Circadian Lighting Design: Leveraging the Melanopic Efficacy of Luminous Radiation Metric

Lighting design projects often include multiple design constraints. For example, a lighting design should meet target light levels, limit glare and provide appropriate color fidelity while not exceeding the power or energy budget defined for the project. For select projects, circadian considerations have recently been added to the design criteria list. Circadian lighting is defined as lighting that influences a non-visual, physiological response within the human body. When circadian design criteria are included, the goal for the lighting system is to provide proper circadian support by stimulating the circadian system only during the day.

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Today, circadian lighting design is typically based on delivering specified melanopic irradiance levels to the occupant during the day and remaining below a specified level of melanopic irradiance during the night. To bridge the gap from typical photopic lighting design to circadian lighting design, a useful metric is the "melanopic efficacy of luminous radiation." For each light source, this metric relates the melanopic irradiance to photopic illuminance and is calculated from its spectral power distribution (SPD).

Recent research at the CLTC, funded by the California Energy Commission, shows that today's commercial lighting products can support these emerging circadian principals and that the use of existing metrics can assist lighting designers in meeting both visual and non-visual design goals. Specifically, CLTC determined that for typical phosphor-converted (PC), blue-pump, LED, white light sources the melanopic efficacy of luminous radiation is positively correlated with today's common color fidelity metrics. With these LED sources, selection of high color fidelity products is shown to produce light that is more effective at stimulating the circadian system as compared to low fidelity alternatives. In appropriate applications, designers can better ensure a positive impact on alertness and productivity for occupants by simply specifying higher fidelity lighting.

New Discovery. In 2000, researchers identified a new type of photoreceptor in the human eye. This photoreceptor is known as melanopsin, which is distinct from rod and cone cells.[1] Melanopsin is found in intrinsically photosensitive retinal ganglion cells (ipRGCs). Melanopic flux is measured on a scale weighted based on the ipRGCs, in contrast to standard photopic flux, which is measured on a scale weighted based on the eye's perception of brightness. Researchers have not come to a firm consensus on the action spectrum of light that maximally stimulates the circadian system; however, current research shows that melanopic flux is a significantly better predictor of circadian impact than photopic flux. This makes melanopic flux an appropriate circadian lighting design metric given the data available. Consequently, melanopic flux is now included in some industry lighting standards, including *The WELL Building Standard Version 2*, to help address lighting's non-visual impact on building occupants.

The *CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light* (CIE S 026/E:2018) defines the melanopic efficacy of luminous radiation ($K_{mel, V}$) as the ratio of the melanopic radiant flux to luminous flux, or "melanopic efficacy," produced by a light source. When comparing two light sources, the source with higher melanopic efficacy produces more melanopic irradiance per unit photopic illuminance (measured in foot candles, or lux), which correlates with increased human circadian system impacts.

Having higher melanopic efficacy means that a light source provides stronger, circadian system stimulus at the design light level. This is a desirable quality in spaces that are primarily occupied during the day and rarely occupied at night, such as offices and schools. In other spaces that are occupied during all portions of the day, such as hospitals and dormitories, proper circadian design calls for significantly higher circadian stimulus during the day and low circadian stimulus at night. For these more complicated spaces, implementation of a circadian lighting design typically requires a color tunable lighting system to enable daily variation in melanopic efficacy.

Data Collection. CLTC compiled 206 normalized spectral power distribution (SPD) datasets for commercial, PC, blue-pump, LED white light sources available over the last 10 years. The collection includes data from both indoor and outdoor LED luminaires taken from CLTC testing and the IES TM-30-15 calculator tool. The IES TM-30-15 calculator tool includes SPD datasets for a wide range of light emitter types (e.g. PC LEDs, RGB LEDs, fluorescents, HIDs, etc.). CLTC included only data from PC, blue-pump LEDs in its analysis.

To compare two SPDs visually, it is useful to normalize the curves based on photopic flux. Normalization based on photopic flux reveals wavelength ranges where one source produces more power relative to another, at equivalent photopic light levels. **Figure 1** shows two normalized, PC, blue-pump LED SPDs of the same correlated color temperature (CCT) with varying color fidelity.

PC, blue-pump LEDs work by converting short-wavelength, blue light produced by the LED to longer-wavelengths (yellow through red) using a phosphor. This gives these LEDs a distinctively shaped SPD, with a narrow peak at shorter wavelengths from the blue-pump LED (typically around 455 nm) and a broad peak at longer wavelengths from the phosphor.

The melanopic action spectrum generally falls along the

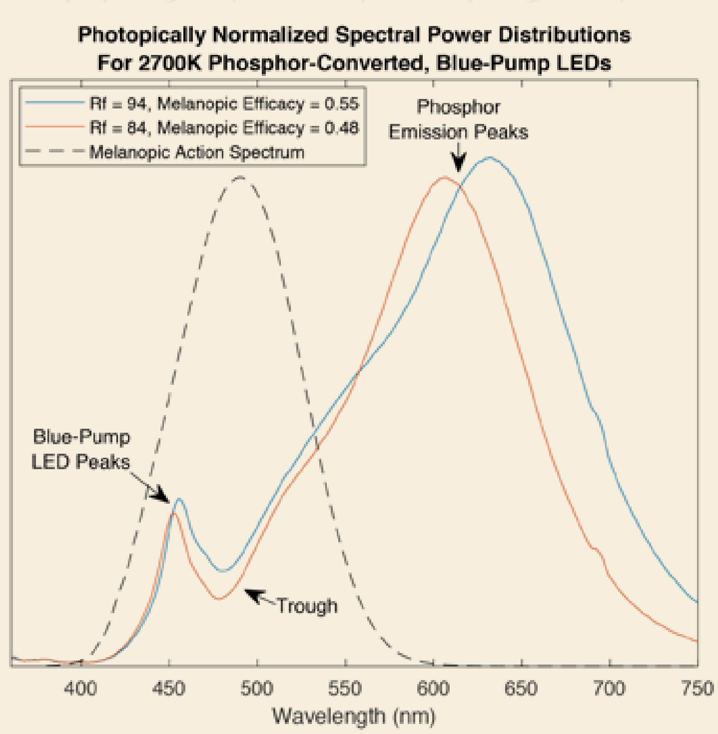

Figure 1. Photopically normalized SPD for 2700K PC blue-pump LED light sources compared to the melanopic action spectrum.

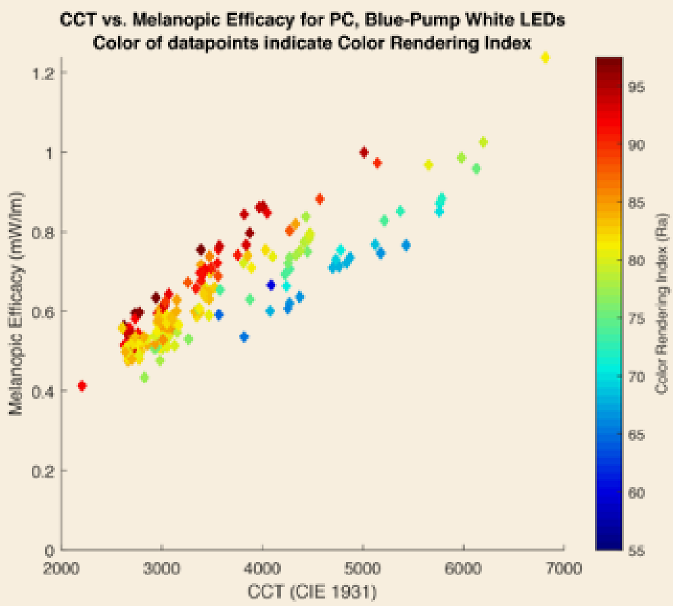

Figure 2. The relationship of CCT, K_{mel}, V, and R_a for 206 different PC blue-pump LED light sources.

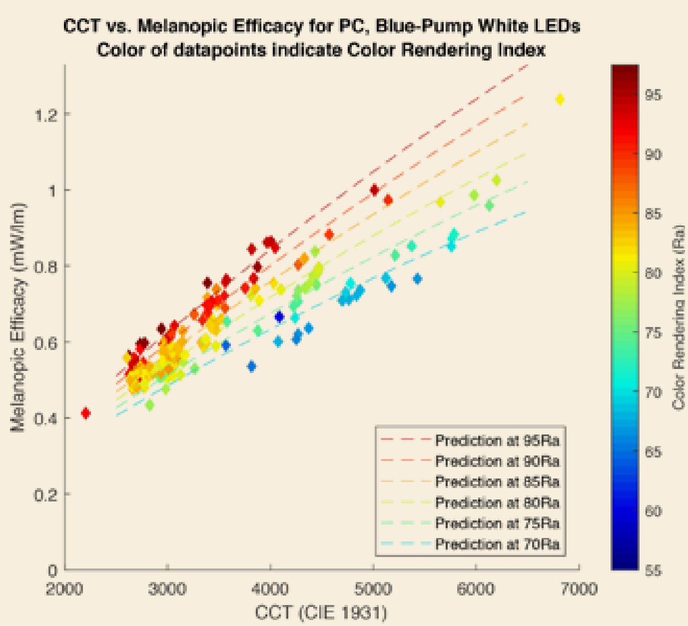

Figure 3. The predicted effects of CCT on melanopic efficacy of luminous radiation for color fidelity values ranging from 70 to 95 CRI R_a.

trough between the shorter and longer wavelength peaks for most PC, blue-pump LEDs. However, in a typical high color fidelity, PC, blue-pump LED, more power is produced in this trough area (blue line in Figure 1) as compared to a low color fidelity source (red line in Figure 1). When this occurs, the higher fidelity, PC, blue-pump LED will produce more melanopic flux at a given photopic flux as compared to its lower color fidelity counterpart.

CLTC further analyzed the relationship, specifically focusing on the following three lighting metrics:

- Correlated color temperature (CCT)
- Melanopic efficacy of luminous radiation (K_{mel}, V)
- Color fidelity (CRI R_a)

CLTC mapped the relationship between each LED's color fidelity, its melanopic efficacy and its CCT. This analysis resulted in two key conclusions:

1. CCT and the melanopic efficacy of luminous radiation are related. For two PC, blue-pump LED light sources with different CCT, the higher CCT LED will typically have a higher melanopic efficacy of luminous radiation as compared to the lower CCT LED.

2. Color fidelity and melanopic efficacy of luminous radiation are also related. For two PC, blue-pump LEDs with identical CCT and different color fidelity, the higher color fidelity LED will typically have a higher melanopic efficacy as compared to lower color fidelity LED.

Results of the analysis are provided in **Figure 2.** While only R_a is shown, analysis was performed using both the IES TM-30-18 R_f and CRI R_a. Both color fidelity metrics showed similar correlation with melanopic efficacy.

To estimate typical increases for PC, blue-pump LEDs represented by this dataset, CLTC created a statistical model to determine values for sources with CRI R_a ranging from 70 to 95 CRI R_a. **Figure 3** shows the predicted effects of CCT on melanopic efficacy for the complete range of modeled color fidelity values.

The model calculates the expected increase in melanopic efficacy due to increasing color fidelity for a specified CCT. **Table 1** provides the percent increase for typical CCTs at 80 CRI and 90 CRI. Of particular interest is the increase in melanopic efficacy of 11.7% resulting from a move from 80 CRI to 90 CRI for a 4000K source. This is a standard CCT for interior office spaces. This percent increase in melanopic efficacy of luminous radiation is similar to the typical decrease in photopic efficacy (lm/W) for this difference in color fidelity. This means that to produce a target melanopic irradiance level, typical fixtures will use the same amount of power regardless of which color fidelity is specified.

These results are based on SPDs from hundreds of commercially available LED luminaires. However, not all high fidelity, PC, blue-pump LEDs are equivalent. The LED industry is constantly innovating, and SPD can vary significantly from one product to the next. When implementing a circadian lighting design, lighting designers should request and compare the melanopic efficacy metric for each light source under consideration.

The Takeaway. For circadian lighting designs, results of this analysis point to high color fidelity PC, blue-pump LED light sources being a viable option for meeting circadian design goals, even when maximizing energy efficiency is paramount. This is due to the typical percent increase in melanopic efficacy being very similar in magnitude to the typical decrease in photopic efficacy that can occur when selecting a high color fidelity source. For a lighting design with circadian goals, it may be equally or more energy efficient to use high color fidelity PC, blue-pump LEDs as opposed to a low color fidelity counterpart.

Next Steps. In recent news, the DesignLights Consortium (DLC) released an updated draft standard, *Draft 1: DLC SSL Technical Requirements Version 5.0*. This standard has a targeted effective date of January 1, 2020. If adopted in full, this version contains a requirement that the SPD for the spectral range of 380-780 at one-nanometer increments must be reported to DLC by manufacturers of all solid-state lighting products. Additionally, if adopted, this requirement will create a large SPD database for commercially available light sources. Such a database will greatly accelerate the ability of research institutions to provide meaningful analysis of lighting characteristics and aid the lighting industry in adopting new, associated metrics. ◎

CCT	MELANOPIC EFFICACY AT 80 CRI	MELANOPIC EFFICACY AT 90 CRI	PERCENT INCREASE
2,700 K	0.485	0.533	9.8%
3,000 K	0.541	0.597	10.3%
3,500 K	0.631	0.701	11.1%
4,000 K	0.717	0.801	11.7%
5,000 K	0.880	0.992	12.7%

Table 1. The calculated percent increase in melanopic efficacy of luminous radiation as a result of increase in color fidelity at typical CCTs.

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