31 July 2017

Paper for submission to ICOM/ICAMT
Flanders, Belgium 2017

WHAT COLOR IS WHITE LIGHT?

By
Steven Rosen, FIALD, IES, President & Creative Director, Available Light
Salem, Massachusetts, USA
steven@availablelight.com

LEDs have presented the museum exhibition world with a completely new paradigm. These are light sources that consume less energy, last forever, produce no heat, produce no artifact degrading UV or IR radiation, and--if you listen the to PR spin machine--will even tie your shoes for you!

In fact, LEDs have proven to be a groundbreaking and outstanding tool in the toolbox of exhibition professionals but, like any technological revolution, traditional lighting 101 basics are now outdated and are in need of revision and expansion. This paper explores the world of white light produced by LEDs.

But, to begin, it is important to explore and celebrate the Building Blocks of a Lighting Design, as without this basic understanding of how a lighting designer performs their craft little else matters.

I. CONTRAST – Creating visual interest
   Everything we perceive, we perceive by contrast: salty/sweet, loud/quiet, rough/smooth, floral/stink and, of course, bright/dark. Without the contrast (Figure 1) of highlight to shadow, the brain could not resolve three-dimensional form.

Fig. 1 - Contrast • National Museum of American History

II. RHYTHM – Defining attitude and visual space

Like a syncopated field of natural dune grasses dancing in the wind to the visual delight of a rigid and precise courtyard colonnade, rhythm (Figure 2) is an organizing tool of design that delivers satisfaction to the viewer.

Fig. 2 - Rhythm • National Museum of the American Indian

III. LAYERS & ACCENTING – Composition / Leading the eye

Rarely is a good lighting design constructed of a single light source hanging in the middle of a built environment. The result would be flat, dull, and glare-filled space. But, like creating a painting of many brushstrokes and glazes, a well-conceived lighting design is built of layers (Figure 3) that may include ambient light, specific accent lights, color washes, etc.

Fig. 3 - Layering • Witte Museum, San Antonio, Texas

IV. DYNAMIC – Angle / Movement / Change over time

Understanding the geometry of light is critical to a successful lighting design. The angle of light is a dynamic relationship between an object being illuminated and the person receiving the visual clues. This dynamic dance affects everything from controlling uncomfortable/debilitating glare to understanding space and object perception.

Natural light (Figure 4) is anything but static. Both shadow and color temperature shift significantly—albeit somewhat predictably—over the arc of the daylight portion of each 24-hour cycle. How we perceive and respond to the world is intensely motivated by our response to natural conditions. Theatrical lighting, on the other hand, with its ever-changing array of lighting angles and modulating colors is meant to artificially direct our attention (both towards and away from things) while extreme modulation of color is meant to affect us both aesthetically and emotionally.

Electric light in architecture is beginning to take its cue from both the shifting of natural light and the methods by which theatrical lighting is controlled.

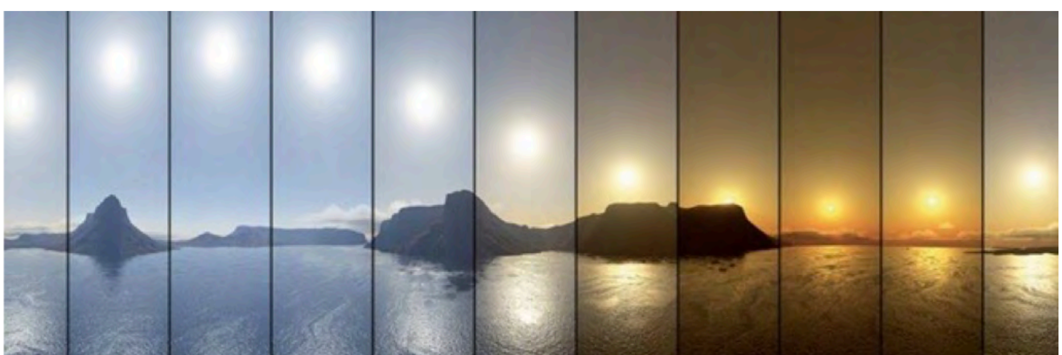

Fig. 4 -Dynamic Lighting

The notion of light modulating over time is emotionally breathtaking. More, there is palpable connection between light and music. Volume, timbre, rhythm, tempo, etc. are all words that can be used to describe both music and light. The rests between notes in a score are like contrasting highlight and shadow. From elongated morning shadows to the power of overhead high noon sun, mood and timbre are intense and tangible. In winter, the blue of north sky appearing in the shadows of low angle direct sunlight is a fantastic reminder of how magical and emotive is light.

What Color is White Light?

Our brains are always seeking to find equilibrium and a general understanding of our surroundings. In an illuminated space, that struggle is to perceive and define a reference white. If a person walks into a room filled with blue light (Figure 5) in time, the brain will adapt, “white-balance,” and perceive the space in normal white—this is remarkable.

Fig. 5 - Airplane interior bathed in blue light before takeoff.

But subtle variations of color contrast can also generate impactful visual information for the eye. For instance, the contrast of a glass box lobby space, lit with warm electric light, viewed from without against a cool late afternoon/early evening sky creates an almost electric composition (Figure 6).

Fig. 6 - Color Contrast, Penn State Hershey Medical Center

The crashing contrast of warm light embraced by a blue sky surround makes the edges of objects more crisp, rich, and dramatic. Many a lighting designer has used the rules of color theory to enliven or romanticize a space. Compositionally manipulating subtle color shifts and contrast can create visual interest in a space and help suggest a lighting hierarchy to direct focus so people subconsciously comprehend how to navigate an unfamiliar setting.

The primary colors of pigment (paint, if you will) are Red, Yellow, and Blue; theoretically, all other colors can be created from these primaries but RYB cannot be mixed, to use them they must be available. The absence of color is white. The result of mixing equal amounts of RYB is black; this process is called subtractive color mixing. Things change a little when looking at the primary colors of light which are Red, Green, and Blue. The absence of color is blackness. The result of mixing equal amounts of RGB is white; this process is called additive color mixing.

The eye perceives color via reflected light: light hits an object, the object reflects wavelengths of light that define that object, and the brain perceives a color based on those two factors.

Any light source (the sun, an incandescent light bub, an LED, etc.) produces a very specific Spectral Power Distribution based on RGB (light). An object possesses a Spectral Reflectance Distribution based on RYB (pigment) and it only reflects wavelengths of light that exist in the color of that object. For instance, a red apple reflects almost exclusively red light. So, if a warm (2700K) white light—which is rich in red wavelengths—illuminates the apple a vibrant red specimen, perfect for sinking your teeth into, will be revealed! (Figure 7)

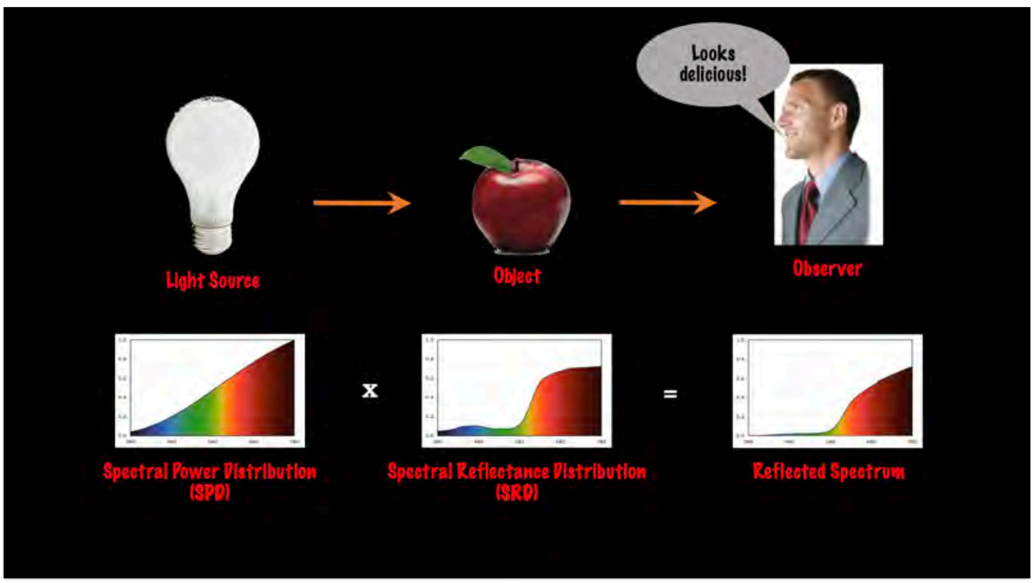

Fig. 7 - Color Perception, with thanks to Kevin Houser & Tony Esposito, Penn State University

However, if that same apple was to be illuminated with a cool (6000K) light—which is rich in blue wavelengths—the resulting perceived color might be a darkish less appealing shade of red apple. The question becomes: how does one have a conversation about evaluating color?

Two metrics are currently used to describe color in light. As mentioned above, color temperature describes the color of the light. Natural daylight is dynamic, over the course of the day the color temperature of light is constantly modulating.

CRI-color rendering index is the second metric that has long been the system used to rate the ability of a light source to render color accurately. But this system, which uses eight pastel colors to test a light source, has long been considered to be simplistic, inaccurate, and out-of-date. This is especially true when rating the CRI of a non-continuous spectrum light sources like LED. In the last few years, a new color rendering metric scale, TM-30, has been enacted by the Illuminating Engineering Society of North America. Not only does this rendering process embrace 100 reference colors it also adds another quantifier that helps to describe color rendering: R_g or Saturation. In looking at at the classic 1931 CIE Color Chromaticity Chart (figure 8).

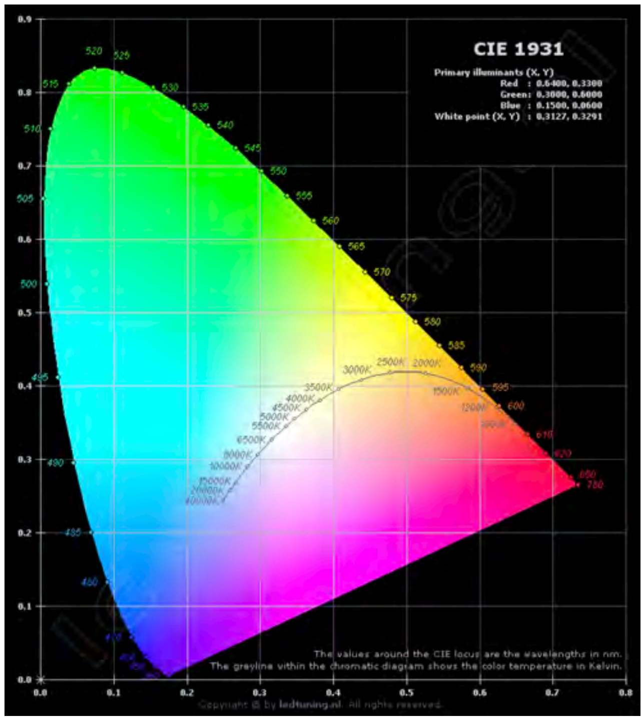

Fig. 8 - 1931 Chromaticity Chart

One will see specific plotted points that identify Correlated Color Temperature (CCT) along what is know as the blackbody radiator curve. The chart simplistically suggests that each of these points (3000K, 10000K, etc.) is a specific point within this color space. But this presumption is incorrect.

In fact, an axis can be struck across any point on the blackbody radiator curve and any point on that line will measure as the same color temperature (figure 9).

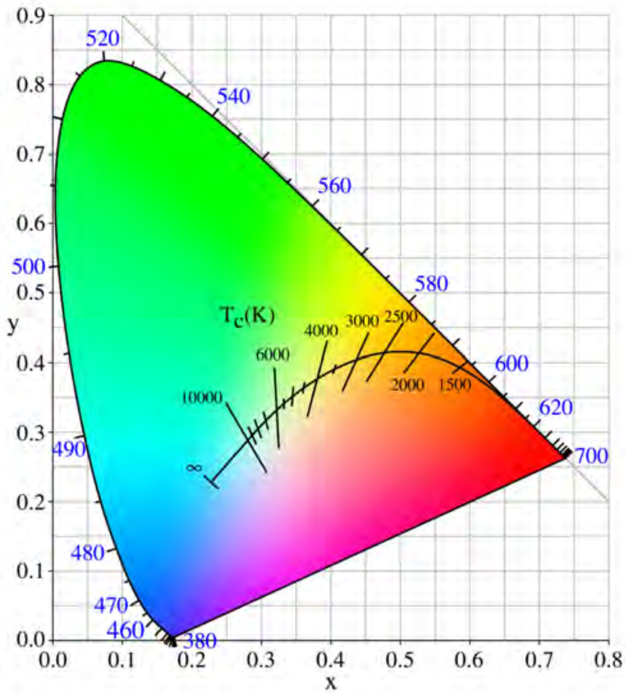

Fig. 9 - Gamut Saturation

Although CCT is maintained along the axis, the apparent hue is modified. As the point moves up and away from the blackbody curve, the color becomes more saturated (R_g). Conversely, as the point moves down and away from the point the hue appears to desaturate (Figure 10).

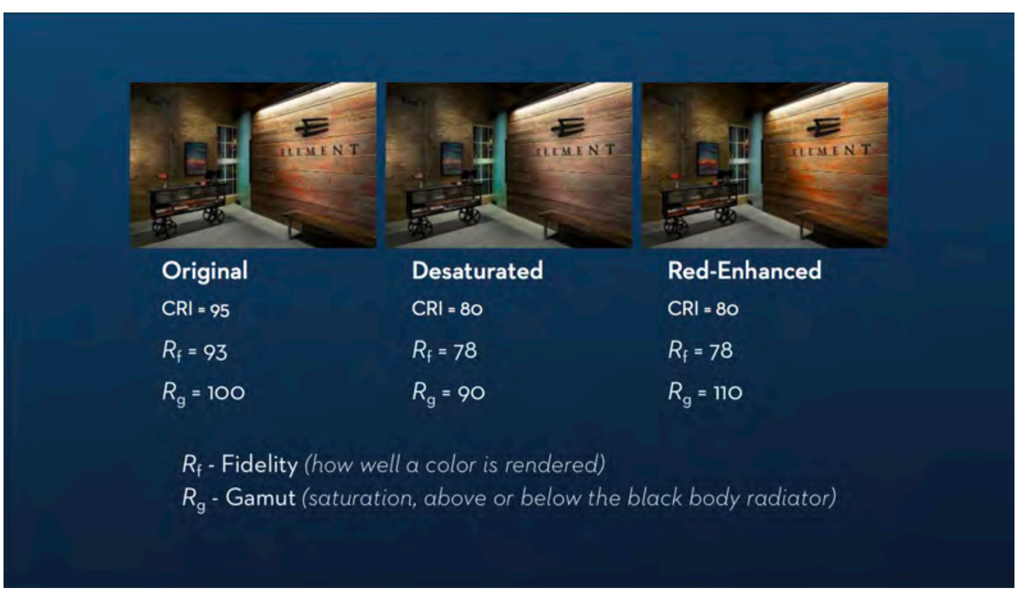

Fig. 10 - TM-30 illustration • courtesy Houser, Royer, David & Esposito

The TM-30 standard uses an easy to interpret Color Vector Graphic (figure 11)

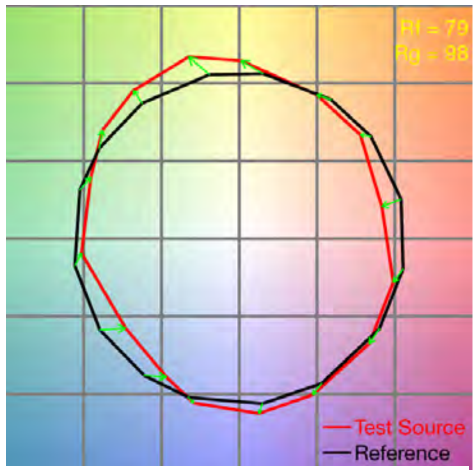

Fig. 11 - TM-30 Color Vector Graphic

to illustrate how a particular light source relates to the reference white light for that assigned CCT. Plotted points outside the black circle indicate saturation, plotted points inside the black circle show de-saturation.

Dimming & Flicker

In the old days, dimming an incandescent light bulb was a relatively simply task: reduce the voltage to the lamp and the hot glowing tungsten filament reduced output. A distinctive characteristic of dimming incandescent was that the color temperature also went down making the apparent color of the light warmer. Because LEDs are solid state devices, dimming is not nearly as technically easy to accomplish. A number of LED dimming strategies exist and it is important to understand that the right combination of LED, electronics driver, and dimmer device must all be perfectly compatible for a satisfactory dimming experience to occur. If all the components of the system are not in harmony, disturbing strobing effects or flicker can occur. It also may not be possible to dim to a low enough intensity for a particular application. Finally, when dimming LEDs, the apparent color temperature of the light does not significantly change. This can be an issue; for example, the lighting of a restaurant at night is more romantic if the light becomes more amber as the lights are dimmed. Many manufacturers are now offering warm-to-dim technology where, as an LED source is dimmed, a red or amber LED slowly comes on to make the light seem as it is warming as it is dimmed.

Conservation/Light Spectrum

Regrettably, any radiant light source ultimately damages sensitive objects. The ultimate compromise for conservators is to identify the least amount of exposure required to assure enjoyment by museum visitors while doing everything possible to prolong the life of these objects for generations to come.

As it causes damage without any benefit to the viewer, non-visible radiation (UV & IR) should be removed from the spectral output of all gallery light sources. The good news is that most LEDs emit virtually no UV radiation (Figure 12) and very little infrared.

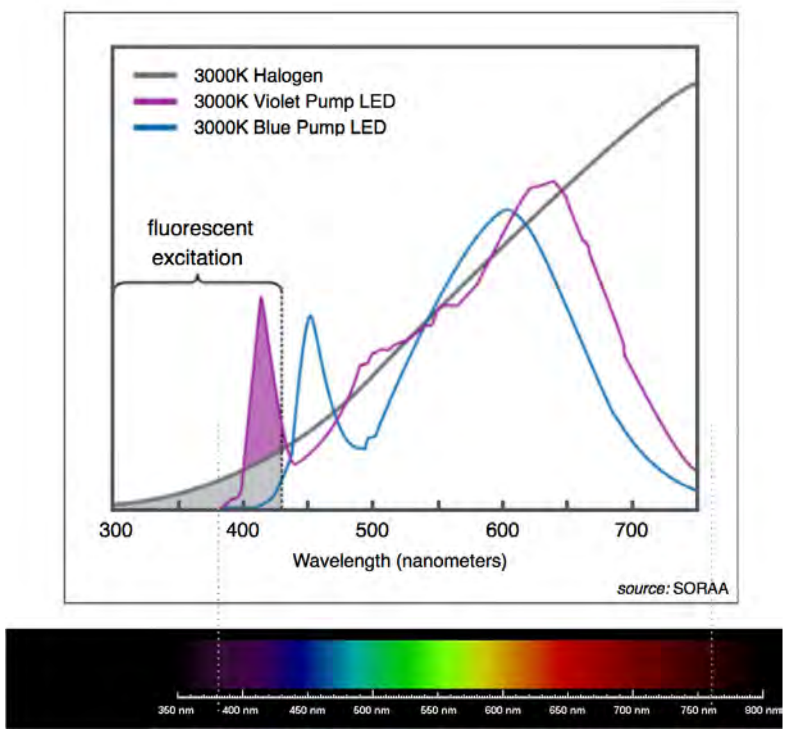

Fig. 12 - Examples of spectral distribution

Hopefully this paper has left the reader with a much better understanding and appreciation of both lighting design tools and modulation of color in LED lighting systems.

Glass Flowers Exhibit, Harvard Museums of Science & Culture

National Archives Rotunda, Washington DC