Advancing Light Quality for Human Preference

Advances in LED technology, combined with emerging research in human preference lighting, have enabled the development of light sources that more effectively render colors that humans prefer. In order to maximize efficacy, typical 80 CRI LEDs are over-saturated in the blue and green spectrums and under-saturated in the red spectrum. The latest research on color preference demonstrates that humans prefer being immersed in environments where red colors are slightly over-saturated, indicating that current LED technology is not ideal for human preference. This paper will cover the history of light quality and efficacy, new metrics to assess quality of light, and designing for human preference.

QUALITY VERSUS EFFICACY

Since the inception of the Edison bulb, the two central ideas of lighting have been to increase the efficacy, the Lumens Per Watt (LPW) of the light source, or to increase the quality of the light source. Unfortunately for consumers, those ideas have generally opposed each other, resulting in a compromise toward efficacy, typically at the expense of quality.

For a space to have a pleasant feel and for colors to appear natural, a light source must render colors comparable to a blackbody radiator, such as the sunlight. For this reason, spaces illuminated with incandescent or halogen light sources appear welcoming and generally quite pleasing. With the invention of the fluorescent light bulb, incandescent light sources became comparatively inefficient. In large spaces, due to energy concerns, it became impractical to use the pleasant, incandescent sources and the lighting community embraced the efficient, fluorescent sources.

In the past few years, highly efficient LEDs have easily surpassed fluorescent bulbs in efficacy, with LPW values over 140 in some cases. But even with LEDs, the tradeoff between quality and efficacy has remained: highly efficient LEDs are over-saturated in the blue and green spectrums and are not pleasant to live or work under.

However, specifiers, building owners, and even governing bodies recognize that LEDs have surpassed the efficacy levels of fluorescent light sources, and providing opportunities to improve the overall quality of light in a space, as seen in Figure 1. A market shift has begun towards quality of light initiatives, including circadian tuning, tunable white, warm dimming and spectral tuning, among others. New building standards have also emerged, such as the WELL Building Standard, focusing on human health and wellbeing over energy efficiency. The movement towards quality of light is an opportunity for designers to create spaces that humans ultimately prefer.

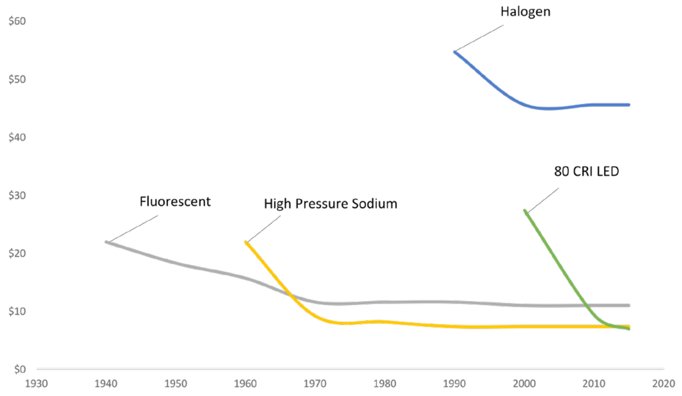


Figure 1: Efficiency of light sources and annual operating cost over time. Based on a 2x2 troffer at 3500K and usage of 12 hours/day for 260 days at $.10/kWh.

TOOLS TO ASSESS QUALITY

A pleasant space has always been easy to identify. However, given the limited measurements for light quality, it is difficult to accurately measure and quantify what makes the space pleasant. Color rendering has been the main means to evaluate light quality, with the Color Rendering Index (CRI) used since the 1960s to produce an average color rendering score. Generally, a score above 80 is desired and a score over 90 indicates more red content and more naturally rendered colors. However, because only eight color samples are used to produce the average and because a true red is not included in the eight samples, the CRI score is not comprehensive. In other words, simply increasing the CRI of a light source does not necessarily mean that the rendered colors will be more pleasant.

In 2015, the IES released the TM-30-15 color standard to succeed CRI. Akin to CRI, TM-30-15 includes measurements for rendered color. Unlike CRI, TM-30-15 is broken into three different metrics:

- Fidelity Index (Rf), which measures the accuracy of a light source and is similar to CRI,
- Gamut Index (Rg), which measures saturation,
- A Color Distortion Graphic, which is a visual representation of color saturation by hue bin.

Because TM-30-15's fidelity measurement, Rf, uses ninety-nine color samples compared to CRI's eight, TM-30-15 data encompasses more color points and provides an improved method to compare a product to its reference source, which at 3500K is a blackbody radiator. Examples of TM-30-15 values for a typical 80 CRI LED are seen in Figure 2 and Table 1.

Figure 2: TM-30-15 Color Distortion Graphic for a typical 3500K 80 CRI

Fidelity, Rf	82
Gamut, Rg	98

Table 1: TM-30-15 Fidelity and Gamut for a typical 3500K 80 CRI LED.

LIGHTING FOR HUMAN PREFERENCE

Advances in LED technology, combined with emerging research in lighting for human health and human preference, have enabled designers to create spaces that are more human-centric.

Focal Point has established Preferred Light as a solution to elevate the overall pleasance of a space and to produce more vibrantly rendered colors. Using a custom LED mix, Focal Point defines Preferred Light using TM-30-15 metrics as having a fidelity (Rf) of 89, a gamut (Rg) of 107, and over-saturating Hue Bin 16, deep red content, by 9% at a Color Temperature of 3500K, as shown in Figure 3.

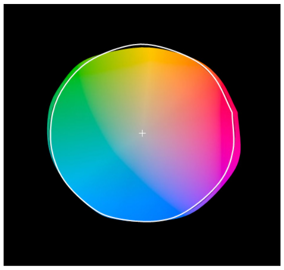


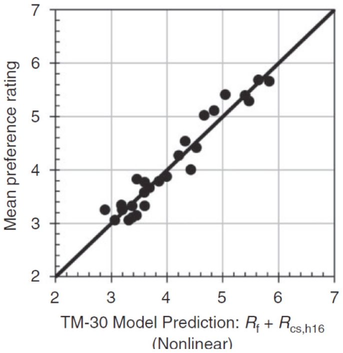
Figure 3: TM-30-15 Color Distortion Graphic for Preferred Light

The metrics for Preferred Light are derived from two independent studies: one conducted at Pacific Northwest National Laboratories[1] (PNNL) and one from Pennsylvania State University[2] (PSU). While keeping the Color Temperature (CCT) and illuminance constant at 3500K, both studies varied the fidelity, gamut, and color saturation to determine what types of light people prefer.

The PNNL study, published in June 2016, was used to promote the benefits of the TM-30-15 test method over traditional CRI measurements. PNNL created a “typical room” for the experiment and populated it with a broad variety of items, shown in Figure 4. A selection of 28 participants representing a cross-section of age and gender evaluated the space under different rendered light conditions. Responses from the test were evaluated statistically to enable the prediction of preference and a regression formula was developed, which is shown in Figure 5. Based on the PNNL regression analysis, the target Hue Bin 16 saturation values should be between 2% and 16%, the fidelity should be above 74, and the gamut should be above 100. The high-level conclusion of the model was that people prefer more red content.

Following the report from PNNL, the PSU study was published in December 2016. Most notably, researchers at PSU changed the method in which participants judged the space. The PNNL test was executed similarly to an “eye doctor test”, in that each participant evaluated several light sources in one seating. Recognizing that people easily detect differences in light, PSU sought to confirm the findings with an “absolute” test. To do so, PSU tested only one rendered light per day; the experimental setting is shown in Figure 6. This assured that preferences were not influenced by the other test sources previously seen by the participants. Akin to PNNL, PSU targeted a cross-section of participants, with a total of 40 participants. The PSU study converged with the PNNL report for preference, finding that the most preferred light sources over-saturated the red content, measured with Hue Bin 16. It also asserted that maintaining a gamut over 100, while generally preserving a fidelity of at least 60, tends to produce a more preferred light source. Figure 7 illustrates which light sources participants favored, as measured by fidelity and gamut.

Figure 4: Photograph of the windowless experimental room used at PNNL with a mirror and four object groups: artwork, consumer goods, clothing and natural objects. Approximate dimensions of the room were 10.1 ft. by 12.1ft with a ceiling height of approximately 9.8 ft.



$$\text{Preference} = 7.45 - 0.041\, R_f - 9.99\, R_{cs,h16} - 0.90\, R_{cs,h16}^{2} + 106.6\, R_{cs,h16}^{3}$$

$$r^2 = 0.94$$

Figure 5: Best fit regression model for determining participant preference ratings.[1]

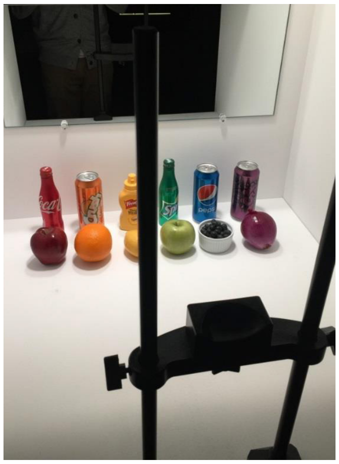


Figure 6: Experimental apparatus with object layout.[2]

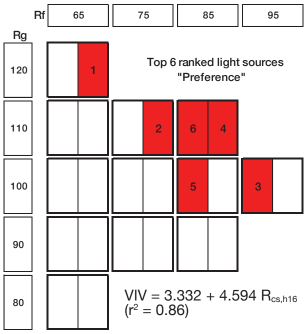


Figure 7: Top ranked SPDs for overall ratings—by scale

The preference model, as defined by PNNL and PSU, creates clear guidelines against which any light source can be measured and quantitatively described. Typical 80 CRI and 90 CRI LEDs unfortunately do not meet the criteria to be considered preferred light sources, as shown in Figure 8. The preference models do, however, give a sizeable target range that many LED spectrums can easily achieve. To narrow down the range, Focal Point chose to evaluate three targeted spectrums at their facility, each of which met the preference model.

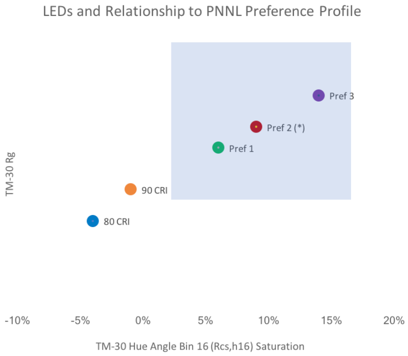


Figure 8: PNNL preference model used to create Focal Point’s three spectrum profiles.[1]

An occupied office was selected for the test in order to ensure that the light source could be evaluated over extended periods of time, when accomplishing various tasks. Akin to the PNNL and PSU studies, a cross-section of the population was selected consisting of internal employees and hundreds of visitors, initially unaware of the experiment. Focal Point found Pref 2, the middle spectrum, to be the most preferred. Participants generally perceived Pref 3 as favorable, but also commented that objects began to look unpleasantly vibrant and artificial. Pref 1 was deemed slightly more subdued than Pref 2, which resulted in a loss of the impact in the space.

Because of the increased red content in the spectrums of the preference models, a preferred light sacrifices efficacy. LEDs require more power to produce red content, resulting in a loss of efficacy of approximately 35% when comparing Preferred Light to standard, 80 CRI, 3500K LEDs and 24% when comparing it to standard, 90 CRI, 3500K LEDs. As LED efficacy gains plateau, this tradeoff still results in efficacies far superior to that of fluorescent light sources or early LEDs, and in a marginal impact on operating cost over time, as demonstrated in Figure 9.

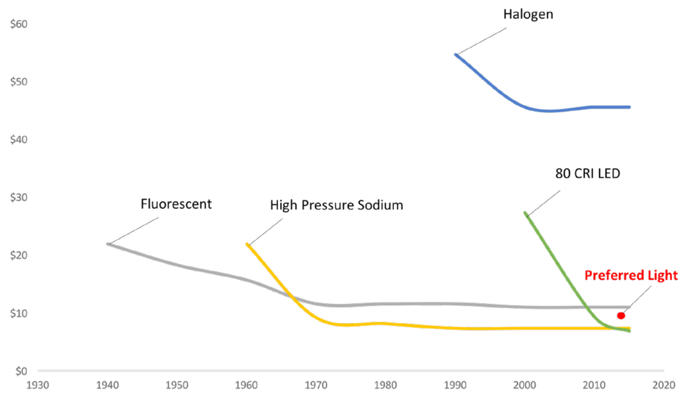


Figure 9: Efficiency of light sources and annual operating cost over time. Based on a 2x2 troffer at 3500K and usage of 12 hours/day for 260 days at $.10/KW-hr.

CONCLUSION

Lighting designers have always focused on improving the overall quality of light in architectural spaces. With advances in LED technology and constant improvements in efficacy, there is more flexibility today to enhance environments through higher quality light sources and without a significant drop in efficacy. As a result, designers have more resources enabling them to create spaces where people prefer to live and work. Based on emerging research in human preference lighting, along with new evaluation tools such as TM-30-15, there is a path to specifying a color spectrum that humans generally prefer. By using TM-30-15 and specifying a light source with a fidelity over 74, a gamut over 100, and oversaturating Hue Bin 16 by 2%-16%, a more preferred light can be generated. This preferred spectrum results in more natural skin tones, warmer wood tones, and increased vibrancy of objects, allowing designers to ultimately achieve a color rendering that humans prefer.

References

1 (Royer, MP, et al. “Human Perceptions of Colour Rendition Vary with Average Fidelity, Average Gamut, and Gamut Shape.” Lighting Research Technology, 26 June 2016, pp. 1–26.)

2 (Esposito, T. (2016). Modeling Color Rendition and Color Discrimination with Average Fidelity, Average Gamut, and Gamut Shape (Doctoral Dissertation). Pennsylvania State University.)