appearance of either light source they were asked to indicate no difference. A sample version of the survey used can be seen in Appendix G.

Experiment Results and Discussion

Vividness

The results for the first test performed are shown in Figure 7.1 and Figure 7.2 where the vividness of the color swatches was rated in comparison to that of the reference lamp. From the figures shown it can be seen that all test lamps underperformed compared to the reference lamp in terms of vividness. This result is somewhat surprising as LED lamps tend to saturate colors over their incandescent counterparts. While methods were taken to explain the definition of what vividness is to the test participants, the possibility does exist that confusion for the exact meaning of vividness did occur during the experiment. Nonetheless, a dominant majority preferred the reference lamp over that of each test lamp.

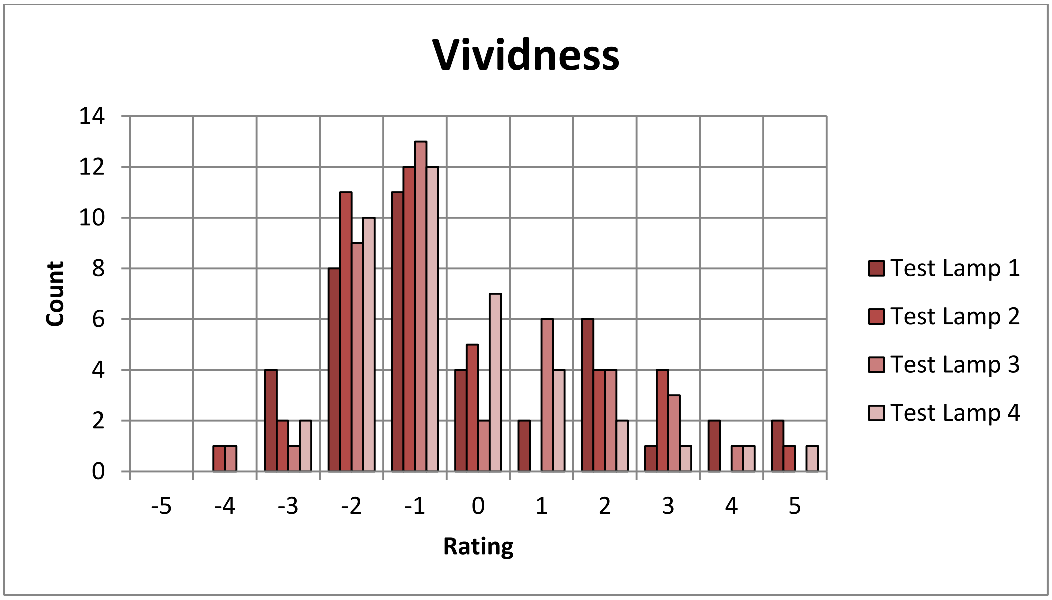


Figure 7.1: Vividness Bar Chart

It is worth noting that though the majority did favor the reference lamp, they did so only in a marginal dimension, that is their rating rarely exceeded a -2; moreover, a statistically significant number of observers still felt that the LED lamps were more vivid in some capacity.

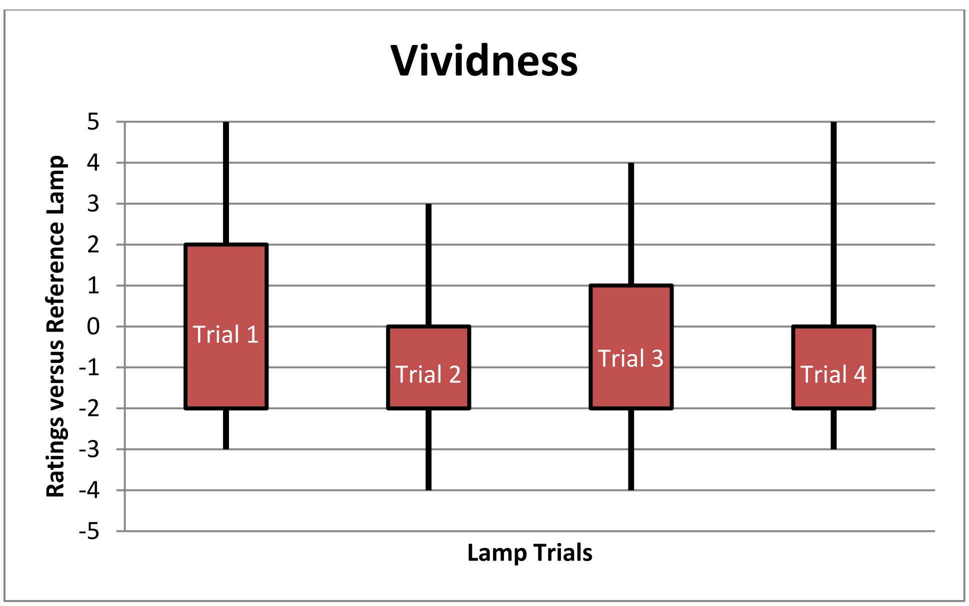


Figure 7.2: Vividness Box and Whisker Chart

Naturalness

The second test asked observers to rate which colors seemed more natural in appearance. The purpose of measuring the apparent natural appearance of the color swatches was to see if there was any significant correlation between how observers may expect colors to appear and how they prefer them to appear. From Figure 7.3 and Figure 7.4 it can be seen that a majority of observers felt that the LED test lamps gave a more natural appearance of the color swatches. Unfortunately, it is difficult discern whether natural appearance and preferential appearance had a direct relation to each other as data for overall color preference favored neither the LED test lamps or the reference lamp.

One possible reason for the dominant preference of the LED test lamps for natural appearance is how the lamp rendered cooler colors. The LED test lamps lack the stronger red component of the visual spectrum compared to the halogen reference lamp. This fact equates to stronger color appearance of cooler colors (such as blue and violet) when placed closely to the warm colors (such as red and orange). The cooler color appearance is thus resembling that of the cooler color temperature of natural daylight. It is worth investigating in further studies how the surrounding effects of color (in this experiment the white background of the viewing portal) change the preference towards natural appearance.

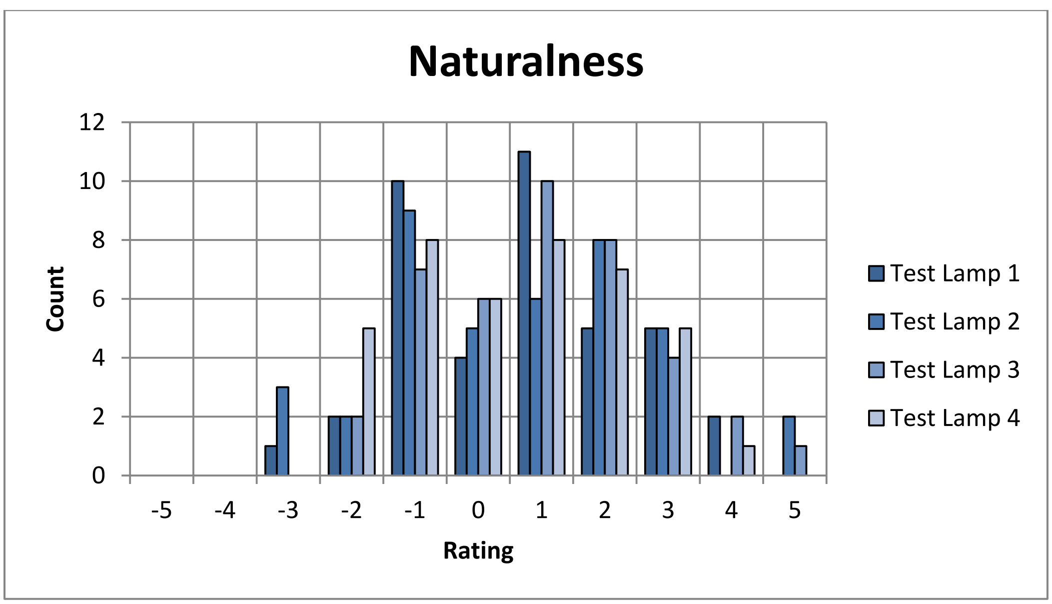


Figure 7.3: Naturalness Bar Chart

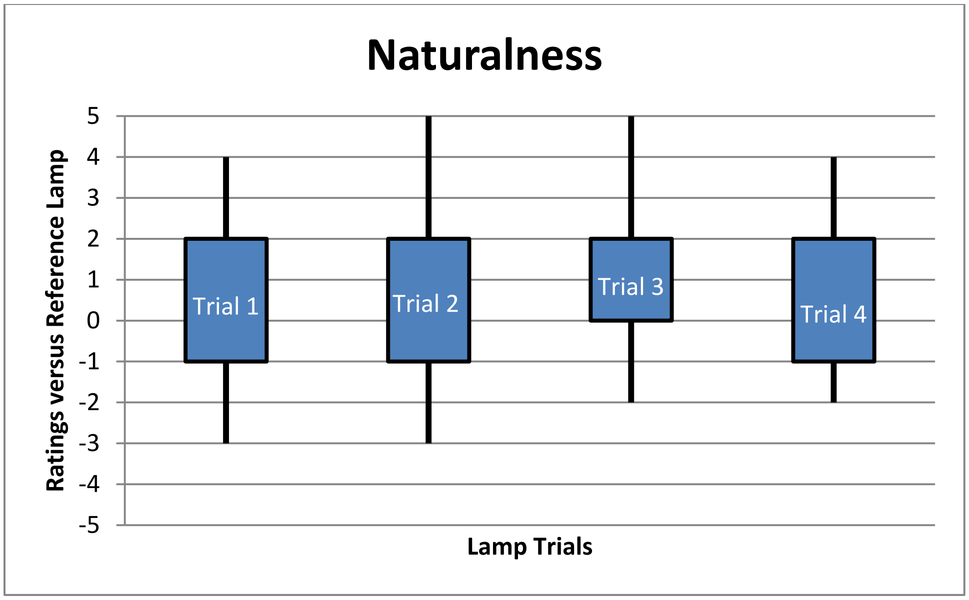


Figure 7.4: Naturalness Box and Whisker Chart

Overall Color Preference

The third test conducted during the experiment asked participants to give their overall preference of the colors in the illumination box. As shown in Figure 7.5 and Figure 7.6, the personal preference of observers favored neither the LED test lamps nor the reference lamp. There was relatively even distribution of preferences between both lighting technologies. Interestingly, the distribution of preferences resembles a Gaussian curve where the standard observer would have no preference over either light source. This observation is significant because LEDs have a considerably different CRI to that of incandescent source but are perceptually equal.

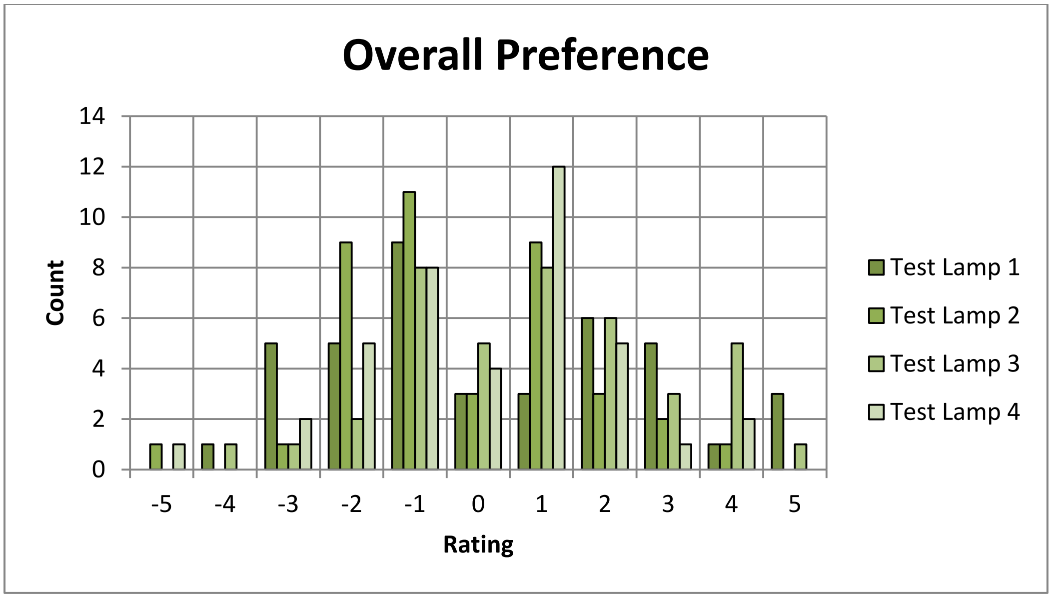


Figure 7.5: Overall Preference Bar Chart

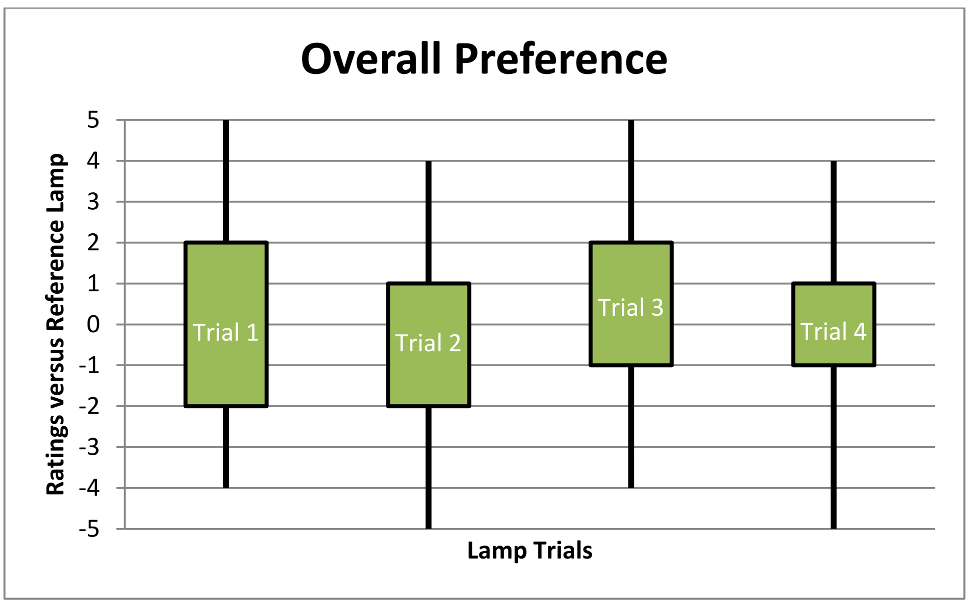


Figure 7.6: Overall Preference Box and Whisker Chart

Individual Color Preference

The final test conducted differed from the previous tests by asking participants to gauge between the reference lamp and a test lamp which individual colors had a better appearance. Participants were asked to choose the reference portal (A), the test viewing portal (B), or no perceptual difference (ND) when it came to each color. The results for each lamp are graphically shown in Figures 7.7 through 7.11.

Based on the figures shown it is apparent where LEDs are both lacking and succeeding in color appearance comparatively to that of incandescent light sources. In each test it was shown that the warm color components of the lighting spectrum were dominantly preferable under the reference source. This outcome is expected as LEDs that use a phosphor down conversion for the creation of white light lack intensity towards the red portion of the visible spectrum. Adding to this notion, it might be expected that the reference lamp would also be more favorable towards yellow because of warm appearance yet the opposite is true based on experiment results. This is also to be expected because of the down conversion process of the LED lamps (as discussed in Chapter 4). LEDs have a significant yellow component in their spectral power distribution and this is apparent when analyzing the survey preference results. The same is true for the preference of blue and violet as LEDs have a strong color component for those regions of the visible spectrum; however, upon closer inspection of the violet color preferences a certain level of ambiguity exists as a statistically significant number of observers had no preference towards either light source. This ambiguity towards light source preference for violet may exist because the sample color swatch used for violet is not actual violet but rather purple (purple has a red component to it while violet does not). With the lack of the red portion of the color spectrum present for the LED lamps, preference for violet (or rather purple) became harder to judge either way. The color green had no statistically significant preference towards either light source.

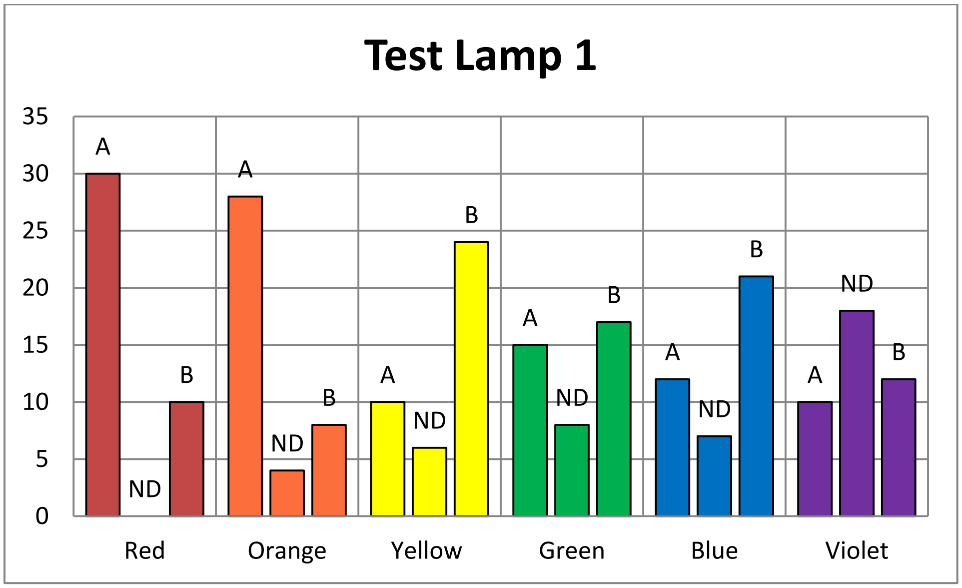


Figure 7.7: Test Lamp 1 Color Preference Bar Chart

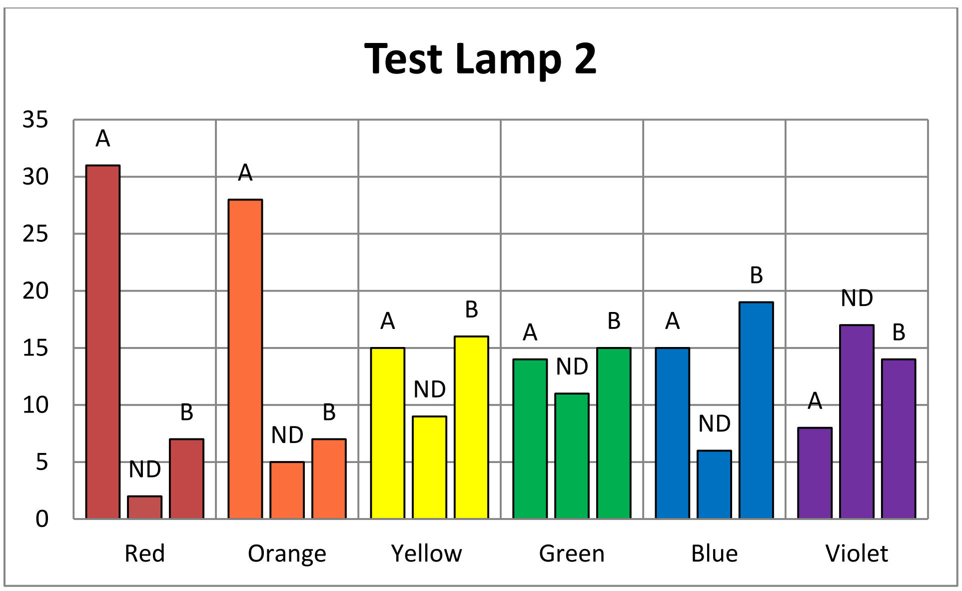


Figure 7.8: Test Lamp 2 Color Preference Bar Chart

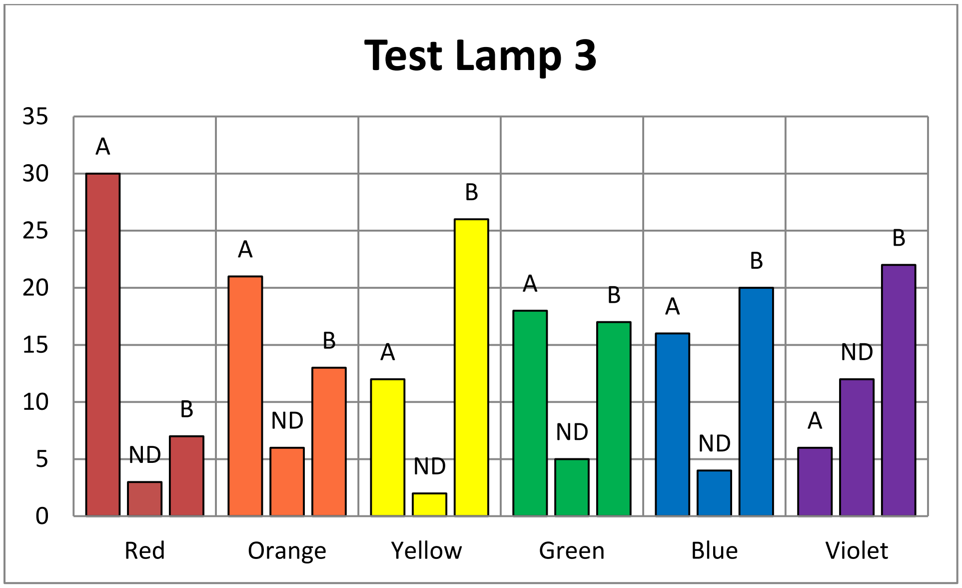


Figure 7.9: Test Lamp 3 Color Preference Bar Chart

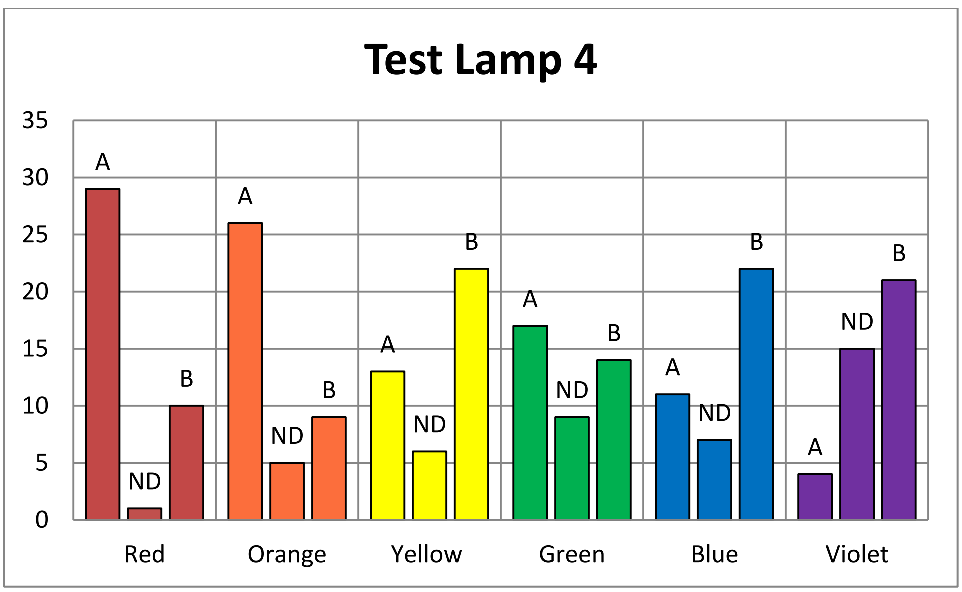


Figure 7.10: Test Lamp 4 Color Preference Bar Chart

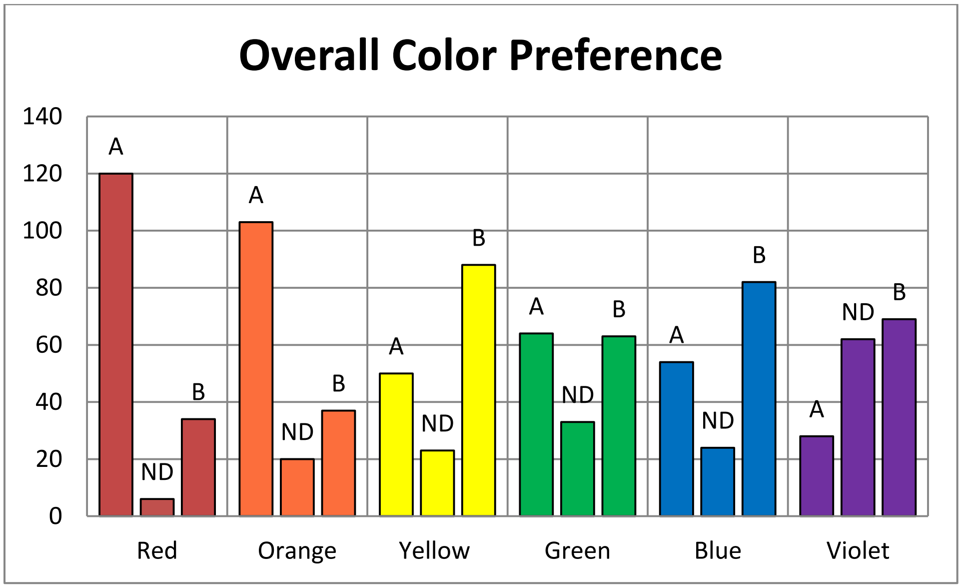


Figure 7.11: Overall Color Preference Bar Chart

Conclusion

After testing multiple LED light sources of significantly lower CRI than that of a halogen lamp it is apparent that the CRI is not an adequate way unto itself to judging overall lamp color quality. This finding is consistent with tests and recommendations which have been performed in the past.

The first three tests conducted in the experiment gauged the amount of preference that observers had for or against LED lamps in terms of vividness, naturalness, and overall preference. Through each test, no significant factor was apparently damaging to the color appearance of LEDs even though common convention of the CRI system would argue otherwise. The results from the experiment reinforces the idea that there is a disassociation between the objective nature of the CRI system and the subjective nature of human color preference; indeed, towards this end LED lamps in general expose the long lingering faults which have existed in the CRI system.

The fourth test conducted in the experiment reinforces how the CRI scale is outdated, yet it also demonstrates where LED lamps in general are lacking. Two color swatches (yellow and blue) appeared dominantly favorable under LED lamps while two others (purple and green) also created no perceptual color preference differentiation. These results are significant because they show that an LED lamp source with a lower CRI can create a more perceptually pleasing color than that of a lamp with a higher CRI. Alternatively, the results from the fourth test show how LEDs are still lacking when it comes to the red component of the color spectrum. LED lamps could significantly benefit from the addition of a red component of the visible spectrum as it would not only create more vibrant warm hues but also help the overall color rendering quality of the lamp. The simple addition of a red diode to a phosphor LED lamp could achieve this. Because a sort of ambiguity exists to which actual lamp type is better suited for color appearance from this test, the usefulness of another color quality scale (such as CQS) is substantiated. With multiple scales measuring various color properties of lamps, a more educated and well-rounded decision can be about lamp selection.

One takeaway from the test results is that in applications where specific color appearance is critical; LEDs may or may not be the proper choice for illumination. Where warm color tones such as red and orange are critical in appearance, LED lamps would not be the recommended lamp type to utilize; conversely, the opposite may be held true where blue and yellow color hues are most critical. Ultimately, where color appearance is a concern, a designer should always verify color quality with mock-up tests of a sample lamp in order to properly make a decision. It should be remembered that color preference can be highly subjective in nature and it is likely that no single metric will encompass everyone’s preference.

With the advancement of lighting technologies in recent decades it has become apparent that one metric for the measurement of color quality is not enough to substantiate the multidimensional nature of color. From a testing and reporting perspective, it would be beneficial to begin supplementing the CRI rating of lamps with additional information such as color saturation and gamut area (much like the CQS system); moreover, from a consumer perspective, the reporting of how individual primary and secondary colors appear under a given lamp on the box label (next to the CRI rating) would help better inform those purchasing lighting products.

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Appendix A - Normalized Cone Fundamentals

Wavelength (nm)	L-bar	M-bar	S-bar
390	0.00002	0.00002	0.00106
395	0.00006	0.00006	0.00331
400	0.00017	0.00019	0.01021
405	0.00047	0.00054	0.03046
410	0.00109	0.00129	0.07440
415	0.00220	0.00279	0.16005
420	0.00361	0.00496	0.27206
425	0.00521	0.00786	0.39165
430	0.00701	0.01148	0.51008
435	0.00993	0.01764	0.67209
440	0.01318	0.02478	0.82847
445	0.01657	0.03271	0.93380
450	0.02043	0.04170	1.00000
455	0.02441	0.05062	0.96909
460	0.03030	0.06364	0.94104
465	0.04031	0.08441	0.94219
470	0.05157	0.10658	0.85599
475	0.06480	0.13095	0.71961
480	0.07968	0.15669	0.56704
485	0.09673	0.18487	0.43766
490	0.11673	0.21627	0.32989
495	0.14660	0.26269	0.25818
500	0.18698	0.32355	0.20312
505	0.24042	0.40280	0.15183
510	0.30771	0.49898	0.10779
515	0.38608	0.60495	0.07874
520	0.46505	0.70623	0.05522
525	0.53604	0.78740	0.03770
530	0.60266	0.85538	0.02519
535	0.66084	0.90644	0.01656
540	0.72491	0.95729	0.01070
545	0.77751	0.98620	0.00685
550	0.81773	0.99359	0.00435
555	0.86356	1.00000	0.00275
560	0.89812	0.98187	0.00173
565	0.93566	0.96051	0.00110
570	0.96731	0.92005	0.00070
575	0.98689	0.86081	0.00044
580	0.99128	0.78103	0.00029
585	1.00000	0.70060	0.00018
590	0.99366	0.61693	0.00012
595	0.97105	0.52702	0.00008
600	0.92685	0.43457	0.00005

605	0.87753	0.35062	0.00003
610	0.81015	0.27552	0.00002
615	0.73424	0.21264	0.00002
620	0.65116	0.16022	0.00000
625	0.56913	0.11866	0.00000
630	0.48182	0.08731	0.00000
635	0.39975	0.06341	0.00000
640	0.32858	0.04542	0.00000
645	0.26491	0.03166	0.00000
650	0.20606	0.02253	0.00000
655	0.15711	0.01577	0.00000
660	0.11768	0.01080	0.00000
665	0.08668	0.00735	0.00000
670	0.06309	0.00508	0.00000
675	0.04533	0.00351	0.00000
680	0.03211	0.00242	0.00000
685	0.02242	0.00166	0.00000
690	0.01540	0.00113	0.00000
695	0.01072	0.00078	0.00000
700	0.00746	0.00054	0.00000
705	0.00518	0.00037	0.00000
710	0.00355	0.00026	0.00000
715	0.00243	0.00018	0.00000
720	0.00168	0.00012	0.00000
725	0.00116	0.00009	0.00000
730	0.00081	0.00006	0.00000
735	0.00056	0.00004	0.00000
740	0.00039	0.00003	0.00000
745	0.00028	0.00002	0.00000
750	0.00020	0.00002	0.00000
755	0.00014	0.00001	0.00000
760	0.00010	0.00001	0.00000
765	0.00007	0.00001	0.00000
770	0.00005	0.00000	0.00000
775	0.00004	0.00000	0.00000
780	0.00003	0.00000	0.00000

Table A.1: Computed Cone Fundamentals

Appendix B - Normalized Values for CIE 1932 2° Standard Observer

Wavelength (nm)	X	Y	Z
380	0.0014	0.0000	0.0065
385	0.0022	0.0001	0.0106
390	0.0042	0.0001	0.0201
395	0.0077	0.0002	0.0362
400	0.0143	0.0004	0.0679
405	0.0232	0.0006	0.1102
410	0.0435	0.0012	0.2074
415	0.0776	0.0022	0.3713
420	0.1344	0.0040	0.6456
425	0.2148	0.0073	1.0391
430	0.2839	0.0116	1.3856
435	0.3285	0.0168	1.6230
440	0.3483	0.0230	1.7471
445	0.3481	0.0298	1.7826
450	0.3362	0.0380	1.7721
455	0.3187	0.0480	1.7441
460	0.2908	0.0600	1.6692
465	0.2511	0.0739	1.5281
470	0.1954	0.0910	1.2876
475	0.1421	0.1126	1.0419
480	0.0956	0.1390	0.8130
485	0.0580	0.1693	0.6162
490	0.0320	0.2080	0.4652
495	0.0147	0.2586	0.3533
500	0.0049	0.3230	0.2720
505	0.0024	0.4073	0.2123
510	0.0093	0.5030	0.1582
515	0.0291	0.6082	0.1117
520	0.0633	0.7100	0.0783
525	0.1096	0.7932	0.0573
530	0.1655	0.8620	0.0422
535	0.2258	0.9149	0.0298
540	0.2904	0.9540	0.0203
545	0.3597	0.9803	0.0134
550	0.4335	0.9950	0.0088

555	0.5121	1.0000	0.0058
560	0.5946	0.9950	0.0039
565	0.6784	0.9786	0.0028
570	0.7621	0.9520	0.0021
575	0.8425	0.9154	0.0018
580	0.9163	0.8700	0.0017
585	0.9786	0.8163	0.0014
590	1.0263	0.7570	0.0011
595	1.0567	0.6949	0.0010
600	1.0622	0.6310	0.0008
605	1.0456	0.5668	0.0006
610	1.0026	0.5030	0.0003
615	0.9384	0.4412	0.0002
620	0.8545	0.3810	0.0002
625	0.7514	0.3210	0.0001
630	0.6424	0.2650	0.0001
635	0.5419	0.2170	0.0000
640	0.4479	0.1750	0.0000
645	0.3608	0.1382	0.0000
650	0.2835	0.1070	0.0000
655	0.2187	0.0816	0.0000
660	0.1649	0.0610	0.0000
665	0.1212	0.0446	0.0000
670	0.0874	0.0320	0.0000
675	0.0636	0.0232	0.0000
680	0.0468	0.0170	0.0000
685	0.0329	0.0119	0.0000
690	0.0227	0.0082	0.0000
695	0.0158	0.0057	0.0000
700	0.0114	0.0041	0.0000
705	0.0081	0.0029	0.0000
710	0.0058	0.0021	0.0000
715	0.0041	0.0015	0.0000
720	0.0029	0.0010	0.0000
725	0.0020	0.0007	0.0000
730	0.0014	0.0005	0.0000
735	0.0010	0.0004	0.0000
740	0.0007	0.0002	0.0000
745	0.0005	0.0002	0.0000
750	0.0003	0.0001	0.0000
755	0.0002	0.0001	0.0000

760	0.0002	0.0001	0.0000
765	0.0001	0.0000	0.0000
770	0.0001	0.0000	0.0000
775	0.0001	0.0000	0.0000
780	0.0000	0.0000	0.0000

Table B.1 (DiLaura, Houser, Misrtrick, & Steffy, 2011)

Appendix C - Calculated CIE 1932 2° Standard Observer Chromaticity Diagram Coordinates

Wavelength (nm)	*x*	*y*	*z*
380	0.1772	0.0000	0.8228
385	0.1705	0.0078	0.8217
390	0.1721	0.0041	0.8238
395	0.1746	0.0045	0.8209
400	0.1731	0.0048	0.8220
405	0.1731	0.0045	0.8224
410	0.1726	0.0048	0.8227
415	0.1720	0.0049	0.8231
420	0.1714	0.0051	0.8235
425	0.1703	0.0058	0.8239
430	0.1689	0.0069	0.8242
435	0.1669	0.0085	0.8246
440	0.1644	0.0109	0.8247
445	0.1611	0.0138	0.8251
450	0.1566	0.0177	0.8257
455	0.1510	0.0227	0.8263
460	0.1440	0.0297	0.8263
465	0.1355	0.0399	0.8246
470	0.1241	0.0578	0.8180
475	0.1096	0.0868	0.8036
480	0.0913	0.1327	0.7761
485	0.0688	0.2007	0.7305
490	0.0454	0.2950	0.6597
495	0.0235	0.4127	0.5638
500	0.0082	0.5384	0.4534
505	0.0039	0.6548	0.3413
510	0.0139	0.7502	0.2359
515	0.0389	0.8120	0.1491
520	0.0743	0.8337	0.0919
525	0.1142	0.8262	0.0597
530	0.1547	0.8058	0.0395
535	0.1929	0.7816	0.0255
540	0.2296	0.7543	0.0161

545	0.2658	0.7243	0.0099
550	0.3016	0.6923	0.0061
555	0.3374	0.6588	0.0038
560	0.3731	0.6244	0.0024
565	0.4087	0.5896	0.0017
570	0.4441	0.5547	0.0012
575	0.4788	0.5202	0.0010
580	0.5125	0.4866	0.0010
585	0.5448	0.4544	0.0008
590	0.5752	0.4242	0.0006
595	0.6029	0.3965	0.0006
600	0.6270	0.3725	0.0005
605	0.6482	0.3514	0.0004
610	0.6658	0.3340	0.0002
615	0.6801	0.3198	0.0001
620	0.6915	0.3083	0.0002
625	0.7006	0.2993	0.0001
630	0.7079	0.2920	0.0001
635	0.7141	0.2859	0.0000
640	0.7191	0.2809	0.0000
645	0.7230	0.2770	0.0000
650	0.7260	0.2740	0.0000
655	0.7283	0.2717	0.0000
660	0.7300	0.2700	0.0000
665	0.7310	0.2690	0.0000
670	0.7320	0.2680	0.0000
675	0.7327	0.2673	0.0000
680	0.7335	0.2665	0.0000
685	0.7344	0.2656	0.0000
690	0.7346	0.2654	0.0000
695	0.7349	0.2651	0.0000
700	0.7355	0.2645	0.0000
705	0.7364	0.2636	0.0000
710	0.7342	0.2658	0.0000
715	0.7321	0.2679	0.0000
720	0.7436	0.2564	0.0000
725	0.7407	0.2593	0.0000
730	0.7368	0.2632	0.0000
735	0.7143	0.2857	0.0000
740	0.7778	0.2222	0.0000
745	0.7143	0.2857	0.0000

750	0.7500	0.2500	0.0000
755	0.6667	0.3333	0.0000
760	0.6667	0.3333	0.0000

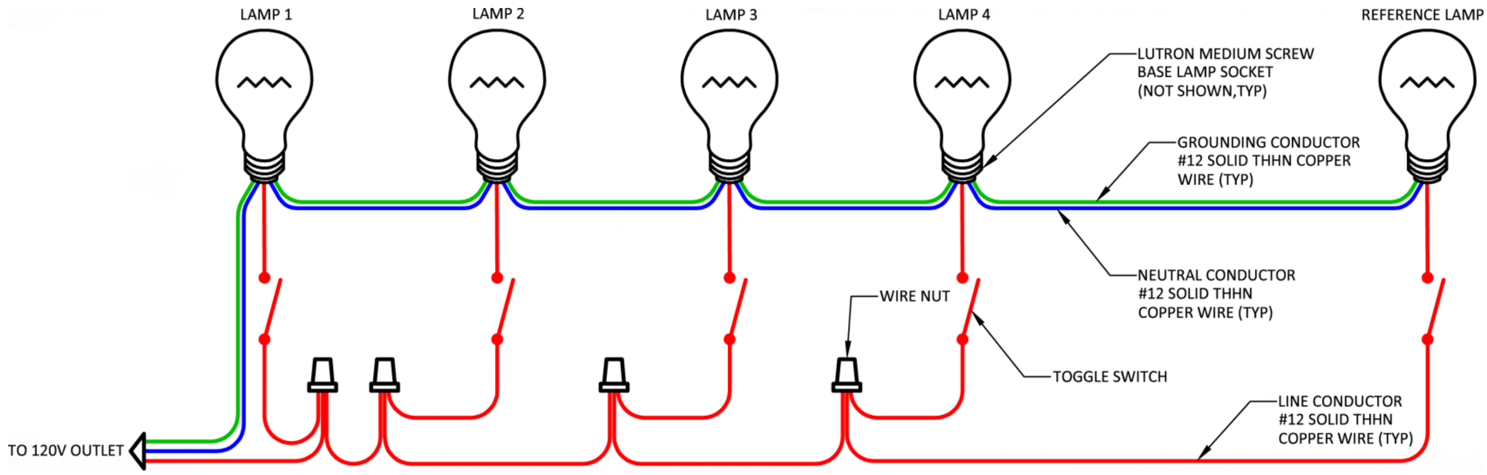
Table C.1 (DiLaura, Houser, Misrtrick, & Steffy, 2011)

Appendix D - Matlab Code for CIE Diagram

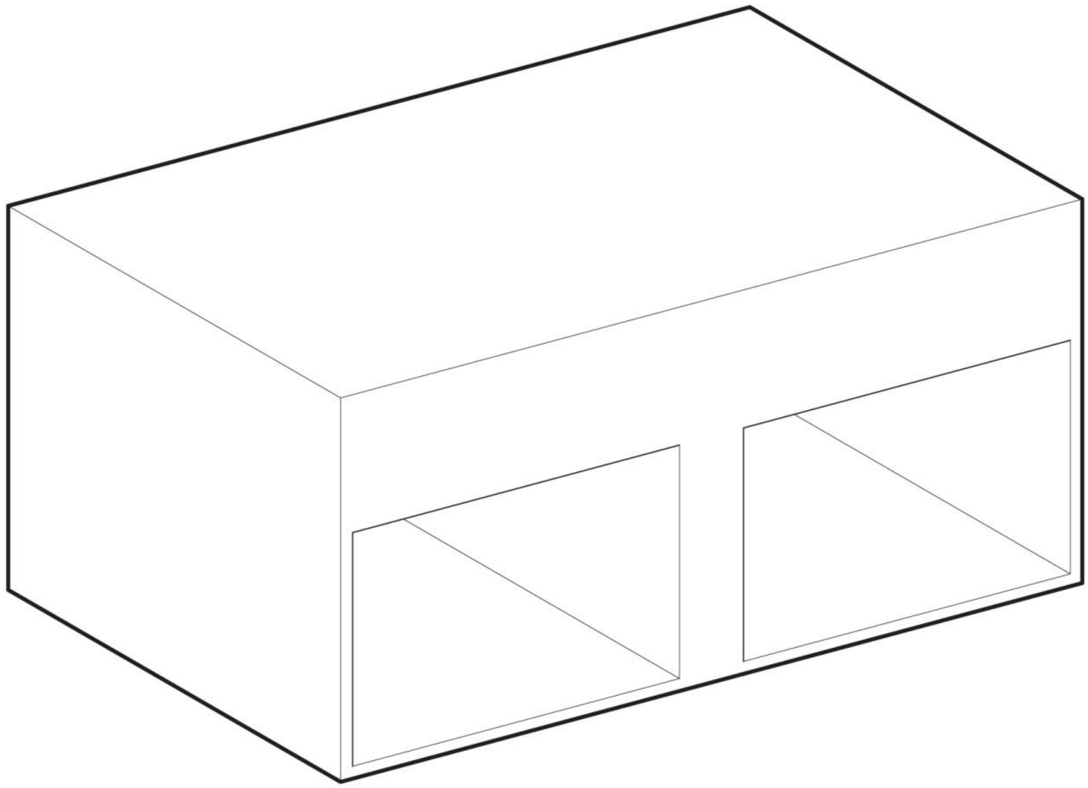
```
function CIE
clear all
close all
M = importdata('derp.txt', '\t')
i = M(:,1)
x = M(:,2)
y = M(:,3)
z = M(:,4)
length(z)

h1 = figure
hold on
%h = scatter3(x,z,y,20.,i,'filled'), view(-60,60)
h = color_line3(x,z,y,i,'Linewidth', 4)
%h = color_line3([x(77), x(1)], [z(77), z(1)], [y(77),y(1)], [i(77), i(1)])
view(40,35)
% set(get(h,'Parent'), 'YScale', 'log')
set(gca,'FontSize',16)
axis square
ylabel( 'z','fontsize',16, 'interpreter', 'latex')
xlabel('x','fontsize',16,'interpreter', 'latex')
zlabel('y','fontsize',16)
get(h)
```

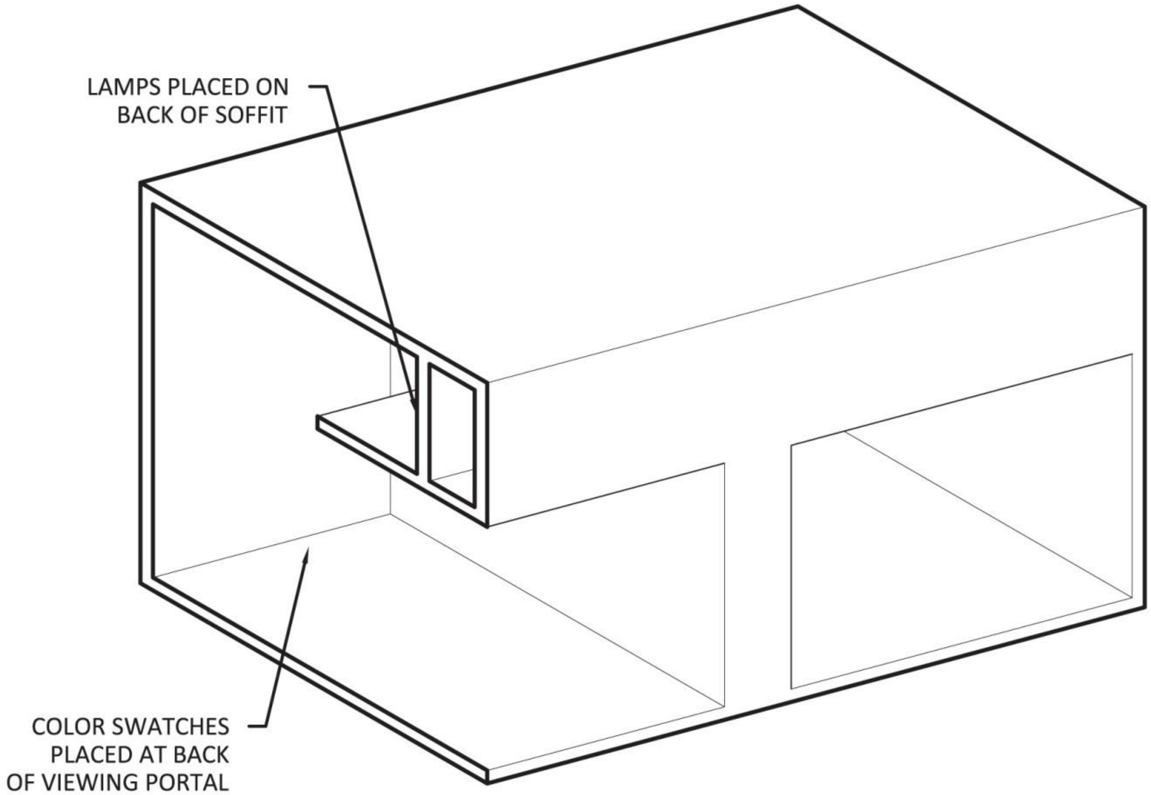
Appendix E - Wiring Diagram



Appendix F - Color Rendering Station

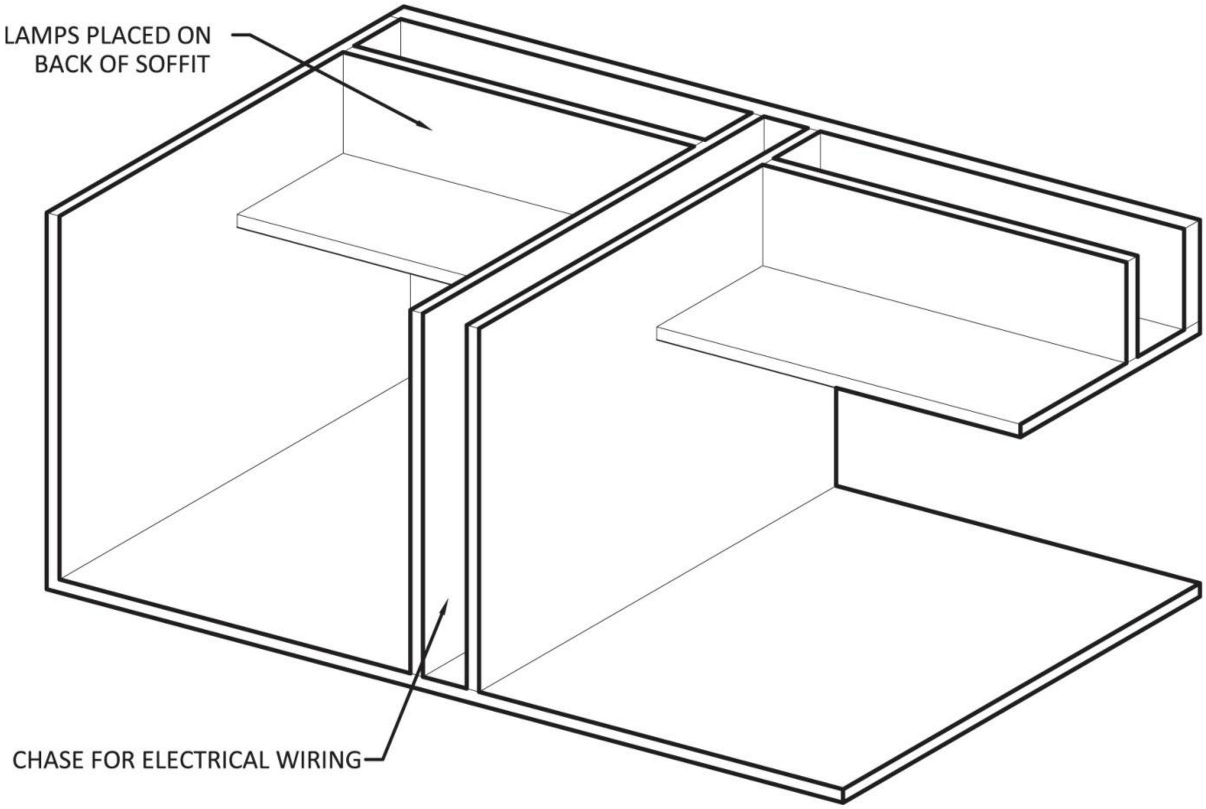


01 FRONT PERSPECTIVE
SCALE: 1" = 1'-0"



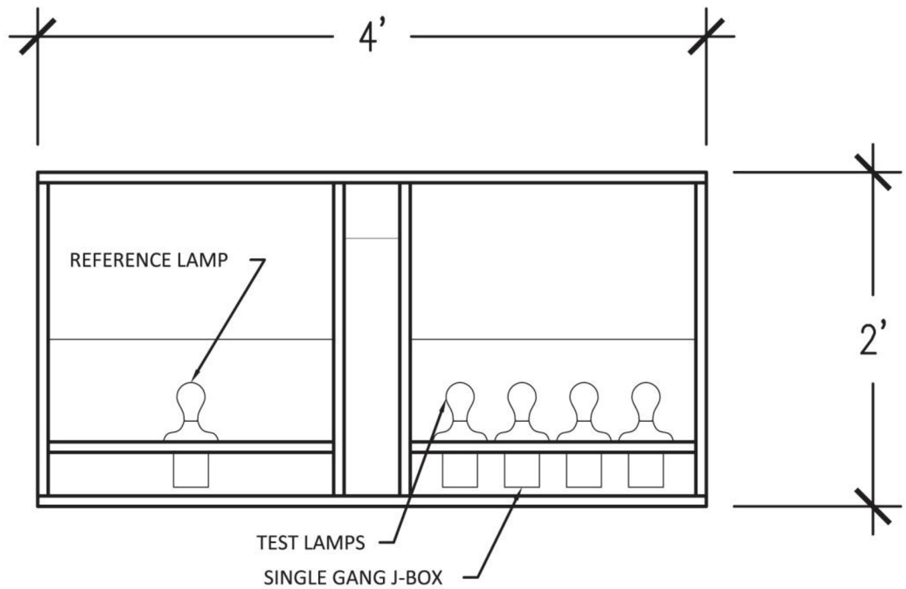
02 FRONT SECTION PERSPECTIVE

SCALE: 1" = 1'-0"

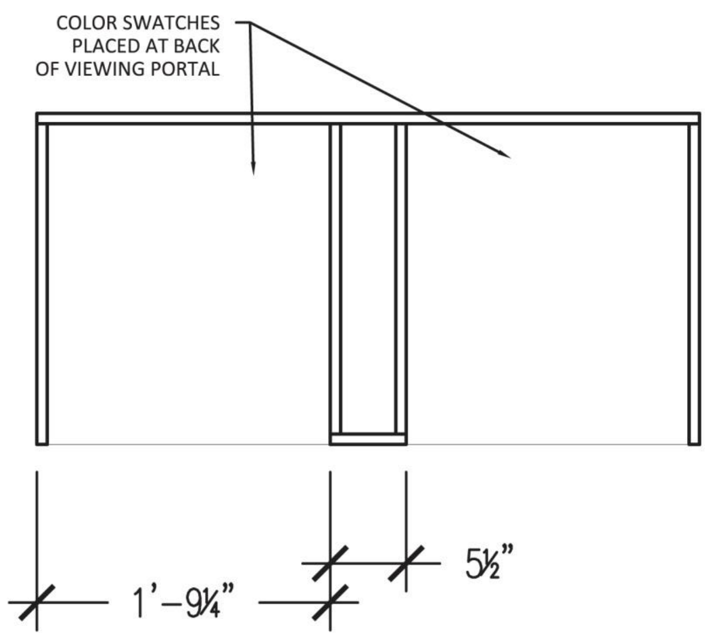


03 REAR SECTION PERSPECTIVE

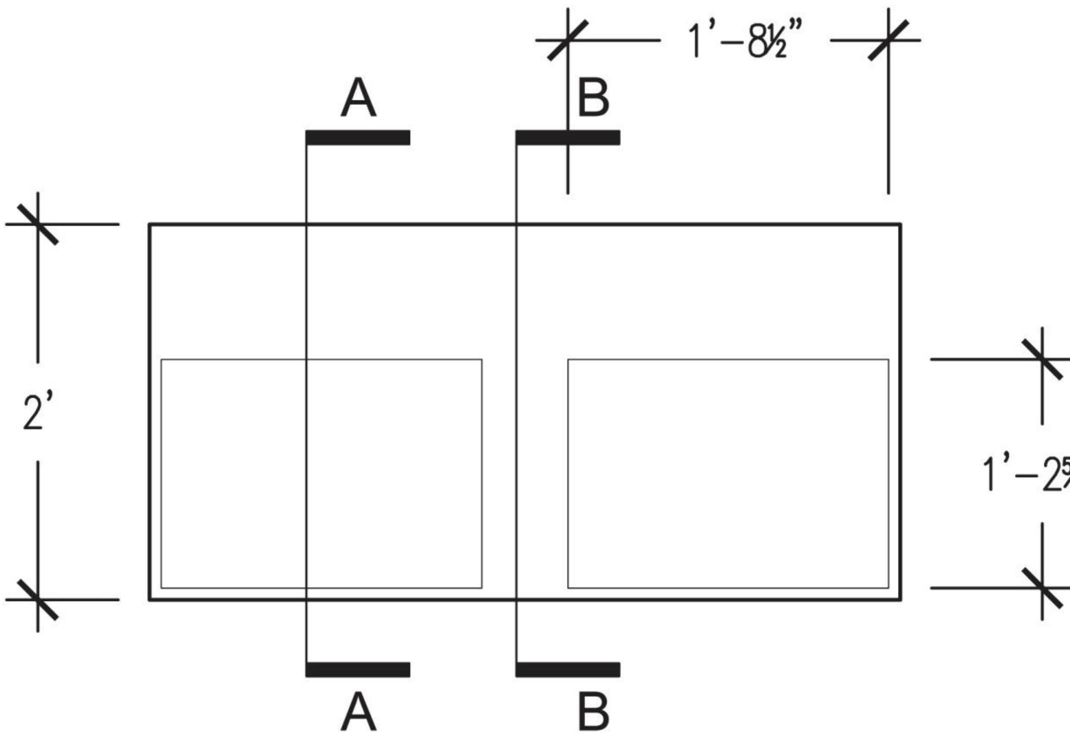
SCALE: 1" = 1'-0"



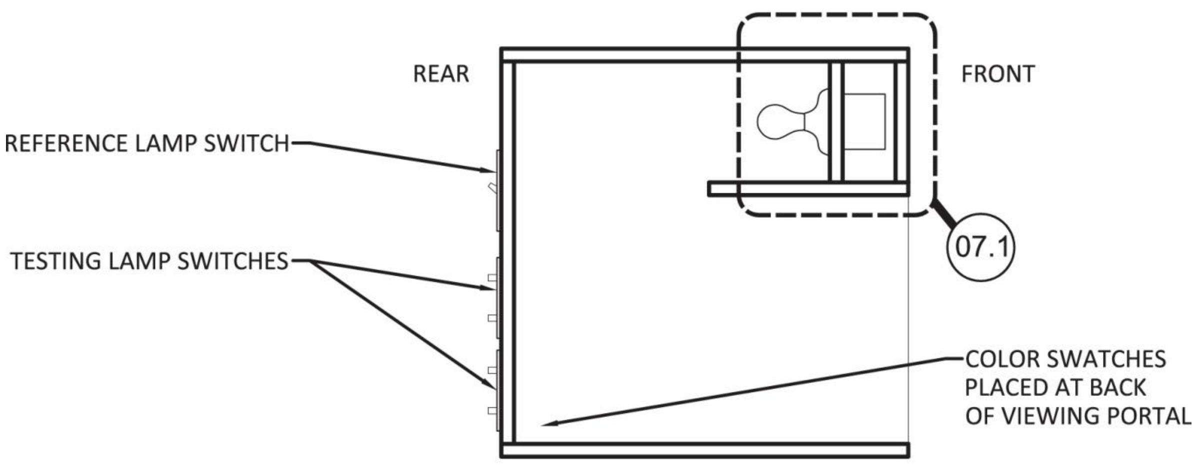
04 PLAN AT 20" ABOVE TABLE TOP
SCALE: 1" = 1'-0"



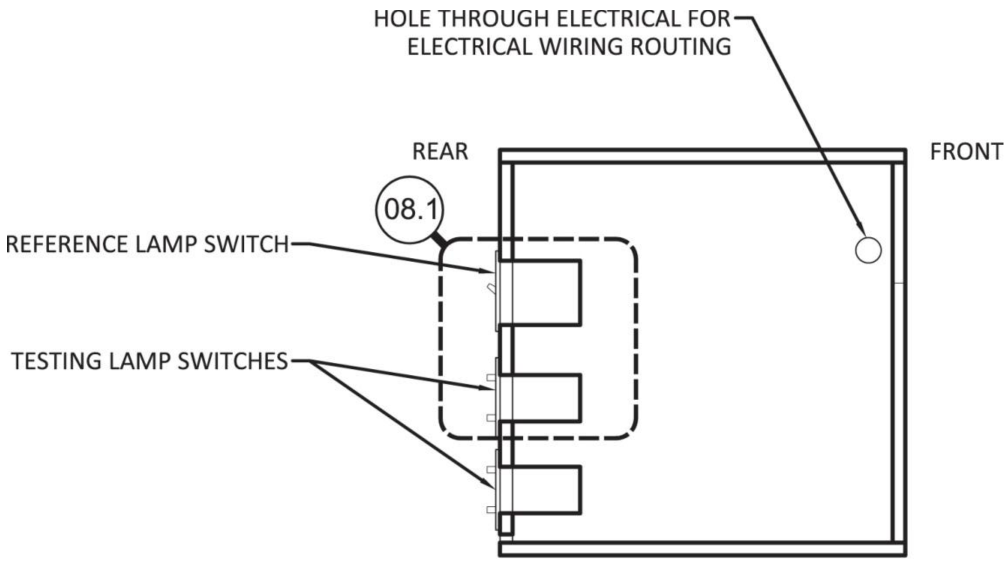
05 PLAN AT 6" ABOVE TABLE TOP
SCALE: 1" = 1'-0"



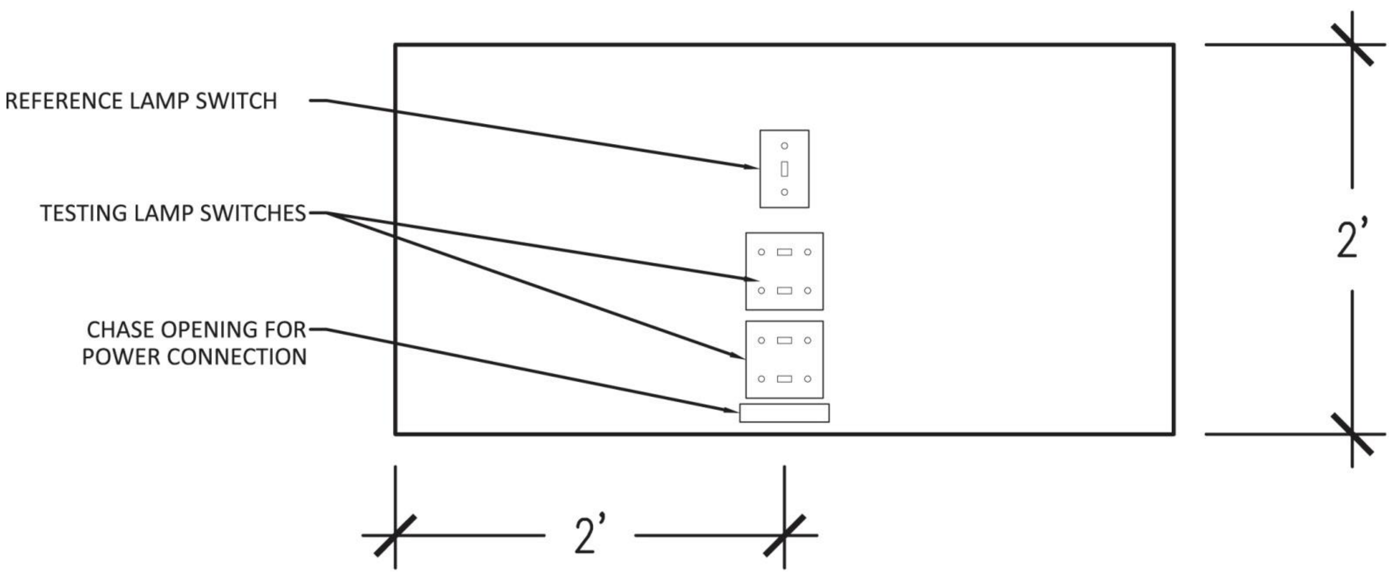
06 FRONT ELEVATION
SCALE: 1" = 1'-0"



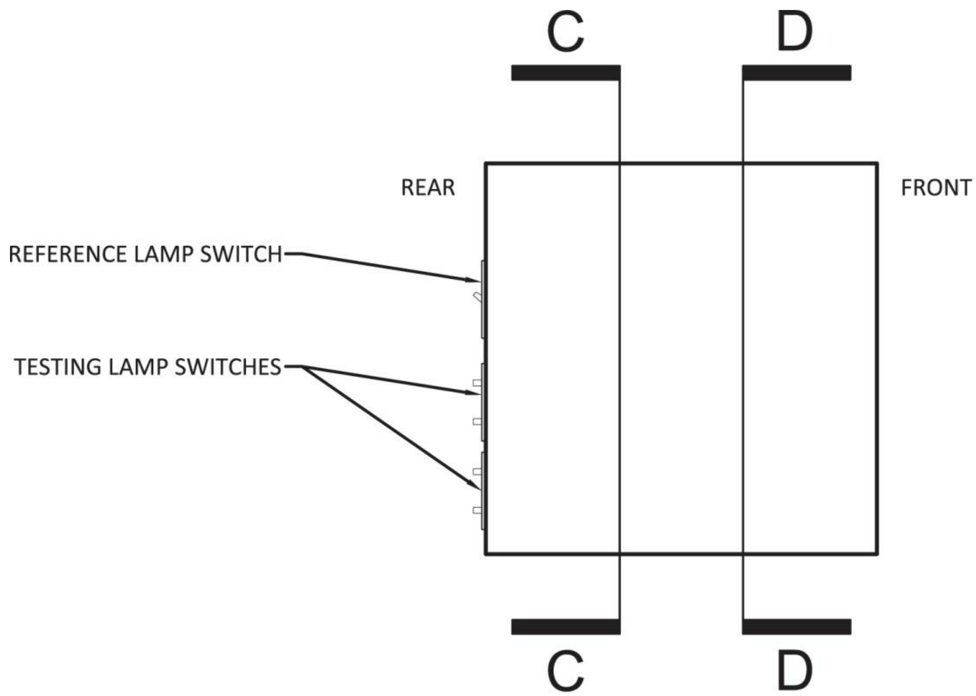
07 SECTION A-A
SCALE: 1" = 1'-0"



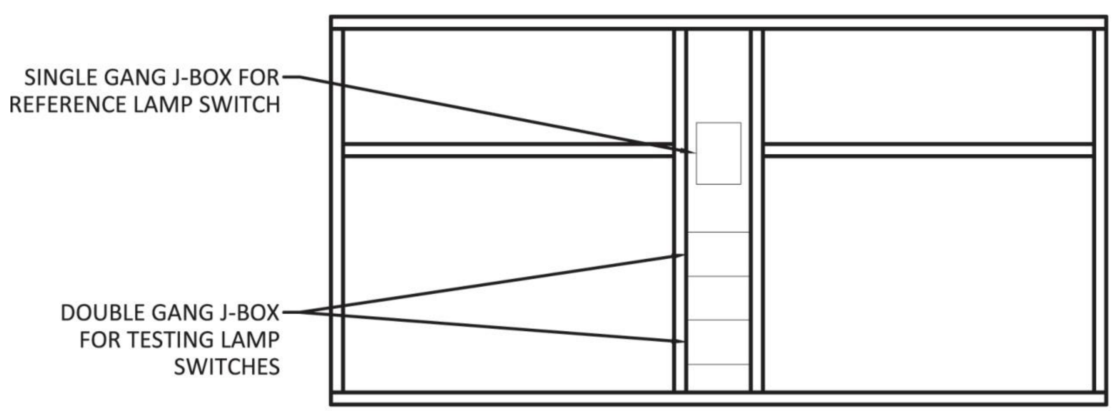
08 SECTION B-B
SCALE: 1" = 1'-0"



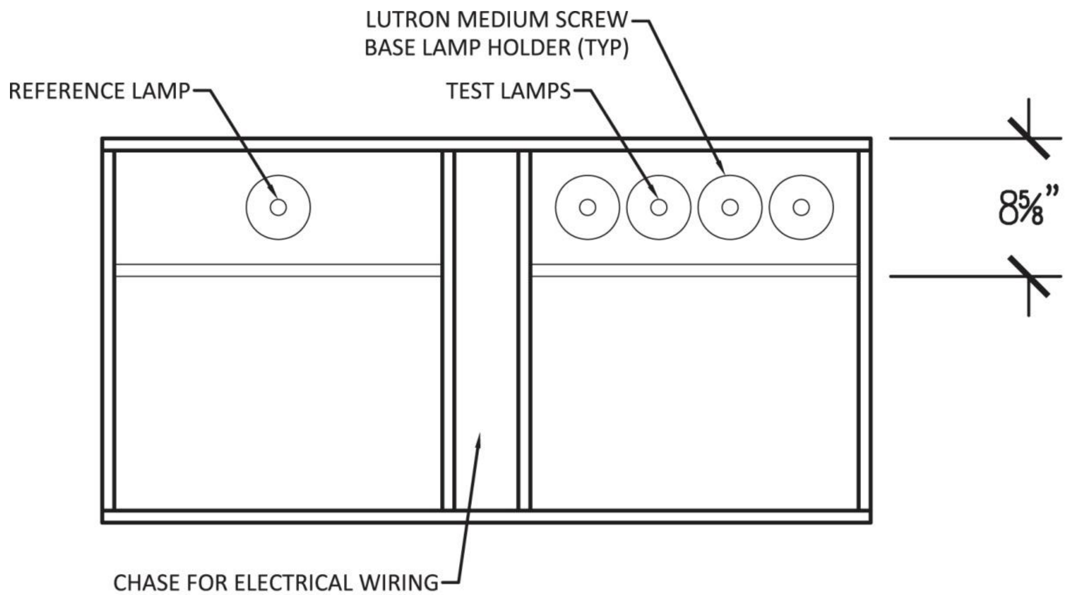
09 REAR ELEVATION
SCALE: 1" = 1'-0"



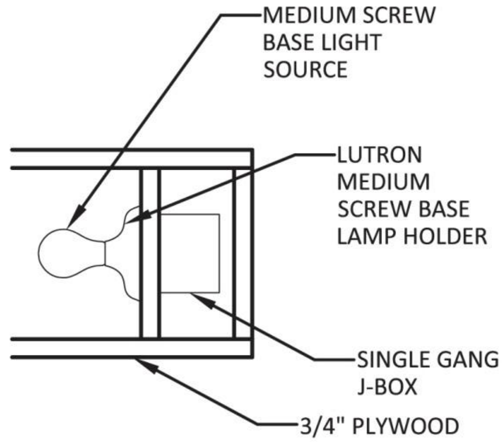
10 SIDE ELEVATION
SCALE: 1" = 1'-0"



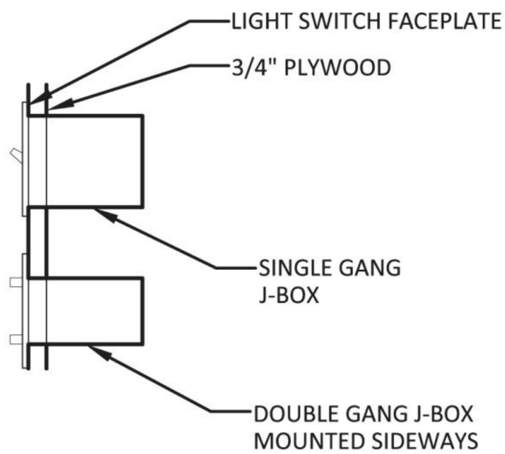
11 SECTION C-C
SCALE: 1" = 1'-0"



12 SECTION D-D
SCALE: 1" = 1'-0"



13 DETAIL 07.1
SCALE: 1-1/2" = 1'-0"



14 DETAIL 08.1
SCALE: 1-1/2" = 1'-0"

Appendix G - Color Preference Survey

Color Preference Survey

The purpose of this survey is to model a correlation between light source CRI and human color preference.

Please indicate the following:

Gender: Male or Female

Age: ________________

You are asked rate the light in the viewport B against the light source in viewport A on a -5 to 5 scale (-5 being the worst and 5 being the best) in terms of various color qualities outline below in a series of test.

TEST 1: Please rate the **VIVIDNESS** (saturation) of the lights in portal B compared to portal A.

Test 1, Trial 1

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

Test 1, Trial 2

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

Test 1, Trial 3

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

Test 1, Trial 4

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

TEST 2: Please rate the **NATURALNESS** (appearance in nature) of the lights in portal B compared to portal A.

Test 2, Trial 1

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

Test 2, Trial 2

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

Test 2, Trial 3

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

Test 2, Trial 4

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

TEST 3: Please rate the **OVERALL QUALITY** of the lights in portal B compared to portal A.

Test 3, Trial 1

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

Test 3, Trial 2

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

Test 3, Trial 3

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

Test 3, Trial 4

Worst					No Difference					Best
-5	-4	-3	-2	-1	0	1	2	3	4	5

TEST 4: Please choose which **INDIVIDUAL COLORS** appear more favorable under light source A or B. If no difference is apparent, choose no difference (ND).

Test 4, Trial 1

Source	Red	Orange	Yellow	Green	Blue	Violet
A						
ND						
B						

Test 4, Trial 2

Source	Red	Orange	Yellow	Green	Blue	Violet
A						
ND						
B						

Test 4, Trial 3

Source	Red	Orange	Yellow	Green	Blue	Violet
A						
ND						
B						

Test 4, Trial 4

Source	Red	Orange	Yellow	Green	Blue	Violet
A						
ND						
B						

Appendix H - Survey Results – Quantities

Vividness											
	-5	-4	-3	-2	-1	0	1	2	3	4	5
1	0	0	4	8	11	4	2	6	1	2	2
2	0	1	2	11	12	5	0	4	4	0	1
3	0	1	1	9	13	2	6	4	3	1	0
4	0	0	2	10	12	7	4	2	1	1	1
Naturalness											
	-5	-4	-3	-2	-1	0	1	2	3	4	5
1	0	0	1	2	10	4	11	5	5	2	0
2	0	0	3	2	9	5	6	8	5	0	2
3	0	0	0	2	7	6	10	8	4	2	1
4	0	0	0	5	8	6	8	7	5	1	0
Overall Preference											
	-5	-4	-3	-2	-1	0	1	2	3	4	5
1	0	1	5	5	9	3	3	6	5	1	3
2	1	0	1	9	11	3	9	3	2	1	0
3	0	1	1	2	8	5	8	6	3	5	1
4	1	0	2	5	8	4	12	5	1	2	0

		Red	Orange	Yellow	Green	Blue	Violet
1	A	30	28	10	15	12	10
	ND	0	4	6	8	7	18
	B	10	8	24	17	21	12
2	A	31	28	15	14	15	8
	ND	2	5	9	11	6	17
	B	7	7	16	15	19	14
3	A	30	21	12	18	16	6
	ND	3	6	2	5	4	12
	B	7	13	26	17	20	22
4	A	29	26	13	17	11	4
	ND	1	5	6	9	7	15
	B	10	9	22	14	22	21
Totals	A	120	103	50	64	54	28
	ND	6	20	23	33	24	62
	B	34	37	88	63	82	69

Appendix I - Cut Sheet, Test Lamp 1

FEIT ELECTRIC

LED LAMP SPECIFICATIONS

Applications
Table Lamps
Floor Lamps
Ceiling Fans
Wall Sconces

Benefits
Full Range Dimming
Energy Efficient: Up to 80% Less Energy than Standard Incandescent
No Ultraviolet - Safe for Artwork
Color Consistency
Low Heat
Durable
Long Life

Features
Dimmable
Instant On To Full Brightness
100% Direct Replacement
Energy Star Approved
UL/CUL Listed
Dry Location Rated
FCC Compliant
RoHS Compliant
100% Mercury Free
3 Year Warranty
Warm White

Specifications	
ITEM NUMBER	**A19/OM450/LED**
INPUT POWER (WATTS)	7.5
INCANDESCENT EQUIVALENT (WATTS)	40
INPUT LINE VOLTAGE	120
BASE TYPE	E26 (Medium)
LUMENS	450
LUMEN EFFICACY (LPW)	60
CCT	3000K
CRI	>80
BEAM ANGLE	300°
MOL	4.5"
DIAMETER	2.5"
RATED LIFE HOURS	25000
POWER FACTOR	>.70
INPUT LINE FREQUENCY (Hz)	60
MILLIAMPS (mA)	98
NUMBER OF LEDS	18
LED CHIP	SSC
MINIMUM STARTING TEMPERATURE	-4°F

Feit Electric Company   4901 Gregg Rd. Pico Rivera, CA 90660   Tel. 562-463-2852   www.feit.com

Appendix J - Cut Sheet, Test Lamp 2

LightingScience
Welcome to the Light Ages

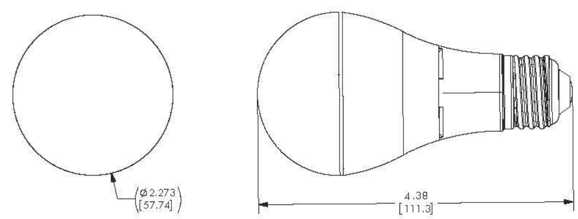
DEFINITY™ GP19

FEATURES[1]

L70 lumen depreciation design criteria	Up to 50,000 hours Based on usage.
Housing	Aluminum / Plastic
Socket	E26
Operating Temperature	-20°C to +40°C
MOL	4.38 in, 111.30mm
Voltage	120V
Weight	3.8 oz., 108g
Power Factor	≥.90
Warranty	5 year limited

BENEFITS

- Dimmable to 5% of light on most dimmers.[2]
- RoHS compliant – contains no mercury or lead.



Specifications supplied are nominal. Please refer to the DOE's Lighting Facts Tolerance Guidelines.
[1] Values are nominal, advances from further innovation, specifications are subject to change.
[2] See dimmer compatibility chart page on next page.

NAFTA COMPLIANT
This product qualifies as an originating good under the terms of NAFTA.

ORDERING INFORMATION \\ DFN 19 40WE WW 120

Family		Product		Wattage Equivalency		Color (CCT)		Voltage	
DFN	Definity	**19**	DFN19	**40WE**	40 Watt Equivalent	**W27**	Warm White 2700K	**120**	120 Volt
						WW	Warm White 3000K		
						NW	Neutral White 4000K		
						CW	Cool White 5000K		

NORTH AMERICAN CERTIFICATIONS

RoHS COMPLIANT · Intertek · FC

ENVIRONMENT

DRY

LightingScience

SCD-00013 DFN 19_REV C

877-999-5742 | www.lsgc.com
1227 South Patrick Drive | Satellite Beach, FL 32937

GP19

DIMMER CAPABILITIES

LUTRON DIMMERS:
Diva: DVCL-153PD, DVW-603-PGH
Skylark: CTCL-153PDH, S-600PR
Lumea: LG-103PH, LGCL-153PH
Toggle R: TGCL I53PH

GP19[1]

Part Number	Base Type	Wattage	Lumens	Voltage	Efficacy	CRI
DFN 19 40WE NW 120	E26	6W	470	120	78	82
DFN 19 40WE WW 120	E26	6W	450	120	75	82
DFN 19 40WE W27 120	E26	6W	450	120	75	82
DFN 19 40WE CW 120	E26	6W	480	120	80	82

NW: Neutral White **WW:** Warm White **W27:** Warm White 2700K **CW:** Cool White

Recommended number of lamps per 600 watt dimmer[2]

While an LED lamp may draw as few as 10 watts continuously, it could have an in-rush current spike (maximum, instantaneous input) which may limit the number of lamps you can install on one dimmer. The following table provides a recommended maximum quantity of DEFINITY lamps that should be used on a typical approved 600W dimmer.

Ex: Max number of A19 60W lamps, with an 80W in-rush, that can be used on 600W dimmer = 7

DFN LED Lamp	Lamp In-Rush Current Equivalent	Max # of Lamps per 600W Dimmer
A19 40 W	80 W	7
A19 60 W	80 W	7

Visit www.lsgc.com/energystar for list of ENERGY STAR qualified lamps.

Specifications supplied are nominal. Please refer to the DOE's Lighting Facts Tolerance Guidelines.
[1] Values are nominal, advances from further innovation, specifications are subject to change.

CAUTIONS

- Turn power off before inspection, installation, or removal.
- Risk of Electric Shock – Use in dry locations only. Do not use where directly exposed to water or weather.
- Do not open – no user serviceable parts inside.
- North America use on 120VAC, 50 - 60 Hz circuits.
- This device is not intended for use with emergency exit fixtures or emergency exit lights.
- This device complies with Part 15 of the FCC rules and has been tested and found to comply with the limits for a Class B digital device. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. Any changes or modifications not expressly approved by the manufacturer could void the user's authority to operate the equipment.

877-999-5742 | www.lsgc.com
1227 South Patrick Drive | Satellite Beach, FL 32937

Appendix K - Cut Sheet, Test Lamp 3

2013, January 8
data subject to change

Highlight with dimmable LED retrofit downlighting

PAR20 Indoor Flood LED

Philips PAR20 Dimmable LED lamps bring innovation to familiar applications and deliver excellent dimming performance.

Benefits

- Saves 43 watts of energy when compared to a 50W halogen PAR20**
- Long life properties-- lowers maintenance costs by reducing re-lamp frequency
- Will not fade colors, avoids inventory spoilage
- Contains no mercury
- Emits virtually no UV/IR light in the beam
- 3-year or 5-year limited warranty depending upon operating hours

Features

- 25,000-hour rated average life+
- Smooth dimming to 10% of full light levels*
- Projects a 25° beam angle
- Instant-on light

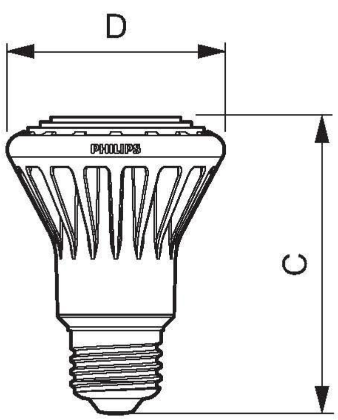
LED

PHILIPS
sense and simplicity

Related products

7W, PAR20, Dimmable

Dimensional drawing



7PAR20/END/F25 4000 DIM 6/1

Product	C (Norm)	D (Norm)
LED 7W CW 4050K 120V PAR20 Dimmable	-	-
LED 7W 2700K 120V PAR20 25D DIM	-	-
LED 7W E26 3000K 120V PAR20 25D DIM	-	-

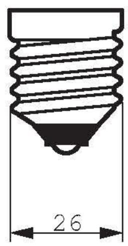
General Characteristics

Product number	Full product name	Cap-Base	Bulb	Rated Avg. Life (Hours)
410100	7PAR20/END/F25 4000 DIM 6/1	-	PAR20	45000 hr
418574	7PAR20/END/F25 2700 DIM 6/1	E26	PAR20	45000 hr

Product number	Full product name	Cap-Base	Bulb	Rated Avg. Life (Hours)
418582	7PAR20/END/F25 3000 DIM 6/1	E26	PAR20	45000 hr

2013, January 8
data subject to change

Installation diagrams



E26

Light Technical Characteristics

Product number	Full product name	Color Code	Beam Angle	Beam Description	Approx. MBCP	CRI	Color Temp. (Kelvin)	Rated Luminous Flux
410100	7PAR20/END/F25 4000 DIM 6/1	CW	25 D	25D	1200 cd	-	4050 K	285 Lm
418574	7PAR20/END/F25 2700 DIM 6/1	WW	25 D	-	1300 cd	80	2700 K	310 Lm
418582	7PAR20/END/F25 3000 DIM 6/1	WH	25 D	-	1300 cd	80	3000 K	310 Lm

Electrical Characteristics

Product number	Full product name	Wattage	Voltage	Line Frequency	Dimmable
410100	7PAR20/END/F25 4000 DIM 6/1	7 W	120 V	-	Yes
418574	7PAR20/END/F25 2700 DIM 6/1	7 W	120 V	60 Hz	Yes

Product number	Full product name	Wattage	Voltage	Line Frequency	Dimmable
418582	7PAR20/END/F25 3000 DIM 6/1	7 W	120 V	60 Hz	Yes

www.philips.com/lighting

2013, January 8
data subject to change

Appendix L - Cut Sheet, Test Lamp 4

www.sylvania.com/ledr

ULTRA LED PAR20 Lamps
Dimmable

Key Features & Benefits

- Dimmable to 10%*
- Rated at 25,000 hours life (L_{70})
- Available in 2700K and 3000K color temperature
- Medium base
- RoHS compliant
- UV, IR and Mercury free

* Performance may vary depending on dimmer used in application. Please refer to Compatible Dimmer List (RETRO-DIM) for a list of compatible dimmers or visit www.SYLVANIA.com/ledr

LED technology offers reduced energy and maintenance costs when compared with conventional light sources. Lasting 10 times longer and using only 8 watts, LED PAR20 lamps are a high-quality replacement for 35W halogen PAR20 lamps. They are free of UV and IR radiation, minimizing discoloration and fading of materials. These lamps are rated at 25,000 hours with a correlated color temperature (CCT) of 2700K or 3000K. Both color temperatures are available with 25° and 36° beam angles.

This device complies with part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation. For FCC Part 15 user information, please see www.sylvania.com/fcc15b.

Product Offering

Ordering Abbreviation	Wattage (W)	Color Temperature	Beam Angle	Lumens
LED8PAR20/DIM/827/NFL25	8	2700K	25°	320
LED8PAR20/DIM/827/FL36	8	2700K	36°	320
LED8PAR20/DIM/H/830/NFL25	8	3000K	25°	400
LED8PAR20/DIM/H/830/FL36	8	3000K	36°	400

Application Information

Market Segments

- Art galleries and museums
- Hospitality
- Residential
- Retail

Applications

- Accent/display lighting
- Recessed downlighting
- Track lighting

Application Notes

1. UL 1993 listed
2. Operating temperature range between -40°F and +113°F (-40°C and +45°C)
3. Suitable for use in damp locations when used in a UL rated fixture where protected from the weather.
4. Suitable for dimmers or in luminaires controlled by a dimmer
5. Not intended for use with emergency light fixtures or exit lights
6. Not to be used in enclosed fixtures
7. Not to be used in enclosed insulated ceilings

SEE THE WORLD IN A NEW LIGHT SYLVANIA

RETRO049R2 6/12

Specification Data

Catalog #	Type
Project	
Comments	
Prepared by	

Ordering Information

Item Number	Ordering Abbreviation	Wattage (W)	Base Type	Input Voltage (VAC)	Average Rated Life (hrs.)[1]	Typical Lumens (lm)[2]	CCT[3]	CBCP (cd)	Beam Angle	CRI[4]	Power Factor
78802*	LED8PAR20/DIM/H/830/NFL25	8	Medium	120	25,000	400	3000K	2000	25°	85	0.9
78803*	LED8PAR20/DIM/H/830/FL36	8	Medium	120	25,000	400	3000K	675	36°	85	0.9
78653	LED8PAR20/DIM/827/NFL25	8	Medium	120	25,000	320	2700K	1150	25°	85	0.94
78654*	LED8PAR20/DIM/827/FL36	8	Medium	120	25,000	320	2700K	670	36°	85	0.94

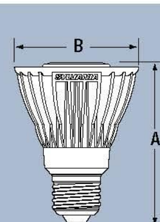
*ENERGY STAR® qualified
1. Hours lifetime with 70% lumen maintenance 2. Thermally stable typical lumens (±10%)
3. Thermally stable typical CCT (±10%) 4. CRI – Color Rendering Index

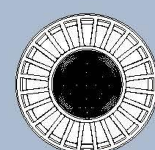
Ordering Guide

LED	8	PAR20	/	DIM	/	H	/	830	/	NFL	25
LED Lamps and Retrofits	Wattage: 8	Lamp Type: PAR20		Dimmable		H: High Output		CRI, CCT: 830: 80+ CRI, 3000K CCT		Beam Type: NFL: Narrow Flood FL: Flood	Beam Angle: 25° or 36°

Lamp Dimensions

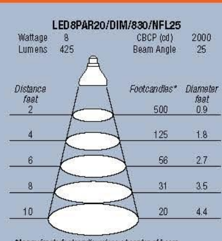
	(A) MOL (inches)	(B) Diameter (inches)
LED8PAR20/DIM	3.4	2.5



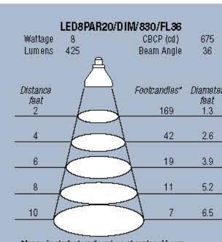


Illuminance Cone Diagrams

Similar Halogen	35PAR20
Watts (W)	35
Avg. Rated Life (hrs)	2,500
Lumens	360
CBCP (cd)	800
Beam Angle	30°



Similar Halogen	35PAR20
Watts (W)	35
Avg. Rated Life (hrs)	2,500
Lumens	360
CBCP (cd)	500
Beam Angle	40°



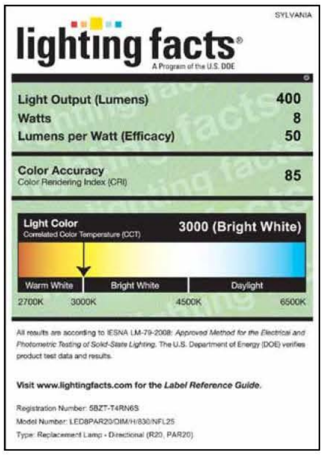
Energy Savings

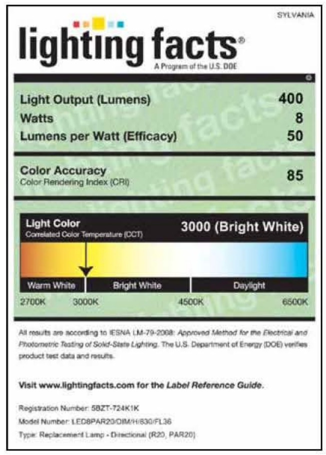
Basic Product Description	LED Life (hrs.)	Similar Halogen	Halogen Life (hrs.)	Watts Saved	Energy Savings*	LED Life vs. Halogen
LED8PAR20/DIM	25,000	35PAR20	2,500	27	$74	10x

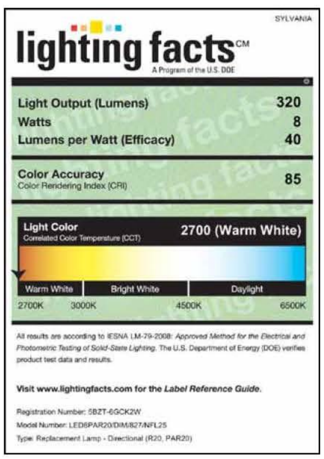
*Energy savings over life of lamp calculated at $0.11/kWh

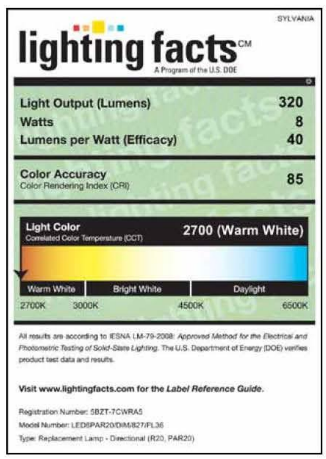
Sample Specification

Lamp(s) shall be an ULTRA LED PAR20 lamp with a medium base. Lamp(s) shall have an average rated life of 25,000 hours at L_{70}. Lamps should have a typical CRI of 85 and lumen output between 320-400.









United States
OSRAM SYLVANIA
100 Endicott Street
Danvers, MA 01923

Trade
Phone: 1-800-255-5042
Fax: 1-800-255-5043

National Accounts
Phone: 1-800-562-4671
Fax: 1-800-562-4674

OEM/Special Markets
Phone: 1-800-762-7191
Fax: 1-800-762-7192

Display/Optic
Phone: 1-888-677-2627
Fax: 1-800-762-7192

SYLVANIA Lighting Services
Phone: 1-800-323-0572
Fax: 1-800-537-0784

Canada
OSRAM SYLVANIA LTD.
2001 Drew Road
Mississauga, ON L5S 1S4

Trade
Phone: 1-800-263-2852
Fax: 1-800-667-6772

OEM/Special Markets/Display/Optic
Phone: 1-800-265-2852
Fax: 1-800-667-6772

SYLVANIA Lighting Services
Phone: 1-800-663-4268
Fax: 1-866-239-1278

Mexico
OSRAM MEXICO
Headquarters
Tultitlan/Edo de Mexico
011-52-55-58-99-18-50

www.sylvania.com

Appendix M - Cut Sheet, Reference Lamp

TCP

Halogen 442172B2 Specifications

Halogen

Catalog Number	
Notes	Type

Applications:

Perfect for most applications: Use where a standard incandescent is used.

- Table Lamps
- Floor Lamps
- Ceiling Fixtures
- Wall Sconces
- Vanities
- Track Lighting

Features and Benefits:

- Enhances all colors in a room – Tru Color rendering
- Low cost, energy efficient incandescent replacement
- 1000 hour Life, Dimmable, No Mercury
- Frosted Version
- Saves up to 28% in energy costs over incandescent
- Better light quality compared to similar Halogen

442172

Best Service

Best Quality

- In house testing shows consistant lumen output with TCP branded Halogens vs. Halogens of competition
- TCP's tight quality standards consistently meets minimum EISA specifications

Guaranteed Capacity

- TCP is prepared for the phase out of 100 watt incandescent and the demand for Halogen A lamps

Warranties and Certifications:	Item #	Description	Wattage	Incandescent Wattage Comparison	Initial Lumens	Hour Rating
	442172B2	72W 2PK Frosted	72	100W	1,490	1,000

TCP, Inc.
325 Campus Dr. | Aurora, Ohio 44202 | P: 1-800-324-1496 | tcpi.com

TCP is proud to have been awarded ENERGY STAR Partner of the Year 2010.

ENERGY STAR AWARD 2010 PARTNER OF THE YEAR

Appendix N - Survey Color Swatches

Color Swatch	RGB Values		
	R	G	B
Purple	109	82	137
Green	44	178	107
Blue	61	123	210
Red	194	72	71
Orange	252	110	60
Yellow	253	212	32