Title

Laboratory Evaluation of Tunable White LEDs for Circadian Lighting in Commercial Offices

Permalink

Authors

Shackelford, Jordan
Meier, Alan

Publication Date

2021-04-01

Laboratory Evaluation of Tunable White LEDs for Circadian Lighting in Commercial Offices

ET18SCE1020

Prepared by:

Electric Power Research Institute (EPRI)
Lawrence Berkeley National Laboratory (LBNL)
Prepared For:
Emerging Products
Customer Programs & Services
Southern California Edison

April 2021

SOUTHERN CALIFORNIA EDISON
Energy for What's Ahead℠

Acknowledgements

Southern California Edison's (SCE) Emerging Products (EP) group is responsible for this project. It was developed as part of SCE's Emerging Technologies Program under internal project number ET18SCE1020. Daniel Nguyen conducted this technology evaluation with overall guidance and management from David Rivers. Contact David.g.rivers@sce.com for more information on this project.

Disclaimer

This report was prepared by Lawrence Berkeley National Laboratory (LBNL) under Regents of the University of California, and Electric Power Research Institute (EPRI) for SCE, and funded by California utility customers under the auspices of the California Public Utilities Commission (CPUC). Reproduction or distribution of the whole or any part of the contents of this document without the express written permission of SCE is prohibited. This work was performed with reasonable care and in accordance with professional standards. However, neither SCE nor any entity performing the work pursuant to SCE's authority make any warranty or representation, expressed or implied, with regard to this report, the merchantability or fitness for a particular purpose of the results of the work, or any analyses or conclusions contained in this report. The results reflected in the work are generally representative of operating conditions; however, the results in any other situation may vary depending upon particular operating conditions.

Legal Notice

EXECUTIVE SUMMARY

Tunable white Light-Emitting Diode (LED) systems that allow users to control Correlated Color Temperature (CCT) are often marketed for circadian health, which is an emerging priority in commercial office lighting. However, the energy impacts of meeting circadian criteria with standard non-tunable LEDs and with tunable white LEDs are not well understood. The goals of this project were to implement select commercial lighting systems, including tunable white LEDs, to meet visual and circadian criteria in an office environment, and to quantify lighting performance and energy usage. Most recent studies on tunable white LEDs, circadian lighting strategies, and energy impacts have relied on computer simulations and models. While little research has directly measured tunable LED energy usage for circadian criteria, EPRI has recently published results from a lab-based evaluation of illuminance, spectral output, and energy consumption for several LED products marketed for circadian performance[1]. The research presented here contributes to the field by quantifying the performance of market-available technologies through detailed monitoring of performance parameters (such as illuminance, spectral output, glare, and energy consumption) in a physical space (an office environment).

We evaluated the performance of tunable white LED troffers and pendants through rigorous testing in a mock office environment, including a 300 square foot (ft^2) open-plan interior and perimeter (daylit) zones, at LBNL's FLEXLAB®. Key lighting parameters were measured to evaluate visual and circadian performance, including spectral irradiance measurements (in watts per square meter per nanometer [$W/m^2/nm$]) converted to circadian units. A baseline lighting solution (standard non-tunable dimmable LED fixtures) was implemented to meet task illuminance criteria (300- and 500-lux test conditions) with daylight dimming in the perimeter. The same system was then commissioned to meet visual and circadian criteria through scheduled increases in lighting intensity for a four-hour circadian performance period. Then tunable white LED systems (troffers and pendants) were implemented and tested under the same illuminance and circadian criteria with intensity and CCT changes, to explore the impact of different spectral power distributions on circadian performance and lighting energy.

This research showed that circadian criteria can incur incremental energy costs, as detailed in the Key Findings section of this report. However, with the low energy intensities of LEDs, especially relative to existing building fluorescent systems, prioritizing energy savings over circadian performance may not be necessary. For customers who choose to pursue circadian goals in new construction or retrofit lighting projects, the aim should be to minimize incremental energy cost. The lack of "official" consensus-based standards around circadian lighting design at this time remains a serious hurdle for the lighting community. Nonetheless, from the standpoint of regulators, utilities, and efficiency program implementers, it would seem prudent to provide recommendations, or even incentives, for best practices that support energy efficiency in circadian design, even while waiting for official consensus-based standards.

---

[1] See EPRI Report 3002018553: https://membercenter.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002018553

KEY FINDINGS

- For interior offices with no daylight, circadian criteria required more lighting energy than the LED baseline, and higher light levels than those provided in a 300-lux task illuminance condition; shown in Table ES-1 below, we calculated annual lighting energy increases from 11% to 42%, depending on conditions and retrofit methods (see the Results section of this report). We estimate that LED systems implemented for circadian design still meet building energy code lighting power density requirements and save significant energy over traditional fluorescent systems (for example, 66% savings with tunable pendants).
- For the daylit zone, we found significant energy savings relative to the interior zone from daylight dimming and importantly, meeting circadian criteria required no extra lighting power for the tested conditions.
- Comparing circadian performance per unit lighting power density, we found that at common modern task illuminance levels (300-lux) tunable LED pendants required the least incremental energy to meet circadian criteria. CCT correlated positively with key circadian performance metrics.
- We outlined draft performance criteria for specifying energy-efficient circadian lighting. The rank order of specified criteria is photopic (visual) efficacy first, followed by circadian criteria. Specifying the highest combination of photopic efficacy and Melanopic Daylight Efficacy Ratio (m-DER) may help to identify the most efficient solutions.

TABLE ES-1. SUMMARY OF ENERGY IMPACTS

	500-LUX CONDITION		300-LUX CONDITION	
	ANNUAL ENERGY USE INTENSITY (KWH/FT^2/YR)	ANNUAL ENERGY IMPACT RELATIVE TO LED BASELINE	ANNUAL ENERGY USE INTENSITY (KWH/FT^2/YR)	ANNUAL ENERGY IMPACT RELATIVE TO LED BASELINE
A1. Baseline high-efficacy dimmable LED troffers, no circadian criteria	1.10		0.65	
B2. Dimmable LED troffers, met circadian criteria with 4 hr. intensity increase	1.22	11% more	0.92	42% more
C1. Tunable LED troffers, met circadian criteria with 4 hr. CCT and intensity increase	1.30	18% more	0.92	41% more
C2. Tunable LED pendants, met circadian criteria with 4 hr. CCT and intensity increase	1.34	21% more	0.85	31% more

Note: Energy impacts occur between the hours of 9 am and 1 pm and are therefore off peak.

SUMMARY RECOMMENDATIONS

Based on findings from this project, we developed recommended research priorities and goals to further advance understanding in this field, as well as recommendations to promote energy efficiency in circadian lighting design. These include:

- Specifying LED lighting with high photopic efficacy (a minimum of 125 or 130 lumens/W).
- Specifying LED lighting with high m-DERs (a minimum of 0.69 to 0.80).
- Implementing high-efficiency tunable white or higher-CCT non-tunable LEDs to minimize the incremental energy cost of circadian design.
- Using basic intensity (dimming) controls to schedule increases in light levels to meet circadian criteria only during specified circadian performance periods.
- Prioritizing daylighting, when possible, to minimize or eliminate extra energy needed for circadian criteria.

Utilities, in the role of customers’ trusted energy advisors, can help relay the findings and recommendations from this project to customers who are interested in implementing LED retrofits with circadian criteria in commercial offices. Recommendations for efficient circadian design at the lowest-possible incremental energy cost could also be included in utility codes and standards development efforts. Additionally, education programs for installation and implementation contractors, such as California's Advanced Lighting Controls Training Program (CALCTP), could be updated to include curricula on energy-efficient circadian lighting equipment and strategies based on this study’s findings.

ABBREVIATIONS AND ACRONYMS

ANSI	American National Standards Institute
CALCTP	California's Advanced Lighting Controls Training Program
CCT	Correlated Color Temperature, in degrees kelvin
CEC	California Energy Commission
CHPS	Collaborative for High Performance Schools
CIE	International Commission on Illumination (*Commission Internationale de l´Eclairage*)
CL_A	Circadian Light
CRI	Color Rendering Index
CS	Circadian Stimulus
D65	CIE reference daylight source, at 6500 K
DGP	Daylight Glare Probability
DIN	German Institute for Standardization (*Deutsches Institut für Normung*)
DLC	Design Lights Consortium
DOE	United States Department of Energy
DOS	United States Department of State
DR	Demand Response
E_H	Horizontal Illuminance
EML	Equivalent Melanopic Lux
EPRI	Electric Power Research Institute
EUI	Energy Use Intensity, typically expressed in energy per unit time and often normalized by area, e.g., kWh/ft^2/year
E_V	Vertical Illuminance
ft^2	Square Foot
GSA	United States General Service Administration
HDR	High Dynamic Range
IES	Illuminating Engineering Society
IGU	Insulated Glass Unit

ipRGC	Intrinsically Photosensitive Retinal Ganglion Cells
ISO	International Organization for Standardization
K	Kelvin
kWh	Kilowatt-Hour
LAN	Light at Night
LBNL	Lawrence Berkeley National Laboratory
LD&A	Lighting Design and Architecture Magazine
LED	Light-Emitting Diode
LPD	Lighting Power Density, expressed in watts divided by floor area
LPW	Lumens Per Watt
LRC	Lighting Research Center
LRV	Light Reflectance Value
m^2	Square Meter
M&V	Measurement and Verification
m-DER	Melanopic Daylight Efficacy Ratio
mEDI	Melanopic Equivalent Daylight Illuminance
nm	Nanometer
PNNL	Pacific Northwest National Laboratory
RGB	Red / Green / Blue
SCE	Southern California Edison
SCN	Suprachiasmatic Nuclei
SI	International System of Units of Measurement (*Système International*)
SLR	Single-Lens Reflex
SMUD	Sacramento Municipal Utility District
SPD	Spectral Power Density
UGR	Unified Glare Rating
UL	Underwriters Laboratories
W	Watt

CONTENTS

FIGURES

TABLES

INTRODUCTION

Significant research efforts in the last 20 years have been conducted on the non-visual (or non-image forming) effects of light, including on human circadian health. In the early 2000s, scientists identified novel photoreceptors (Intrinsically Photosensitive Retinal Ganglion Cells, or ipRGCs) in the eye involved in circadian regulation [1], and we now understand that exposure to adequate light during the day is crucial for circadian health (physiological synchrony with the day/night cycle). Based on this understanding, circadian design is becoming a new priority for office lighting systems.

Commercial tunable white LED fixtures are marketed for visual and health benefits and are often proposed to meet new circadian priorities, because changes in color temperature, which fundamentally correspond to changes in spectral power distribution (in other words, the quantities of lighting power at different wavelengths of electromagnetic radiation) can affect circadian performance. Tunable white lighting may play a role in emerging lighting design principles for circadian benefits. When coupled with connected controls, tunable LEDs can enable dynamic lighting strategies, such as varying color temperature and intensity, when needed to provide enhanced spectral content in the wavelengths most effective at activating the circadian system.

The Design Lights Consortium (DLC) defines color tunable LEDs as "products whose CCT can be adjusted via an input control of any type and whose chromaticity approximately follows the blackbody locus, providing white light at all input configurations … while maintaining nominally constant lumen output … white-tunable products include both 'white-white' products that combine the output of two LED primaries, and products with three or more white and/or red/green/blue (RGB) LED primaries [2]." The number of market-available tunable white LED fixtures has grown significantly in recent years. For example, in the DLC's widely-used Qualified Products List, for which LED products qualify based on rigorous technical performance requirements, of more than 175,000 listed troffer and linear ambient fixtures and retrofit kits from myriad manufacturers, almost 5,000 are tunable white models [3].

Though there is now a better understanding of the circadian impact of the lighting environment, significant gaps remain between general recommendations about circadian lighting design and quantitative data on lighting system performance and energy implications. The key question is: what are the energy impacts of meeting circadian criteria using tunable white LEDs compared to a lighting design that uses non-tunable LED systems to only meet traditional visual criteria? To date, limited lab research has been carried out on this topic, with most studies relying on computer simulations and mathematical models. There is clearly a need for applied research to collect important data in real physical space, to validate or refine our current understanding of the impacts and benefits of these strategies in commercial applications.

As the technology (tunable LEDs) and the practice (circadian design) evolve, it is critical that lighting designers, building owners/operators, and electric utilities and program implementers understand the energy implications and think about potential strategies that provide visual and health benefits without dramatic increases in energy usage. The motivation for this project is to bridge this gap with research using commercially-available lighting products implemented for visual and circadian performance criteria, and to quantify visual performance (photopic illuminance and glare levels), circadian performance – Melanopic Equivalent Daylight Illuminance (mEDI) and Circadian Stimulus (CS) – and lighting energy consumption.

REPORT STRUCTURE

The Introduction section of this report spells out the project's motivation and objectives. The Background section provides a general discussion of the science and research around lighting and circadian health, including an introduction of the dominant models for measuring and quantifying circadian performance. We review some of the circadian lighting design guidance and recommendations available today, and present a literature review of some of the research around circadian lighting in offices, as well as energy impacts informing this project.

The Assessment Objectives section states the project goals, and the Technology Evaluation section provides an overview of the lighting systems to be evaluated and circadian lighting strategies to be implemented, including tunable white lighting strategies. The Test Methodology section details the setup, test, and measurement plans, and the experimental performance specification developed to guide the lighting system lab implementation. Several photographs show how the experiment was conducted at LBNL's FLEXLAB.

The Results section summarizes the data collected during lab testing, and discusses the results of our analysis in terms of the energy impacts of implementing non-tunable and tunable lighting systems in interior and perimeter office zones to achieve circadian goals. It also includes evaluation results related to the lighting systems' visual performance, and provides a detailed section on the tunable lighting system options' comparative circadian performance, in terms of circadian impact per unit lighting power density.

This report concludes with the Discussion, Conclusions, and Recommendations sections, which discuss project findings, how they relate to existing standards and best practices, and the "big picture" of circadian design energy impacts. These sections elaborate on performance specifications that could be developed based on this work, and provide recommendations derived from lab tests and results, including an outline of important future research opportunities in this field.

BACKGROUND

To understand the context in which this evaluation takes place, it is important to consider the fundamental science that has brought circadian lighting to the fore. The ways lighting and circadian health interact have been discovered in recent decades. Models for measuring and quantifying light in units relevant to circadian effect are even more recent developments. This section reviews some of the applicable circadian lighting science and summarizes the prominent models for quantifying light in circadian terms.

Circadian design guidance has not been published by the major international bodies that promulgate recommended practices for lighting, and there remains a need for translating the science of circadian lighting into practical applications. Some recommendations and guidelines have emerged from organizations involved in building and equipment standards, and the existing circadian guidance is discussed below. Finally, as this project is concerned with the energy implications of circadian lighting criteria, we include a literature review of recently-published research on this type of lighting and energy, particularly in commercial office spaces.

CIRCADIAN LIGHTING SCIENCE

Light sensed by the human eye provides crucial visual information (for example, image formation in the brain) but research shows it also plays an important role in phenomena related to human health and wellbeing (so-called *non-image-forming functions*). A major scientific finding in lighting and neurophysiology in the early 2000s was the identification of novel photoreceptors in the eye (ipRGCs) which contain the photopigment melanopsin [1]. The ipRGCs, with a unique spectral response peaking in the blue range (around 480–490 nm) [4, 5], along with some input from the “classic” cone and rod photoreceptors [6], are responsible for circadian phototransduction. Light information on the retina, mediated by these photoreceptors, projects via the retinohypothalamic tract to Suprachiasmatic Nuclei (SCN) in our brains, the “internal clocks” that control biological circadian rhythms (including daytime melatonin suppression in the pineal gland) [7]. Thus, exposure to light stimulus helps maintain synchrony between the biological clock and the natural day/night cycle and regulation of the sleep-wake cycle. This system has also been found to play an important role in other physiological effects, including pupillary constriction, acute alerting effects, and neuroendocrine regulation [8].

Traditionally, lighting design principles have focused only on visual criteria, such as luminance (intensity from a source per unit area, in candela/area) and illuminance (lumens/area), characterized by the photopic luminous efficiency function, V(λ) [9], which describes the light we see by weighting radiative flux incident on the retina according to the cone photoreceptors’ spectral response and peaking around 555 nm. With the emergence of circadian lighting science, the lighting manufacturing and design community is beginning to include nonvisual impacts in product developments and design goals. The appropriate “dose” of light throughout the day for circadian benefit, however, is a complex quantity; a function of timing, duration, spectral content of irradiance, intensity, and even history of prior exposure [10].

MODELS FOR QUANTIFYING CIRCADIAN PERFORMANCE

Consensus is still developing on how to measure and calculate the circadian effects of lighting and what quantities are recommended for day-active people. Two models have emerged for converting spectral data into useful circadian response units. Both rely on high-resolution spectral irradiance measurements; in other words, simply measuring photopic illuminance is not sufficient to understand the physiological effects of lighting present in spaces. These models are important to summarize here, because the metrics and units they propose are the basis for current guidance on circadian lighting design.

MEDI

A seminal paper, *Measuring and Using Light in the Melanopsin Age*, was published in 2014 [8] based on the collective efforts of many researchers in the fields of neurobiology, neuroscience, and lighting science. It details light exposure’s role in regulating circadian systems and the influence of ipRGCs, summarizing the neurophysiology and recommending measurement strategies. The paper proposes spectral efficiency functions to convert spectral intensity data into equivalent lux for each retinal photoreceptor type (short, medium, and longwave cones, rods, and melanopsin) with an accompanying Excel-based toolbox. Applying the empirical melanopsin action spectrum of the ipRGCs, Equivalent Melanopic Lux (EML) can be calculated from spectral intensity data, which is meant to be a quantity comparable to photopic lux (illuminance) but for the melatonin-suppression effects of light. The paper does not include recommendations for lighting design or appropriate quantities of light for circadian benefits.

More recently, the International Commission on Illumination (CIE) published S026:2018 *CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light* [11], which formally defines “spectral sensitivity functions, quantities, and metrics to describe radiation for its ability to stimulate each of the five photoreceptor types that can contribute . . . to retina-mediated, non-visual effects of light in humans.” Formal units of these quantities are given in compliance with the International System of Units and Measurements (SI). This system of metrology proposes the quantity of mEDI, which uses a normalization constant to describe lighting in terms of the quantity of reference daylight, in photopic lumens (CIE D65 6500 K reference light source) that would produce the equivalent melanopic response. mEDI has since become a commonly-referenced measure for circadian lighting practice.

CS

The Lighting Research Center (LRC) has also developed a method for quantifying spectral irradiance for the circadian effect, relying on a phototransduction model weighted by the spectral sensitivity of the human circadian system [12], based on published action spectrum data for acute melatonin suppression [6]. This model includes the effects of all photoreceptors on melatonin suppression, and involves a non-additive, non-linear response to polychromatic light sources due to known spectral opponency input to the ipRGCs from the blue-yellow (b-y) color channel. The model first converts vertical irradiance at the eye to the quantity Circadian Light

(CL_A). A transfer function then relates exposure to a given level of CL_A to effectiveness of CS, from threshold (CS = 0.1) to saturation (CS = 0.7). The LRC publishes a calculator for converting Spectral Power Density (SPD) data into CL_A and CS [13].

CIRCADIAN LIGHTING GUIDANCE

To date, limited lighting design guidance has been developed to help translate the science of circadian lighting into practical applications in the built environment. The two most prominent international bodies involved in developing and promulgating consensus-based lighting standards and recommended practices are the Illuminating Engineering Society (IES), based in North America, and Europe's CIE. Neither the IES nor the CIE has proposed a recommended practice for circadian lighting at this point, but both organizations do have committees working toward standards development in this area.

The IES's Light and Human Health Committee, made up of lighting scientists and experts, put forward a technical memorandum on the effect of light on human health in 2008, reaffirmed in 2018 (IES TM-18-08) [14]. The IES is eventually planning to publish a report titled *Recommended Practice for Supporting the Physiological and Behavioral Effects of Lighting in Daytime Environments* [15]. The CIE held an important international workshop on circadian and neurophysiological photometry in 2013, and released a technical note summarizing the workshop's conclusions [16]; a second independent workshop on the subject reconvened in 2019. The CIE has since released a position statement on the non-visual effects of light [17]. This statement supports the use of International Standard CIE S 026:2018 (discussed above) which defines spectral sensitivity functions, quantities, and metrics for circadian effects [11]. The position statement advocates for specifications of circadian design in the indoor lighting environment to be written in terms of mEDI, and clarifies that the CIE is working on revising its international standard for indoor office lighting, ISO 8995-1:2002/CIE S 008:2001, to include guidance on appropriate daytime light exposure for circadian health.

Currently, the most prominent circadian guidance that might be referenced by commercial office project lighting designers comes from the WELL Building Standard®, developed by the International WELL Building Institute™ as a rating system focused on building design for health and wellness [18]. The Q1 2020 version of the WELL Standard, WELL v2, in Feature L03 Circadian Lighting Design requires specific CL_A levels for at least the hours between 9 am and 1 pm (Table 2).

TABLE 2. CIRCADIAN LIGHTING REQUIREMENTS FROM THE WELL BUILDING STANDARD

OPTION 1	OPTION 2 (PROJECTS WITH ENHANCED DAYLIGHT	POINTS
At least 150 EML [136 melanopic equivalent daylight D65]	The project achieves at least 120 EML [109 melanopic equivalent daylight D65] and L05 Part 1 or L06 Part 1 (daylight strategies).	1
At least 240 EML [218 melanopic equivalent daylight D65]	The project achieves at least 180 EML [163 melanopic equivalent daylight D65] and L05 Part 1 or L06 Part 1 (daylight strategies).	3

Note: Per Light Feature L03 Part 1, the above light levels are achieved for at least four hours (beginning by noon at the latest) at a height of 18 inches above the work-plane (vertical plane, at eye) for all workstations in regularly occupied spaces [18].

Underwriters Laboratories (UL), a globally recognized organization for development, testing, and certification of safety and performance standards, released *Design Guideline 24480 for Promoting Circadian Entrainment with Light for Day-Active People* [19] in 2019. This guide outlines performance goals for indoor lighting that encompass circadian performance as well as quality illumination. The guideline generally calls for lighting of greater than or equal to 0.3 CS in the indoor environment for at least two hours between 7 am and 4 pm. The document includes a "quick guide" with steps to achieve the goals with specific lighting levels and times of day, various examples of methods to achieve the goals, and research supporting the guideline.

It should be noted that the IES has released a Position Statement on UL Guideline 24480 [15], urging the lighting industry to exercise caution in using the UL guidance, emphasizing standards for circadian lighting should be based on consensus developed through an accredited American National Standards Institute (ANSI) process. The IES points out that the UL guidance is not an ANSI consensus document.

Because the CIE system relies on long-accepted SI units (the photopic lumen and derivatives) it is quickly gaining broader acceptance as the way to characterize lighting for circadian purposes, hence the adoption of mEDI in existing guidance. The CS model has been around for several years, however, and has been referenced by early adopters in circadian lighting design, including earlier versions of the WELL Building Standard, and is the model proposed by the UL-recommended practice. However, because it essentially develops novel units (CL_A and CS) that are not SI-approved or ANSI accredited, the CS approach has not been universally accepted (see the IES position statement).

Other standards and guidelines on circadian lighting design include:

- Collaborative for High Performance Schools (CHPS) standard [20]

  The 2020 U.S. CHPS standard, version 2.0, includes in its requirements for indoor environmental quality a section on electric lighting performance and circadian lighting (EQ C14.1). The requirement states that all classroom spaces must demonstrate appropriate EML or CS levels (defined as 200 EML or "equivalent" CS) at 75% or more of desk spaces for at least four hours per day (9 am to 1 pm).

- DIN SPEC 67600 Biologically effective illumination – Design guidelines [21]

  This relatively older guidance on circadian lighting practice, published by the German National Standards organization *Deutsches Institut für Normung* (DIN) in 2013, includes prescriptions for "biologically effective illumination" schedules, including those for office spaces where vertical illuminance (E_V) at the eye of 250 lux (photopic) at a CCT of 8,000 K is recommended for at least several hours in the morning, followed by lower E_V (200 lux) at a lower CCT (3,000 K) in the afternoon.

- LRC's Designing with CS [22]

  The design principle of providing a CS of 0.3 to building occupants for some hours of the day has been found beneficial, and is a design principle put forward in a popular *Lighting Design and Architecture* (LD&A) article by the LRC. With dimmable, tunable LED fixtures and controls, this can be achieved by scheduled changes in lighting intensity and color temperature.

LITERATURE REVIEW: CIRCADIAN LIGHTING AND ENERGY IMPACTS

Jarboe et al. [23] used photometric modeling to look at more than 100 combinations of light fixtures, spectral power distributions, and photopic illuminance targets to evaluate strategies for efficiently delivering CS (0.3 or greater) in offices. The research compared results in terms of the ratio of circadian performance, in units CS, per lighting power density (lighting power normalized by area) for the various strategies modeled. The most effective standard overhead lighting fixture configuration the study found for meeting circadian criteria at the least energy was LED troffers at a high color temperature of 6,500 K, though the authors acknowledged such a high CCT might not be accepted by office occupants. An even more efficient strategy tested was supplementing overhead lighting with a low-wattage desktop blue light source facing the occupant. The research also emphasized the importance of vertical-to-horizontal illuminance ratios (E_V/E_H) based on fixture luminous distributions, showing fixtures with higher E_V/E_H ratios were more effective at providing CS.

Another recent simulation-based study on the energy impacts of circadian lighting criteria is by Safranek et al. [24]. This study estimated energy impacts of circadian lighting in offices and classrooms through 45 unique simulations with different fixture outputs and spectral contents, surface spectral reflectances, and desk and view orientations. These authors used circadian design criteria similar to those adopted for this project (discussed in Section 3 below) and found that meeting IES illuminance recommendations was insufficient for attaining circadian goals. This study found lighting energy increases from 10% and 100% to meet circadian recommendations, with a 31% annual energy increase specific to an office environment with high-CCT lighting where lighting power is increased to meet circadian criteria for only a four-hour circadian period per day.

Dai et al. [25] discussed mathematical modeling to determine optimum spectral power densities to achieve a circadian effect (a CS of 0.35) at a lower energy cost. This study used a theoretical approach to developing a new fixture-radiant design space (in contrast to the applied research approach we undertook here). Researchers created a hypothetical improved white light source by mathematically color mixing different LED chips and phosphor combinations to arrive at a system meeting a target CS of 0.35 at an energy savings of up to 29% compared to a traditional high-photopic efficacy design.

Graeber and von Erberich [26] described research funded by the California Energy Commission (CEC) and carried out at the California Lighting Technology Center (CLTC) that compared melanopic efficacy, or melanopic radiant flux (not normalized to equivalent daylight) divided by photopic luminous flux, of over 200 light sources for which SPDs were available. The study found melanopic efficacy positively correlated with the common color fidelity metric Color Rendering Index (CRI) and higher-CCT, higher-CRI sources were the most efficacious from a melanopic standpoint. Reductions in photopic efficacy (lumens/W) for the higher-CRI sources were roughly made up for by increased melanopic efficacy. For a CRI increase from 80 to 90, melanopic efficacy improved about 10% for most color temperatures. The authors concluded that when designing lighting with circadian goals, it may be more energy efficient to use high-CRI phosphor converted blue-pump LEDs rather than tunable white options (multiple LED chip sets to achieve color tuning).

The Sacramento Municipal Utility District (SMUD) has studied the health and behavior impacts of tunable lighting in education settings [27], finding significant energy savings relative to the fluorescent baseline with the tunable lighting system, though system costs were 36% higher than a standard LED solution. The SMUD school projects were also part of a U.S. Department of Energy (DOE) evaluation carried out by Pacific Northwest National Lab (PNNL) on tunable LEDs, energy usage, and circadian performance [28]. The DOE study found that photopic illuminance levels in classrooms may not provide enough light to meet circadian recommendations in terms of CS or EML. The project used a tunable lighting system, measuring results for three CCT settings providing color temperatures at about 6300 K, 4300 K, and 2700 K, all at a 50% intensity setting. PNNL measured E_V and SPD at seated eye height and calculated CS and EML from SPD data. Only the highest color temperature setting at 50% intensity was able to meet the CS target of 0.3. Overall, it was found that illuminances and lighting energy use would need to increase to satisfy recommendations for circadian metrics.

The U.S. General Services Administration (GSA) has also carried out various circadian lighting studies in federal office buildings in the past several years [29]. In *A Case for Circadian Lighting in Federal Buildings* [30] from the Office of Federal High-Performance Green Buildings, the GSA summarizes findings from its studies in five different federal buildings on connections between light and federal office worker health. It identifies various strategies for improved circadian lighting conditions, including daylight prioritization (windows, controls, and integration with electric lighting systems) and attention to interior furniture layout and colors, finishes, and surface reflectances. The LRC has worked with GSA to study connections between lighting and health in federal offices, finding office workers with higher office lighting exposure in the morning had improved sleep and mood outcomes. Figueiro et al. [31] also discussed a federal building case study on lighting and circadian health. Data from the case study confirmed office light exposure promoted circadian entrainment and improved alertness. Office workers were recruited from U.S. Department of State (DOS) facilities, and a novel light source was tested on their desks with programmed lighting interventions designed to promote entrainment and alertness. We found no analysis of the lighting energy implications of circadian interventions in the GSA office studies.

ASSESSMENT OBJECTIVES

Circadian performance is a new priority for office lighting designers, as research has shown the lighting environment exerts an important circadian effect on human health. Because light's color temperature can influence circadian effectiveness, tunable white LEDs are often proposed to meet circadian priorities. This assessment intended to measure the energy impacts of meeting circadian criteria with tunable white LEDs in offices, using select commercial lighting systems specified for visual and circadian performance criteria and operated according to standard office lighting schedules and profiles.

The test had two goals: (1) to produce data on tunable and circadian lighting performance and energy usage in office environments through testing at LBNL's FLEXLAB; and (2) to develop recommendations for implementation based on lab findings. The tested lighting solutions included standard (non-color tunable) dimmable LED luminaires and tunable white LED systems (troffer and pendant form factors) to explore the impact of different spectral power distributions and color temperatures on circadian effects, including schedules with intensity and color temperature changes through the day, to meet circadian performance criteria.

TASKS

- Evaluate commercial tunable LED lighting systems for circadian performance, visual lighting performance, and energy efficiency.
- Evaluate the potential of tunable white LEDs to optimize circadian performance.
- Develop strategies based on tunable white technology to minimize energy consumption and meet circadian criteria.

TECHNOLOGY EVALUATION

This evaluation essentially focuses on a new technology (tunable white LEDs) and a new category of lighting design criteria (circadian performance) applied in commercial office spaces. As we discussed in the Introduction section of this report, the number of market-available tunable white LED fixtures has grown significantly in recent years. These products are often marketed for application in circadian lighting design, which is becoming a priority in some office installations as designers recognize the important role of lighting in circadian health. Though limited circadian design guidance is available, circadian criteria, such as those included in the WELL Building Standard, may play an increasingly-important role in lighting design and implementation going forward.

This evaluation sought to identify the energy impacts of meeting circadian criteria using tunable white LEDs in an office compared to non-tunable LED systems to meet only traditional visual criteria, such as minimum task illuminance values. A non-tunable LED lighting system was considered as the baseline for this evaluation, since it is now standard in commercial offices. This system was specified to meet minimum average illuminance criteria at the task (300-lux and 500-lux test conditions) and consisted of 2' x 4' troffer-style dimmable LED fixtures. Retrofit lighting options compared against this baseline included the same non-tunable system with intensity adjusted to meet circadian criteria; tunable white, dimmable 2' x 4' LED troffers specified to meet visual criteria and circadian criteria; and tunable white, dimmable 4' LED pendant fixtures with direct (downward) and indirect (upward) luminous distributions.

CIRCADIAN LIGHTING STRATEGIES

This technology evaluation considered tunable white LED fixtures, because changes in color temperature can potentially improve circadian performance. Other lighting strategies have also been identified to achieve circadian goals, from increasing lighting intensity with dimming controls to relying on daylighting, where available, to provide the recommended circadian stimulation. Combinations of the strategies discussed below will likely be used to achieve circadian targets in office environments. All of these strategies, except for desktop circadian lighting devices, were considered and quantified in some way in the design and implementation of this technology evaluation.

TUNABLE WHITE LED LIGHTING

Tunable white controls allow for dynamic CCT adjustments that may be used to enhance circadian performance. Higher color temperature lighting tends to be more effective at producing a circadian response, because the melanopsin action spectrum is most sensitive to shorter wavelengths, which are typically more abundant at higher color temperatures (see the Results section of this report, and Figure 23, for a more thorough discussion and illustration of this point). A design strategy for circadian lighting using tunable white LED products may include schedules of higher CCT lighting at certain times of day, since this can increase the effectiveness of the light source at circadian stimulation. The degree of impact on circadian performance must be compared to the degree of impact from intensity adjustments alone, and occupant acceptance of cooler CCTs also should be considered.

OTHER STRATEGIES

Lighting strategies beyond fixture color tuning are available to optimize circadian performance. Some additional considerations are:

- Daylighting: The typical intensity of outdoor light during daytime hours is much higher than electric indoor lighting. In addition, daylight is broad-spectrum and weighted favorably in the melanopic sensitivity range, and essentially free in terms of energy cost. Therefore, an effective strategy may be to prioritize daylighting, where possible, with facade technologies including blinds, shades, reflection, and redirection. With daylighting, circadian requirements are likely easier to meet, minimizing or negating incremental electric lighting power costs. Building perimeter strategies can offset the electric light needed indoors for circadian criteria. For occupant comfort, installations should minimize daylight glare to prevent user interference such as closing automated shades to block direct daylight in the field of view.
- Intensity (or dimming) controls: Increasing light intensity during circadian periods will increase circadian performance. Some studies have found a greater effect by simply increasing intensity as a strategy for stimulating the circadian system, rather than making changes in spectral content through tunable white fixtures [23].
- Luminous intensity distribution: Fixture design, lensing, and optics that increase the E_V/E_H ratio may increase circadian performance, as a higher E_V ratio essentially means more system light enters the occupant’s retina. Higher circadian stimulation per energy unit can be achieved if more luminous flux reaches the eye, but this carries the potential for greater discomfort from glare, which must be considered for occupant comfort.
- Desktop circadian lighting devices: It may be possible to use a low-wattage on-desk light source, such as an appropriately-lensed panel or lamp, that delivers narrow-band lighting tuned to specifically activate melanopic response. With a closer proximity to the occupant and user-flexible/adjustable orientation, less power would be required for equal circadian activation than from the overhead lighting system, so this could be a more energy-efficient strategy. Some studies have proven the effectiveness of such devices [23, 31]. User acceptance is not yet known, and appropriate design is also important to mitigate glare.

TEST METHODOLOGY AND EXECUTION

The test methodology was designed to evaluate the lighting and energy performance of tunable white LED fixtures used to meet circadian performance criteria. The test plan involved several weeks of testing in FLEXLAB, and monitoring all key lighting performance criteria, including lighting power, task illuminance, glare, and spectral irradiance measurements (W/m^2/nm) converted into circadian units. The test plan was meant to deliver data that could be analyzed in depth to assess how tuning controls and color temperature affect circadian performance, and to identify useful metrics for predicting best performance for the least energy cost. Based on the analysis of collected data, recommendations could be developed for specifying efficient circadian systems and for future research priorities.

TEST SETUP

The locations of the walls, furnishings, workstations, light fixtures, and various measurement points are illustrated in Figure 1. In the 20' wide (east-to-west) by 30' deep test cell, a simple cubicle-style office layout was set up. There were two workstations in the perimeter zone, with desks at about 5' to 10' from the window wall, which is south facing. At 15' from the window wall, a full-height foam wall partition was built to bisect the test cell into two zones of 300 ft^2 each: the perimeter (daylit) zone and the interior (non-daylit) zone. Standard overhead lighting consisting of 2' x 4' troffers is shown in the diagram; the troffer form factor was used in the baseline and the first retrofit configurations. Later, LED pendants were installed, centered in the same locations. The fixtures were installed at a typical office fixture density of one per 80 ft^2 of floor area, servicing 240 ft^2 of office area, which did not include the peripheral floor area for circulation in each office zone.

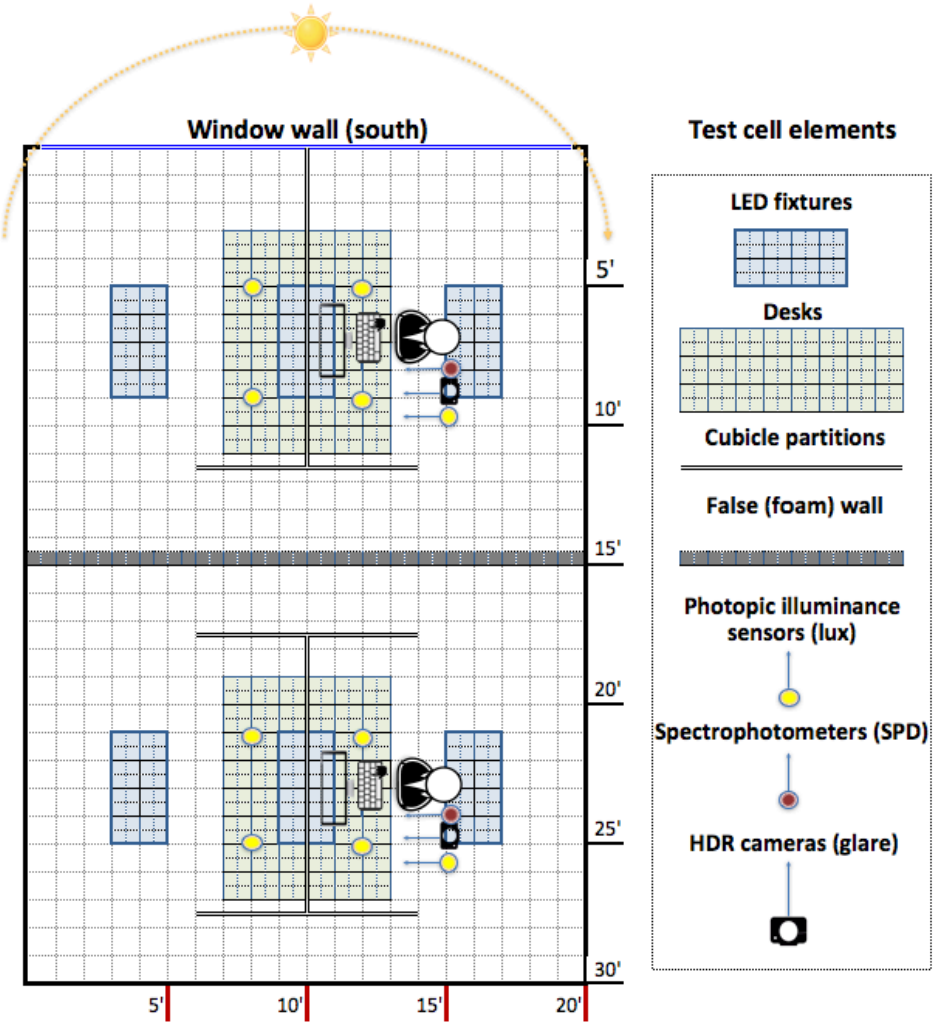


FIGURE 1. FLEXLAB TEST SETUP

Overall lighting system performance is a function of light fixture characteristics and those of the space in which they operate. Table 3 tabulates performance ratings for some of the most important elements in the tests. In addition to features like the light sources' rated luminous efficacy, in Lumens per W (LPW), materials in the room, such as ceilings and walls, interact with the electric lighting system by reflecting incident luminous flux according to their surface reflectances, known as Light Reflectance Values (LRVs). In addition to total LRV, each surface will have a unique spectral reflectance profile at the different wavelengths of incident luminous flux, though this must be measured with a reflectance spectrometer, which was not in the scope of this study. White ceilings and walls, like those in the lab, typically have roughly equal reflectance values across most of the visible range. Surface reflectances of finishes for objects such as cubicle partitions and desks play a role as well, though ratings for these materials were not available. The spectral irradiance measurements taken in the space, primarily at the occupant-view position, included the combined effects of the emitted radiant flux from the light fixtures and the spectral reflectances of the surfaces and objects in the space.

In the perimeter zone, visible light transmitted through the window wall is another important feature, in this case via double-pane Insulated Glass Units (IGUs) with low-emissivity film coating. The window wall's rated transmittance includes the small amount of framing between IGUs, but does not include the effects of the interior blinds, which were lowered across the windows with the louver angle adjusted to mitigate daylight glare.

TABLE 3. RATED PERFORMANCE OF THE TEST COMPONENTS (LIGHTING SYSTEMS, WINDOWS, AND INTERIOR FINISHES)

SYSTEM ELEMENT	PERFORMANCE CRITERION	RATED VALUE
Baseline 2' x 4' LED troffers	Rated luminous output and wattage (maximum)	5684 lumens, 46 W
	Rated efficacy (LPW)	125 LPW
	Nominal color temperature (K)	3500 K
Tunable white 2' x 4' LED troffers	Rated luminous output and wattage (maximum)	4000 lumens, 40 W
	Rated efficacy (LPW)	100 LPW
	Nominal color temperature (K)	3000 K–5000 K
Tunable white 4' LED direct/indirect pendants	Rated luminous output and wattage (maximum)	1050 lumens/foot, 9 W/foot
	Rated efficacy (LPW)	109 LPW (warm white) to 120 LPW (cool white)
	Nominal color temperature (K)	2700 K–6000 K
Perimeter zone south-wall glazing: Double pane IGU, low-emissivity film coated	Visible light transmittance (glass + framing)	0.595
	Window-to-wall ratio	0.48
Interior wall paint	Visible LRV	0.65
Ceiling tiles	LRV	0.88
Carpet	LRV	Unknown (estimated less than 0.20)

TEST PLAN

The test plan was divided into several test phases. For each phase, the intended baseline or retrofit condition and the lighting system used to meet that condition is summarized below. Light fixture specification sheets are provided in Appendix A.

A1. This phase used a baseline non-tunable, dimmable LED system as a standard practice to meet the minimum average illuminance at the task (300-lux and 500-lux test conditions) with no circadian criteria. Included were six DECO brand 2' x 4' troffer-style LED fixtures, with three in each zone (perimeter and interior) and Enlighted wireless controls and sensors. The baseline LED fixtures provided a fixed CCT of 3500 K (nominal).

B1. This phase used the same standard practice lighting and controls system and configuration as the baseline (A1) but system output was adjusted to meet visual performance criteria and circadian performance criteria *all day* (a "worst case scenario" for lighting energy).

B2. This phase used the same lighting and controls system and configuration as the baseline (A1) while meeting visual criteria in the morning and afternoon and adding scheduled intensity increases to meet circadian criteria *from 9 am to 1 pm only.*

C1. This phase used tunable, dimmable LED troffers to meet visual and circadian criteria, and scheduled daily CCT and intensity variations, including higher CCT and intensity from 9 am to 1 pm to meet circadian criteria. Retrofit troffers were six tunable white 2' x 4' LED fixtures with a nominal CCT range of 3000 K to 5000 K. The C1 system consisted of CREE CR series troffers paired with a SmartCast Adjustable CCT Wireless Dimmer, controlled through a SmartCast wireless Intelligence Platform.

C2. This phase was similar to C1, but used tunable, dimmable LED pendants, again meeting circadian criteria with CCT and intensity increased from 9 am to 1 pm. This system included tunable white 4' pendant fixtures with direct (downward) and indirect (upward) luminous distribution and a nominal CCT range of 2700 K to 6000 K. Based on availability and project resources, three such fixtures were installed in the interior zone only. These fixtures were tested in the interior zone from January 6 – 12, 2021, while photometric measurements were simultaneously taken in the perimeter zone without any electric lighting. The pendant system's daylight-dimming performance in the perimeter zone was later calculated based on the performance characterized from interior measurements and daylight measured in the perimeter, adding (as necessary) electric light and power for the perimeter zone when daylight did not meet the 300- or 500-lux task illuminance test condition. The evaluated pendant system consisted of ALW Superplane 2.5 pendants, with two 0 – 10 volt DC channels for proportional dimming and color tuning.

INSTRUMENTATION AND MEASUREMENT PLAN

To quantify lighting system performance during the experiment, the timing, amount, duration, and spectral content of light (spectral irradiance over broad range) was monitored in the test space using various sensors, measurement equipment, and parameters, detailed in the following sections of this report. Table 4 summarizes each parameter, the measurement system used, and the units of the data collected.

From the Measurement and Verification (M&V) data, we characterized visual lighting performance, circadian lighting performance, and system energy performance.

TABLE 4. PARAMETERS MONITORED IN THE LAB EXPERIMENT

MONITORED PARAMETER	MEASUREMENT SYSTEM	UNIT
Spectral irradiance (vertical, eye)	Tripod-mounted compact illuminance spectrophotometers, at occupant seated-view position (4' from floor) facing the workstation	Radiant power density, in W/m^2/nm, from 360 to 780 nm. Converted to mEDI and CS for circadian analysis
Illuminance (horizontal, desk); commonly, "light level"	Illuminance sensors, at desk height (2.5') facing up	Illuminance (lumens/m^2, or lux)
Glare (vertical, eye)	High Dynamic Range (HDR) cameras located at the occupant's seated-view position (4') and facing the workstation, and central processing units for converting the imagery to luminance data and glare values	Daylight Glare Probability (DGP) for the perimeter zone Unified Glare Rating (UGR) for the interior zone
Lighting energy	One-minute average current, voltage, power per circuit	Power (W), energy (kilowatt-hours [kWh]), normalized by area and time: W/ft^2, kWh/ft^2/time (e.g., day or year)

SPECTRAL IRRADIANCE

To determine circadian performance, we used Konica Minolta CL-500A compact illuminance spectrophotometers that measure spectral irradiance at all visible wavelengths (power density per wavelength, in W/m^2/nm) providing SPD measurements at one nm resolution, from 360 nm to 780 nm. These spectral data allow for calculation of circadian metrics, CCT, CRI, and a variety of other lighting quality metrics. Spectrophotometers are much more complex and expensive than typical photopic illuminance sensors, and produce data arrays rather than single points, requiring more processing for data analysis. Accordingly, it was not possible to monitor spectral data throughout the space. Instead, we primarily located spectrophotometers at the location of most significance – the occupant's eye level at seated-view position (though desk-level spectral measurements were taken at times, to supplement). Spectrophotometers were tripod mounted at seated-corneal height, standardized at 4' above the floor, and pointed in the direction of the seated occupant's view. Measurements were taken through each test day, at a defined interval (typically every 30 minutes). A tripod-mounted spectrophotometer was located at one workstation in each zone (perimeter and interior).

Lighting for circadian health was evaluated with the two different metrics, as discussed previously: (1) mEDI, as recommended by CIE and conforming to the standard SI units for photopic luminous flux; and (2) LRC's CS. Monitored spectral data was post processed, to derive mEDI and CS throughout the day.

PHOTOPIC ILLUMINANCE

Photopic illuminance, in lux (lumens/m^2) or foot-candles (lumens/ft^2), is a standard performance criterion for lighting design related to providing adequate light levels for common visual tasks in an office environment. To validate light levels for visual purposes, photopic illuminance sensors were placed on the workplane to capture E_H in lux. Photopic illuminance measurements were taken at one-minute intervals using Licor illuminance sensors. We also computed photopic illuminance from the eye-level spectrophotometer at vertical orientation. From the eye-level E_V and desk-level E_H, we established the ratio of E_V/E_H, which helps describe the lighting system's luminous intensity distribution. The eye-level E_V measurement also allowed us to calculate the ratio of eye-level melanopic equivalent daylight radiant flux to photopic luminous flux (m-DER) discussed in the Results section of this report.

GLARE

Glare is caused by wide or extreme luminance contrast in the field of view, which can lead to discomfort or reduce visual performance, therefore affecting occupant comfort and wellbeing. A variety of glare metrics are used in the lighting industry. A common measure of glare for interior space, with electric lighting only and no daylight source, is UGR. For environments with windows and a combination of daylighting and electric lighting, the DGP metric is commonly used. Glare values in UGR and DGP terms can be computed from high-resolution HDR digital imagery taken by digital Single-Lens Reflex (SLR) cameras.

In this experiment, we measured glare at the same location as the spectrophotometers – the workstation occupant's eye level and view position – representing the field of view occupants experience most. Glare imagery was taken automatically through each day at five-minute intervals. The HDR camera packages include image processing to compute luminance ranges and glare over time.

LIGHTING POWER

The light fixtures' electric power was measured in FLEXLAB over time using lab-grade power measurement circuitry embedded in the test cells at the service panel and junction box levels. Each electric fixture was powered by an individually-monitored circuit so lighting power and energy could be captured over time. Lighting power and energy were then normalized by floor area (ft^2) to compare with the design specification and determine the relative energy performance of the systems and test conditions implemented during the experiments.

PERFORMANCE SPECIFICATION FOR EXPERIMENT

For the FLEXLAB experiment, we defined a performance specification for visual light (illuminance) and comfort (glare), as well as circadian performance (mEDI and CS) and lighting energy usage. The baseline and retrofit LED systems were operated to meet standard visual criteria, principally the IES-recommended practice for minimum average workplane illuminance for desk-based office work [32]. This recommended practice has varied over time from 500 lux in older editions (common in older existing buildings) to current recommended levels of 300 lux (common in many modern office environments). We evaluated performance at both of these design levels.

The lighting systems' performance in terms of glare, which affects occupant comfort, were also evaluated, with maximum glare criteria for perimeter and interior space based on the DGP and UGR metrics, respectively. DGP is based on illuminance at the eye from light sources in the field of view, and the measured luminance and light source position or angle relative to the viewer. The DGP scale is from 0 to 1, with glare classes of imperceptible (<0.35), perceptible (0.35–0.39), disturbing (0.40–0.45), and intolerable (>0.45) [33]. For the perimeter zone, we chose a DGP upper-limit goal of 0.35, since this is the lowest end of what is considered perceptible. The UGR method takes account of the brightness of surfaces (walls and ceilings) and all fixtures in the field of view that contribute to the sensation of glare, with an index ranging from 10 to 30. UGR below 19 is generally recommended for reading, writing, and office work [34]; this is the recommendation we followed for the test specification. The WELL Building Standard UGR limit for offices was below 19 in prior editions, but was lowered to a limit of less than 16 in 2020.

For circadian lighting criteria, we relied on the WELL Building Standard's Feature L03 Circadian Lighting Design [18] and the UL Design Guideline [19]. The longer circadian performance period of the two guidelines, a four-hour period from 9 am to 1 pm, was selected. Lighting energy requirements were drawn from the California Title 24 2019 Building Energy Efficiency Standards [35]. Table 5 lists the performance requirements for visual, circadian, and energy criteria for the FLEXLAB test of commercial office tunable lighting systems.

TABLE 5. PERFORMANCE SPECIFICATIONS FOR THE LAB EXPERIMENT

DESIGN CATEGORY	DESIGN PARAMETER	SPECIFICATIONS	REFERENCE
Visual	Light levels (Illuminance)	Two test conditions: At least 300 lux average at the workplane At least 500 lux average at the workplane	IES RP-1-20, Recommended Practice: Lighting Office Spaces [32] Common practice especially in older systems (existing buildings), previous IES guidance
	Glare	DGP no greater than 0.35 (perimeter zone)	Best practice, developed for this test, with goal of keeping glare at low end of perceptible range [33]
		UGR below 19 (interior zone)	Typical industry guidance; see EN 12464-Lighting of workplaces [34]
Circadian	CS	CS of at least 0.3, at least 2 hours (9 am to 1 pm performance period for our test)	UL Inc. Design Guideline 24480 [19]
	mEDI	At least 218 mEDI vertical, at eye, at least four hrs. (9 am to 1 pm performance period for our test)	WELL Building Standard 2020, Feature L03 Circadian Lighting Design [18]

DESIGN CATEGORY	DESIGN PARAMETER	SPECIFICATIONS	REFERENCE
Energy	Lighting power density	Maximum of 0.6 W/ft^2 (open office)	CA Title 24 (2019) [35]
	Lighting energy use intensity	kWh/ft^2/time. No specified maximum; parameter was used to compare the performance of the systems evaluated.	

TEST EXECUTION

We conducted approximately three weeks of testing in the FLEXLAB experiment, from August 3 to August 14, 2020, and January 6 to 12, 2021. We first characterized baseline lighting system performance, using a dimmable LED troffer system (non-tunable) with scheduled on/off operation (7 am to 7 pm). This system included daylight dimming in the daylit zone, and a lighting power setpoint to meet minimum task illuminance criteria. Then tests were carried out with the same baseline system, but operated to meet visual and circadian criteria. First, lighting power was adjusted to meet circadian criteria all day, essentially a “worst case” scenario from the standpoint of lighting energy. In the next phase, lighting power was increased to meet circadian criteria only from 9 am to 1 pm, which was the circadian period from our performance specification. Finally, two dimmable and tunable white LED systems were tested, with scheduled lighting power and color temperature changes to meet illuminance criteria in the morning and afternoon, and circadian criteria from 9 am to 1 pm (higher CCT and higher intensity). Cooler higher-CCT lighting, with more spectral content in the shorter blue wavelengths, is more effective in eliciting a melanopic response compared to the warmer, lower-CCT lighting. The relationship between color temperature and melanopic response is discussed in more detail in the Results section of this report (Spectral Content, Color Temperature, and Melanopic Equivalent Daylight Efficacy subsection). Details for each test phase are provided in

Table 6 below.

TABLE 6. LIGHTING EXPERIMENT TEST PHASES

TEST PHASE	LIGHTING SYSTEM	PERFORMANCE CRITERIA	OPERATIONAL METHOD	TEST DATE(S)
A1: Standard practice	Baseline dimmable LED system (3500 K nominal, non-tunable)	Visual criteria (300-lux and 500-lux test conditions) all day (no circadian performance criteria)	Fixed lighting power to meet task illuminance criteria; daylight dimming in the perimeter	500 lux: Aug. 3, 2020 300 lux: calculated from Aug. 6, 2020 data
B1: Basic ("worst case") circadian strategy (meet criteria all day)		Visual criteria (300-lux and 500-lux test conditions) and circadian criteria (0.3 CS and 218 mEDI) all day	Higher fixed lighting power to meet circadian criteria (requires more light than visual criteria); daylight dimming in the perimeter	Calculated from Aug. 5, 2020 data
B2: Dimming-based circadian strategy (meet criteria 9 am to 1 pm only)		Visual criteria all day (300-lux and 500-lux test conditions) Scheduled intensity changes for circadian criteria from 9 am to 1 pm	Lighting power set to meet visual criteria in morning and afternoon, and set higher from 9 am to 1 pm to meet circadian criteria; daylight dimming in perimeter	500 lux: Aug. 5, 2020 300 lux: Aug. 6, 2020
C1: Advanced tunable white LED circadian retrofit (LED troffers)	Retrofit dimmable LED troffers with color tuning (3000 K to 5000 K nominal range)	Visual criteria all day (300-lux and 500-lux test conditions) Scheduled intensity changes and CCT changes for circadian criteria from 9 am to 1 pm	Lighting power set to meet visual criteria for morning and afternoon and CCT set to low ("warm") From 9 am to 1 pm: higher fixture power and higher CCT ("cool") to meet circadian criteria; daylight dimming in the perimeter	500 lux: Aug. 13, 2020 300 lux: Aug. 11, 2020

Test Phase	Lighting System	Performance Criteria	Operational Method	Test Date(s)
C2: Advanced tunable white LED circadian retrofit (LED pendants, interior only)	Retrofit dimmable LED pendants with color tuning (2700 K to 6000 K nominal range)	Visual criteria all day (300-lux and 500-lux test conditions) Scheduled intensity changes and CCT changes for circadian criteria from 9 am to 1 pm	Lighting power set to meet visual criteria for morning and afternoon and CCT set to low ("warm") From 9 am to 1 pm: higher power and higher CCT ("cool") to meet circadian criteria Photometric measurements in perimeter zone (no electric lighting), in order to calculate daylight dimming performance	Jan. 6 to 12, 2021

The following photographs show the various elements of the FLEXLAB experiment.[2] Figure 2 shows the interior lighting zones (no daylighting). The foam wall with taped seams and wood furring strips acted as a south wall for the zone, set up to divide the interior from the perimeter zone. It was painted with the same finish as the permanent walls. The two workstations separated by cubicle partitions were centered with respect to the east and west walls, as was the grid of three light fixtures serving roughly 240 ft^2 of office space (peripheral floor area not included). While there were two workstations per zone, only the one shown was monitored with the tripod-mounted spectrophotometer and HDR camera package.

Figure 2. Interior Office Zone Test Setup

---

[2] Images denoted by copyright footer are credited to Lawrence Berkeley National Laboratory, ©2010-2021 The Regents of the University of California, Lawrence Berkeley National Laboratory.

Figure 3 shows the perimeter zone, which was laid out the same as the interior zone but included windows and blinds on the south wall. The blinds were closed for the photograph, but for the test periods, the louvers were tilted at an upward angle (inside edge) of 45 degrees to allow sunlight in while blocking direct rays at the desks to minimize glare. The LED fixtures in this zone were equipped with luminaire-level daylight sensors, to dim the lights based on daylight availability.

FIGURE 3. PERIMETER OFFICE ZONE TEST SETUP

Figure 4 details how the workstations were laid out for the experiments. One workstation each was configured in this manner in the perimeter and interior zone. On the work plane, two photopic illuminance sensors automatically recorded E_H at one-minute intervals. These values were averaged to characterize task illuminance against the performance specification. The laptop situated at the center of the workstation desk was connected to the tripod-mounted spectrophotometer, which took vertical readings at the occupant-view position, recording spectral irradiance data at one-nm resolution (360 nm to 780 nm) for time intervals specified every morning of a given test day (typically every 30 minutes). The spectral data were saved on the laptop hard drive and collected daily for processing into vertical, eye-level photopic illuminance, color temperature, mEDI, and CS. Next to the spectrophotometer were the tripod-mounted digital SLR camera and illuminance sensor, connected to a central processor. These devices took HDR imaging at five-minute intervals each day, and automatically processed the imagery to luminance maps and glare values for the camera's wide-angle lens field of view (120^o).

FIGURE 4. WORKSTATION CONFIGURATION FOR THE FLEXLAB EXPERIMENTS

Figure 5 further illustrates the parallel sensor setup in the occupant-view position. Spectral irradiance was measured using the Konica-Minolta CL500A spectrophotometer shown on the left. Luminance and glare data was collected through HDR imagery using the Canon digital SLR with a fish-eye lens and top-mounted illuminance sensor shown on the right.

FIGURE 5. SPECTROPHOTOMETER AND HDR CAMERA PACKAGE FOR THE FLEXLAB EXPERIMENTS

Figure 6 shows three frames from the seated-occupant point of view, taken from the HDR glare camera during the C2 test with tunable white LED pendants. These images show the system at settings of equal brightness and color temperatures of 2,700 K, 4,000 K, and 6,000 K (upper left, upper right, and lower, respectively).

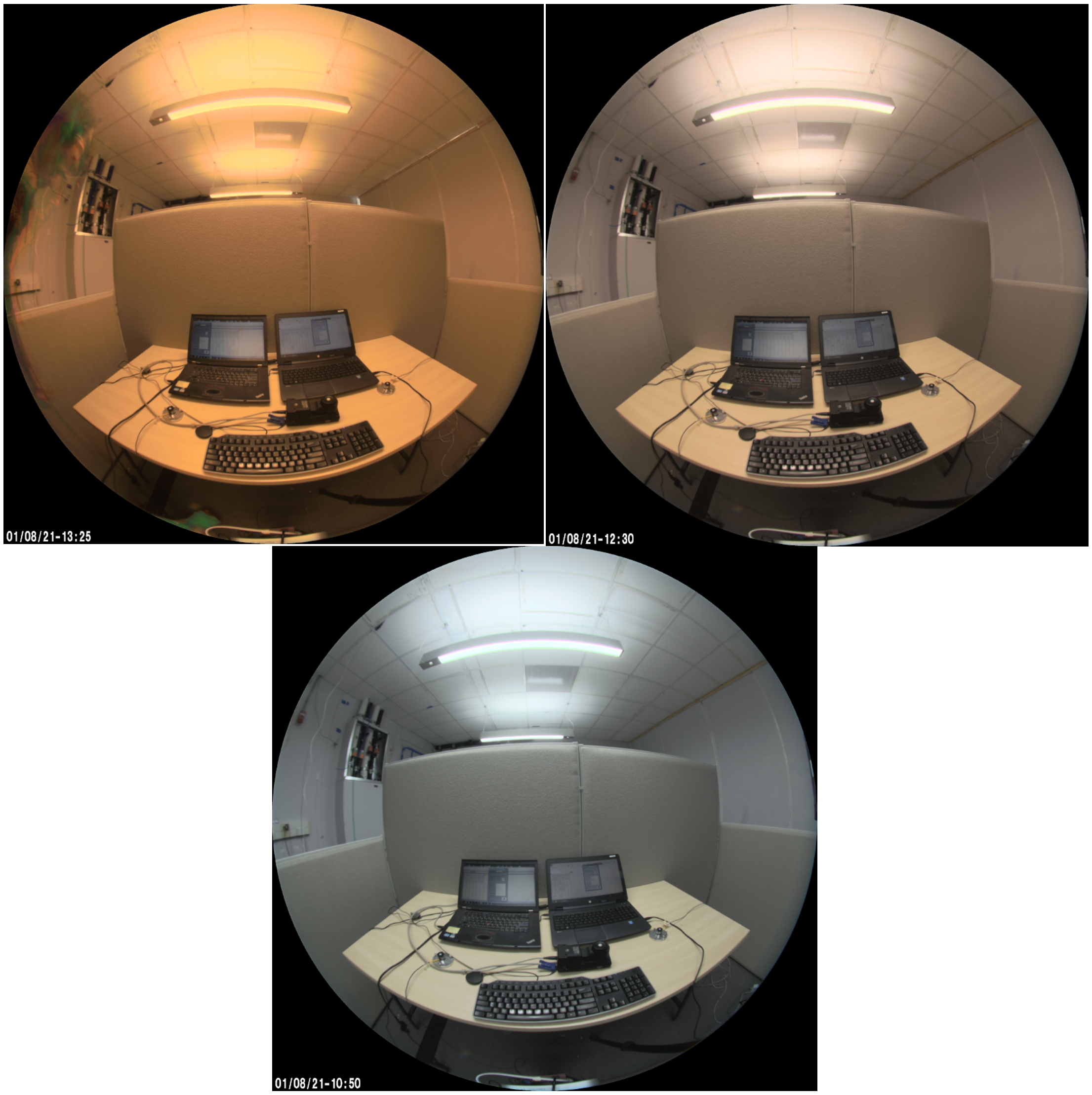


FIGURE 6. PHOTOGRAPHS OF CCT SETTINGS WITH TUNABLE LED PENDANTS

RESULTS

For each test phase, we collected continuous photopic illuminance values at the desk, and lighting power values for each fixture. We normalized lighting power by area, summing wattage for the zone and dividing it by 240 ft^2. At the occupant-view position, we monitored glare at five-minute intervals, and also collected spectral irradiance data, normally at 30-minute intervals, converting those data into CCT, photopic illuminance, and the circadian performance metrics mEDI and CS.

The following plots illustrate one day of monitoring data collected during the FLEXLAB experiments. The plots show time-series task illuminance (Figure 7), lighting power density (Figure 8), mEDI (Figure 9), CS levels (Figure 10), lighting color temperature (Figure 11), and glare values (Figure 12) for the C1 tunable white LED troffer test phase at the 300-lux task illuminance test condition. In Appendix B, similar illuminance, lighting power, circadian criteria, and color temperature plots are provided for retrofit test phases B2 (500- and 300-lux condition), C1 (500-lux condition), and C2 (500- and 300-lux condition).

Following along the x-axis, the monitoring data shows when the lighting system turned on in the morning and off in the evening, and when changes occurred over the course of the day. The orange trendlines for interior data show steady lighting and power levels during the different performance periods each day (standard and circadian). The blue trendlines show perimeter lighting and power levels, which vary due to the influence of daylight through the windows, and corresponding electric light dimming due to daylight. The interior fixtures were scheduled to meet the circadian criteria during the 9 am to 1 pm performance period, which is shown by a shaded area overlaid on the plots. In this window of time, light levels and power increased in the interior zone, and CCT also changed. The design targets for the different performance criteria, such as minimum illuminance at the task (in lux) minimum circadian performance criteria (in mEDI and CS) and maximum lighting power (in W/ft^2) are overlaid on the time-series plots. Please note the monitored data relative to these design targets.

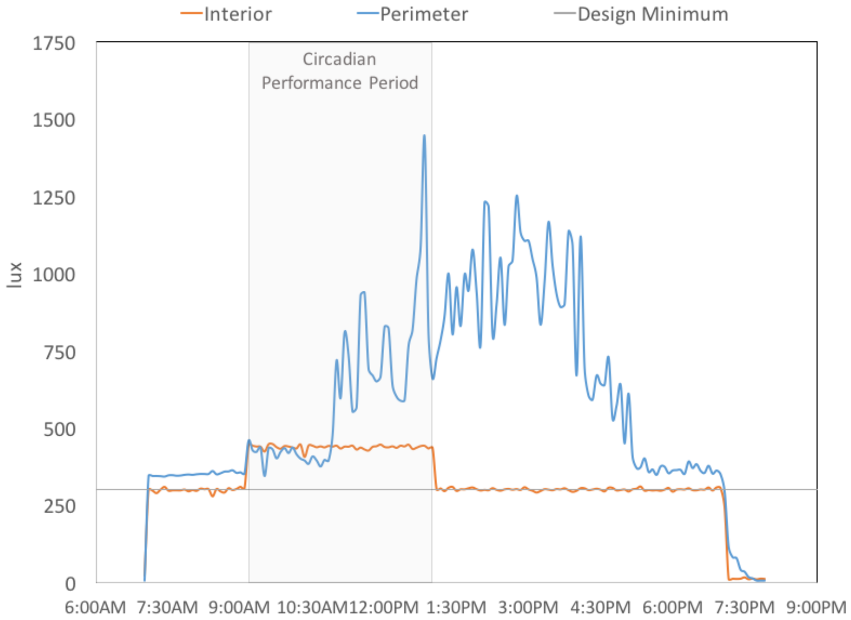


FIGURE 7. TIME SERIES OF TASK PLANE ILLUMINANCE DATA: C1 RETROFIT, 300-LUX TEST

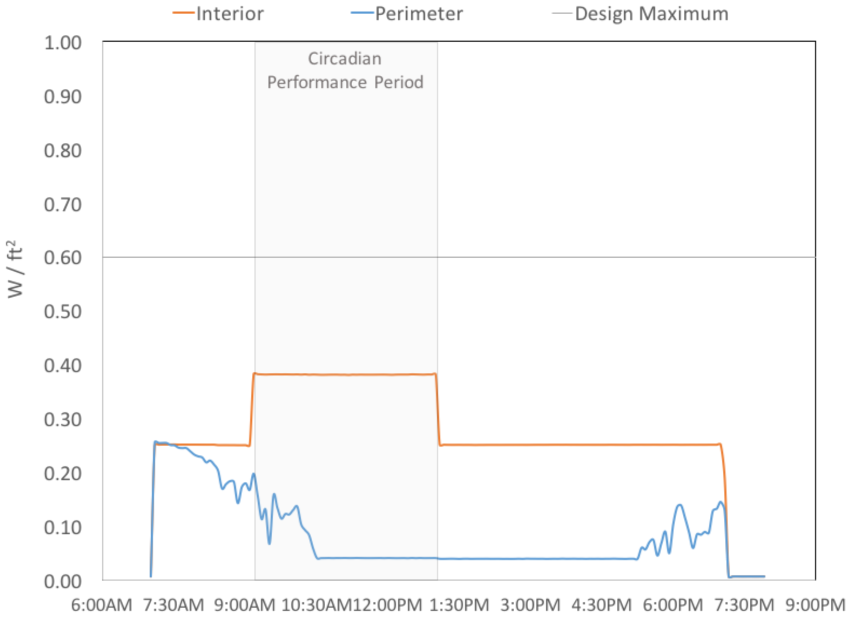


FIGURE 8. TIME SERIES OF LIGHTING POWER DENSITY DATA: C1 RETROFIT, 300-LUX TEST

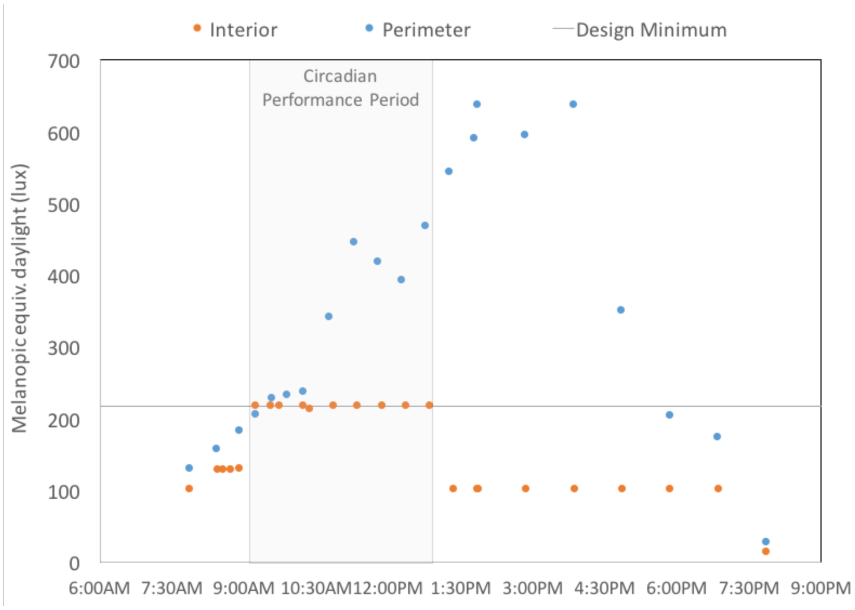


FIGURE 9. TIME SERIES OF mEDI DATA AT OCCUPANT-VIEW POSITION: C1 RETROFIT, 300-LUX TEST

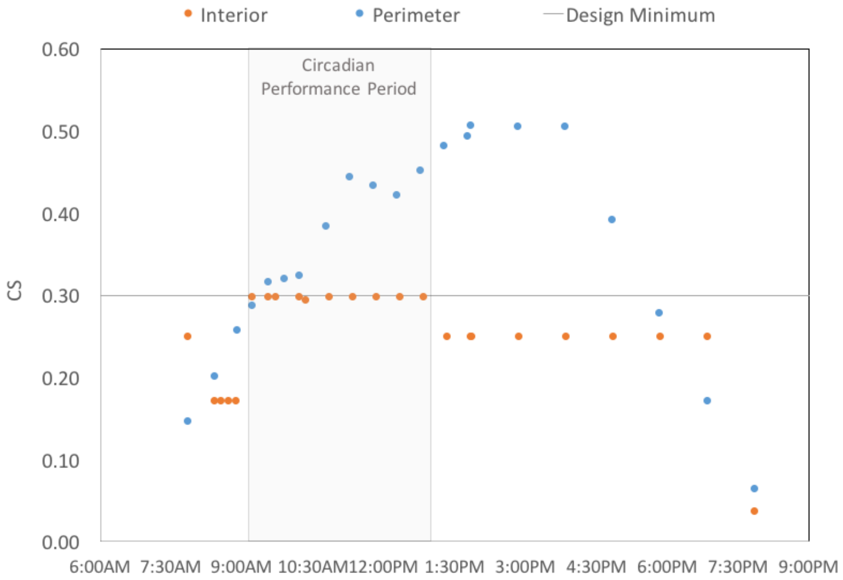


FIGURE 10. TIME SERIES OF CS DATA AT OCCUPANT-VIEW POSITION: C1 RETROFIT, 300-LUX TEST

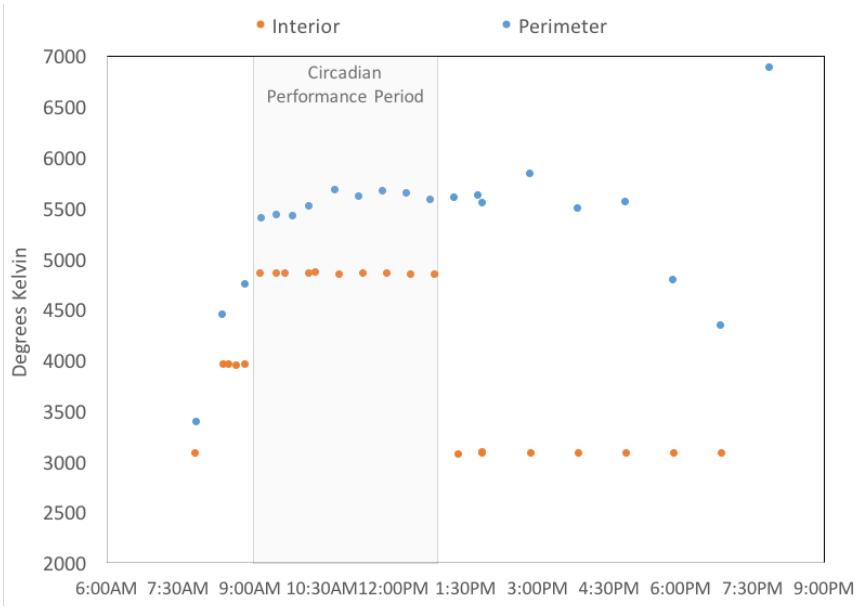


FIGURE 11. TIME SERIES OF CCT DATA AT OCCUPANT-VIEW POSITION: C1 RETROFIT, 300-LUX TEST

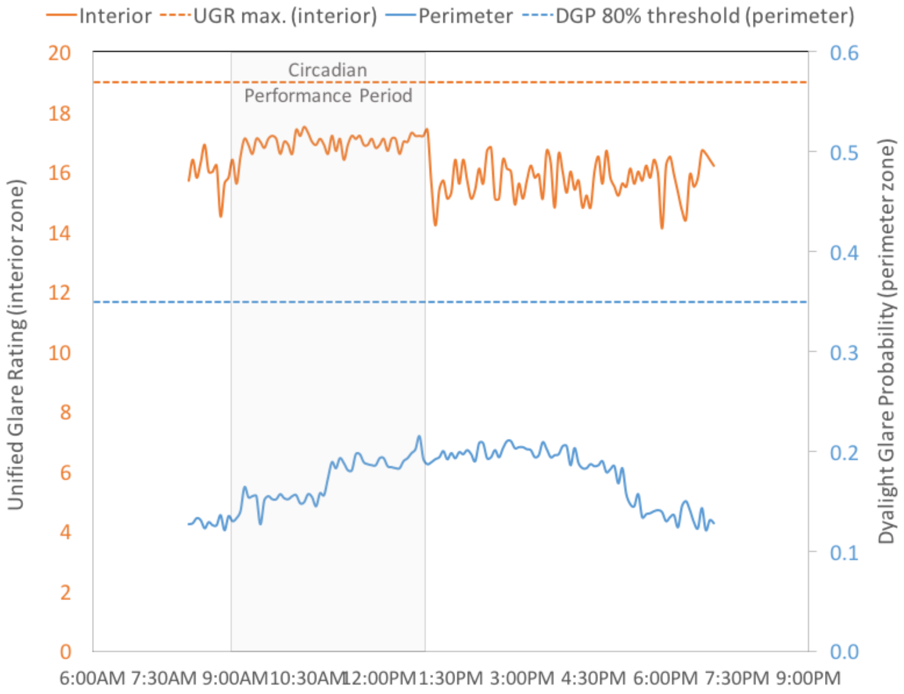


FIGURE 12. TIME SERIES OF GLARE DATA AT OCCUPANT-VIEW POSITION: C1 RETROFIT, 300-LUX TEST

DATA ANALYSIS

ILLUMINANCE AND GLARE

Task illuminance, in units lux (lumen/m^2), was the basic design criterion to which the lighting systems were commissioned. Lighting power setpoints were programmed to provide either 300 or 500 lux, depending on the test condition. We were able to meet these targets with all three lighting systems, without issue.

At the prescribed task illuminance levels, we evaluated glare using HDR imagery and processing. Figure 13 shows false color luminance intensity imagery (candela/m^2) generated by the glare analysis software. The HDR cameras quantified glare conditions from the interior and perimeter zones, using the UGR and DGP values, respectively. Generally, we found all of the lighting systems as tested met the glare criteria laid out in the research performance specification; UGR in the interior zone of below 19, and DGP in the daylit zone of 0.35 or lower.[3] For the range of lighting power settings commissioned for test criteria, the baseline LED fixtures averaged a UGR of 16.7 with a maximum of 18.8 in the interior zone, while DGP averaged 0.18 with a maximum of 0.24 in the perimeter zone. The measured UGR for the tunable troffers in the interior zone averaged 16.7 with a maximum of 18.0, while DGP in the perimeter zone averaged 0.18 with a maximum of 0.23. For the tunable pendants, UGR ranged from 15.8 to 17.5 for the intensities and color temperatures used. The tunable pendants were not installed in the perimeter zone during that test period (see the discussion in the Test Phases section earlier in this report). Therefore, the combined daylight and electric light DGP in the test period zone is not known; however, DGP from daylight alone averaged 0.08 to 0.21.

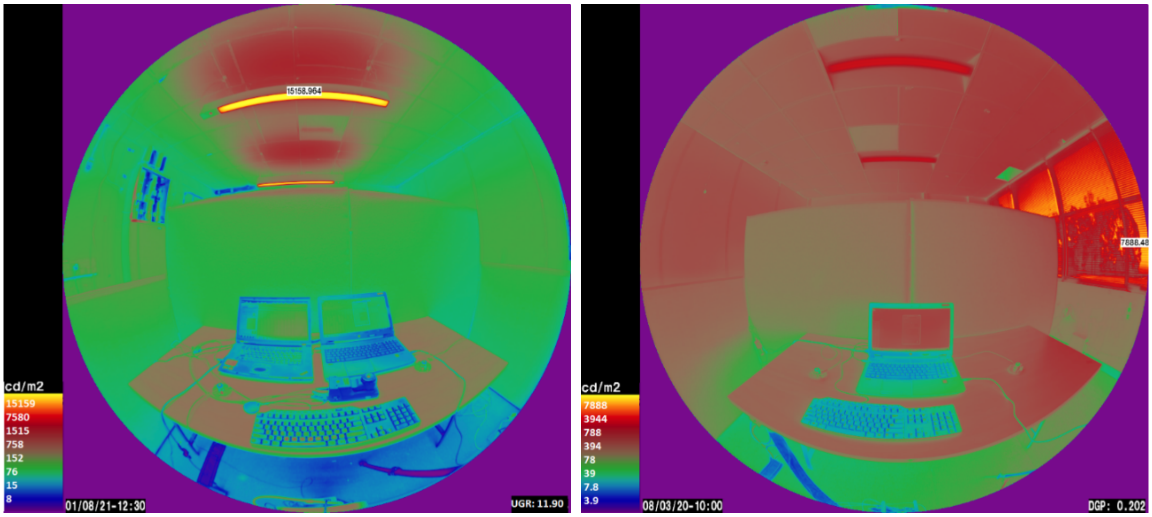


FIGURE 13. HDR FALSE-COLOR LUMINANCE INTENSITY IMAGERY FOR GLARE ANALYSIS (INTERIOR AND PERIMETER ZONES)

---

[3] Note the average UGR values for the baseline and retrofit systems were slightly higher than the latest WELL Building Standard [18] limit of less than 16, which was lowered from the Standard's suggested limit of less than 19 at the time this test's performance specification was developed. The limit below 19 is recommended by EN 12464-Lighting of workplaces [34] and is the limit used for this project.

LUMINOUS INTENSITY DISTRIBUTIONS AND E_V/E_H RATIOS

Previous studies have emphasized that lighting systems with higher proportions of luminous output above the horizontal plane (such as those with higher E_V/E_H) are more efficient for circadian design. After all, radiant flux at the occupant-view position, rather than on the horizontal task plane, is what ultimately reaches photoreceptors and activates circadian response. Jarboe et al. [23] found that an E_V/E_H ratio of at least 0.65 was more effective at meeting the CS levels targeted in their research. For our experiments, the models of troffers (two types) and pendants (one type) implemented in the lab exhibited remarkably similar E_V/E_H ratios of between 0.66 and 0.68. That range exceeds the above recommended minimum for effective circadian design, but because the ratios varied so little, we could not explore the effect of differences in E_V/E_H from our dataset.

ENERGY RESULTS

Quantifying the lighting energy costs of meeting circadian criteria in an office environment is the primary research question motivating this study. After completing the lab experiments, we analyzed the collected energy data to investigate the impacts of intensity (or "dimming") schedules and tunable white lighting controls on energy usage.

INTERIOR ZONE

From continuous energy measurements over a 12-hour operating cycle per day, we estimated an annual Energy Use Intensity (EUI) in the interior zone (normalized by floor area) based on a simple 261 days/year model (52.14 weeks/year, five workdays/week) totaling 3,132 operating hours per year. Note that for a 12-hour operating cycle, the four-hour circadian performance period is only 33% of the day. Our analysis compared annual lighting EUI in the interior zone for the baseline lighting system (A1), consisting of non-tunable LED troffers operated for visual criteria only, to EUI for retrofit options that met visual and circadian criteria, either by intensity adjustments only (B2) or intensity and color temperature adjustments using tunable white LED troffers (C1) and pendants (C2).

Detailed energy results for the interior zone 500-lux and 300-lux test conditions are detailed below. We first summarize findings for both test conditions in Figure 14, which illustrates the estimated annual energy usage of the baseline LED systems and the various retrofit options. The bars in the graph show baseline and retrofit energy for the 500-lux and 300-lux conditions side by side, so the two conditions can be easily compared. In general, we found that meeting circadian criteria in the 300-lux condition required higher light levels during the four-hour circadian performance period, even when we included color tuning to increase circadian performance. For the 500-lux condition, meeting circadian criteria with the non-tunable LEDs required increased light levels during the circadian performance period, but with color tuning, increasing light levels was not necessary – CCT adjustments alone met circadian targets. Overall, the 500-lux test condition used more energy in the baseline and retrofit cases than the 300-lux condition. The incremental impact of raising light levels or using color tunable fixtures for the circadian performance period for the 500-lux condition was lower in relative terms (for example, percent of energy increase).

For the retrofit options that included scheduled intensity increases (B2) and/or color temperature changes (C1, C2) during the circadian performance period, lighting energy increases relative to the baselines ranged from 11% to 21% for the 500-lux test condition and 31% to 42% for the 300-lux test condition. Note that the first tested retrofit option (B1) used the baseline LED fixtures, but increased lighting intensity to meet circadian criteria *all day, rather than just for the scheduled four-hour circadian performance period.* This required the most lighting energy, but in reality, is an unnecessarily energy-intensive option, as dimming controls allow scheduled intensity increases for just the four-hour period, as implemented in the B2 tests.

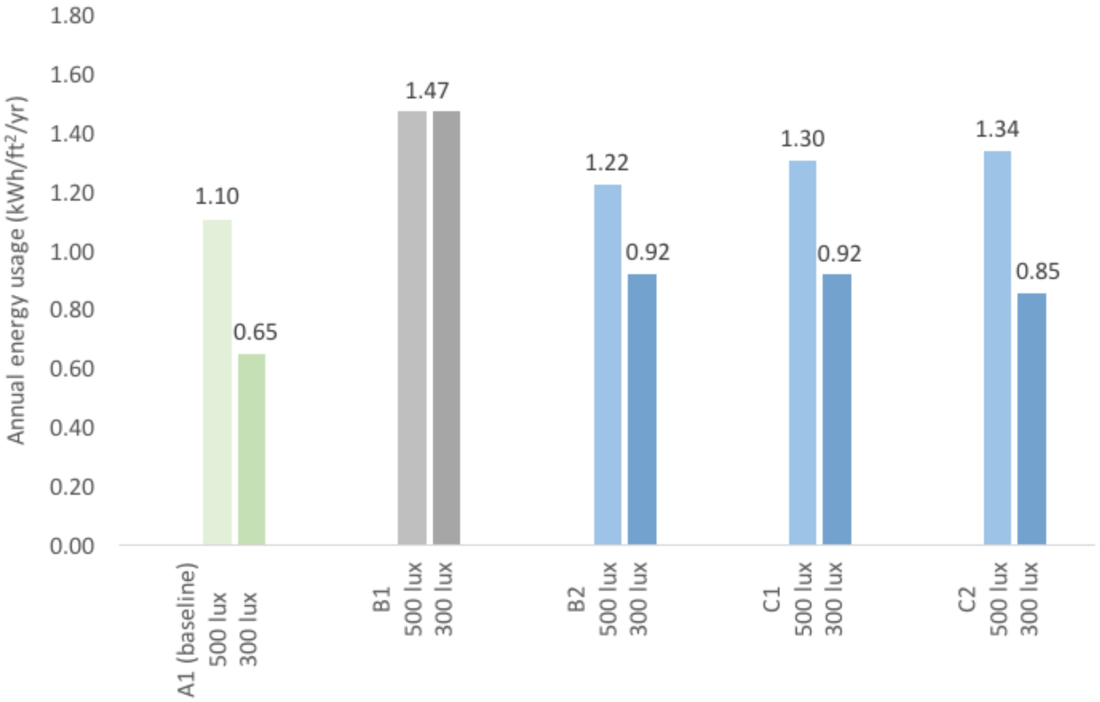


FIGURE 14. COMPARING INTERIOR ZONE ANNUAL LIGHTING ENERGY FOR THE 500-LUX AND 300-LUX TEST CONDITIONS

Table 7 and Figure 15 show energy results for the test condition specifying 500-lux at the task plane, which is the more energy-intensive requirement. For this test condition, the light levels were closer to meeting circadian criteria in the base case. The circadian criteria were achieved at the lowest incremental energy cost with the B2 option by simply brightening the baseline LED fixtures for four hours per day. This required 11% more energy and proved to be more energy efficient than either the tunable troffer (C1) or tunable pendant (C2) options. For the tunable options, changing color temperature alone was actually sufficient to meet circadian requirements during the performance window; light levels did not need to increase. Nevertheless, the C1 and C2 options required 18% and 21% more energy (respectively) than the baseline condition with no circadian criteria. As the tunable fixtures were less efficient in terms of photopic efficacy (luminous flux per W) than the baseline LEDs, the ability to change color temperature to improve circadian performance did not make up for the lower fixture efficacy.

TABLE 7. INTERIOR ZONE ANNUAL LIGHTING ENERGY COMPARISON: 500-LUX TEST

LIGHTING SYSTEMS, PERFORMANCE REQUIREMENTS, AND METHODS PER TEST PHASE	DAILY EUI (WH/FT^2/DAY)	EFFECTIVE LPD (AVG. W/FT^2 THROUGH DAY)	ANNUAL EUI (KWH/FT^2/YR) 12 HR/DAY* 261 DAYS/YR	ANNUAL EUI DIFFERENCE FROM THE BASELINE
A1: Baseline LED troffers. 500 lux on desk at CCT of 3500 K, did not meet circadian target.	4.23	0.35	1.10	n/a
B1: Retrofit using baseline LED troffers with intensity adjustment. Met circadian target *all day* (required 645 lux on desk at a CCT of 3500 K)	5.63	0.47	1.47	33% more
B2: Retrofit using baseline LED troffers with intensity adjustments. 500 lux on desk, 3500 K CCT, intensity increase (+33% power) for circadian hours.	4.68	0.39	1.22	11% more
C1: Retrofit tunable white LED troffers. 500 lux on desk, CCT changes (3000 K / 5000 K / 3500 K) to meet circadian target (no intensity change needed).	4.99	0.42	1.30	18% more
C2: Retrofit tunable white LED pendants. 500 lux on desk, CCT changes (4000 K / 6000 K / 4000 K) to meet circadian target (no intensity change needed).	5.12	0.43	1.34	21% more

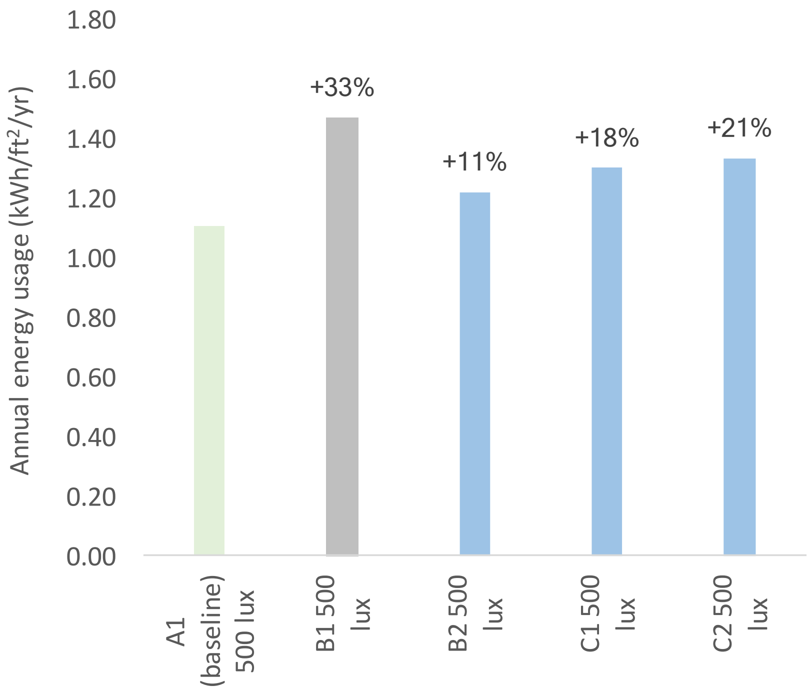


FIGURE 15. INTERIOR ZONE ANNUAL LIGHTING ENERGY COMPARISON: 500-LUX TEST

Table 8 and Figure 16 show EUI results for the less energy-intensive visual design target of 300 lux, which is modern IES recommended practice. For the 300-lux test condition, the lower light levels meant the fixtures needed to be brightened significantly for the four-hour circadian period. For the B2 retrofit option, this required 42% more lighting energy annually. It was slightly more energy efficient to use tunable white troffers (C1) to vary brightness and CCT (up to the maximum setting of 5000 K) for the circadian performance period, requiring 41% more energy than the baseline. The C2 case used tunable pendants with the highest CCT setting (6000 K) during the circadian period, which proved to be the most effective color temperature for circadian performance. For the least incremental energy in the 300-lux case, the tunable pendants were the most efficient circadian option, at 31% more energy than the baseline.

TABLE 8. INTERIOR ZONE ANNUAL LIGHTING ENERGY COMPARISON: 300-LUX TEST

LIGHTING SYSTEM, PERFORMANCE REQUIREMENTS, AND METHODS PER TEST PHASE	Daily EUI (WH/FT^2/DAY)	EFFECTIVE LPD (AVG. W/FT^2 THROUGH DAY)	Annual EUI (kWh/FT^2/yr) 12 HR/DAY* 261 DAYS/YR	ANNUAL EUI DIFFERENCE FROM THE BASELINE
A1: Baseline LED troffers. 300 lux on desk at a CCT of 3500 K, did not meet circadian target.	2.48	0.21	0.65	
B1: Retrofit using baseline LED troffers with intensity adjustment. Met circadian target *all day* (required 645 lux on desk at a CCT of 3500 K).	5.63	0.47	1.47	127% more
B2: Retrofit using baseline LED troffers with intensity adjustments. 300 lux on desk, CCT of 3500 K, intensity increase (+127% power) for 4 hrs. to meet circadian target.	3.52	0.29	0.92	42% more
C1: Retrofit tunable white LED troffers. 300 lux on desk, 4 hrs. intensity increase (+52% power), CCT changes (4000 K / 5000 K / 3000 K) to meet circadian target.	3.51	0.29	0.92	41% more
C2: Retrofit tunable white LED pendants. 300 lux on desk, 4 hrs. intensity increase (+22% power), CCT changes (4000 K / 6000 K / 4000 K) for circadian target.	3.26	0.27	0.85	31% more

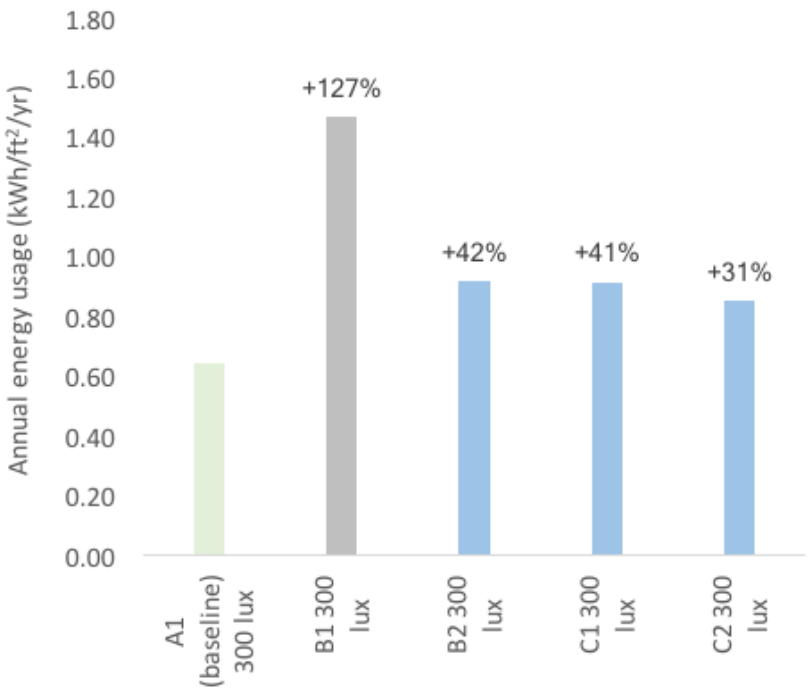


FIGURE 16. INTERIOR ZONE ANNUAL LIGHTING ENERGY COMPARISON: 300-LUX TEST

The 2020 PNNL simulation study on circadian design energy impacts [24] also found a 31% annual energy increase in an office space when meeting circadian criteria for four hours per day via scheduled intensity increases using a high-CCT light (6200 K). Their annual energy model assumed the lighting system operated for 4,000 hours per year, while ours assumed 3,132 hours. If we moved to a 14-hour per day operating cycle (instead of 12) annual operating hours would increase to more than 3,600, with minimal difference in relative energy impact; at the higher operating hours, the C2 option still requires 30% additional energy to meet circadian criteria.

A useful method to visually compare circadian lighting performance and lighting power is given in LRC's *Lighting for Health and Energy Savings: Photometric Calculations* [36]. The authors plotted the CS delivered (y-axis) per unit lighting power density (x-axis), a CS/LPD ratio, for various lighting systems. A higher CS/LPD ratio would indicate a more energy-efficient lighting system for circadian performance. We plot results from our lighting system tests for the interior zone in a similar manner in the following graphs, first comparing mEDI/LPD in Figure 17, then comparing CS/LPD in Figure 18. We included the baseline LED fixtures commissioned to just meet task illuminance requirements as well as the tunable LEDs commissioned to just meet task illuminance and set at different CCT values. In addition, we included circadian retrofit options for the non-tunable and tunable systems, in which four-hour increases in intensity and CCT (when applicable) are made to meet circadian criteria during the circadian performance period only. For those retrofit cases, we plotted "effective" LPD, which is LPD averaged over the course of the 12-hour day.

The graphs show two task illuminance test conditions as clusters on the plots: 300 lux and 500 lux. The cluster of points on the left (with a darker outline) represents the lighting systems commissioned for the 300-lux condition, with and without circadian criteria, while the cluster of points on the right (with the lighter outline) represents the systems commissioned for the 500-lux condition, with and without the circadian criteria. *All plotted points met either the 300-lux or 500-lux condition, and plotted points at or above the mEDI and CS design target lines also met the circadian criteria*.

It is clear from the two data point clusters that higher LPDs are required to meet the 500-lux condition. At that higher illuminance requirement, the lowest average LPD to meet the mEDI target was the non-tunable troffers with intensity increased for four hours. This is in agreement with the Table 7 results above. The tunable troffers and pendants set to higher CCT levels also met the mEDI requirement, but at a higher effective LPD cost. The high luminous efficacy of the baseline LED troffers (125 LPW) helps explain this, which we further examine later in this report.

For the 300-lux test condition, none of the lighting options met the mEDI design target without scheduled increases in intensity and color temperature for the circadian time period. The 300-lux setpoint simply did not provide enough light to meet circadian requirements. The lowest effective LPD that met the circadian criteria was the tunable pendant solution with CCT adjusted to 6,000 K and intensity increased (by about 22%) for the circadian period, also in agreement with the results shown in Table 8.

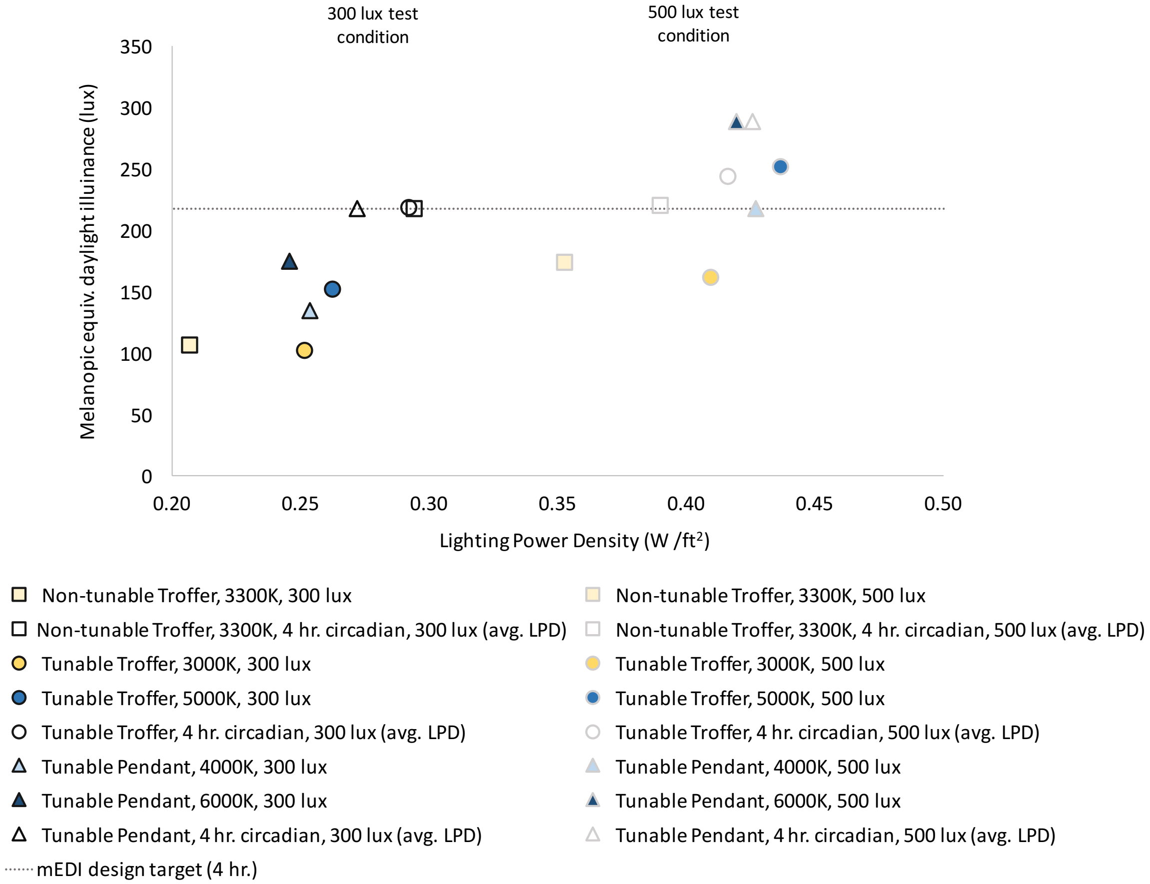


FIGURE 17. CIRCADIAN PERFORMANCE (mEDI) PER UNIT LIGHTING POWER DENSITY (LPD) FOR NON-TUNABLE AND TUNABLE LIGHTING

For CS/LPD, the 500-lux test condition data cluster shows nearly all options met visual and CS criteria. In fact, the baseline non-tunable troffers with a CCT of 3300 K met the CS requirement without any scheduled intensity increase for the circadian period. In general, the CS design target was reachable at a lower energy cost than the mEDI target, especially for lower color temperatures, such as those of the baseline LEDs. While we found lower CCTs to have significantly-worse mEDI performance, we will see that relationship does not hold for CS. For the 300-lux test condition, similar to the mEDI analysis, none of the systems met the CS target without scheduled intensity and color temperature changes. Also, as in the mEDI analysis, the system that met the CS criterion for the four-hour circadian period at the lowest cost was the tunable pendant solution with CCT adjusted to 6000 K and intensity increased.

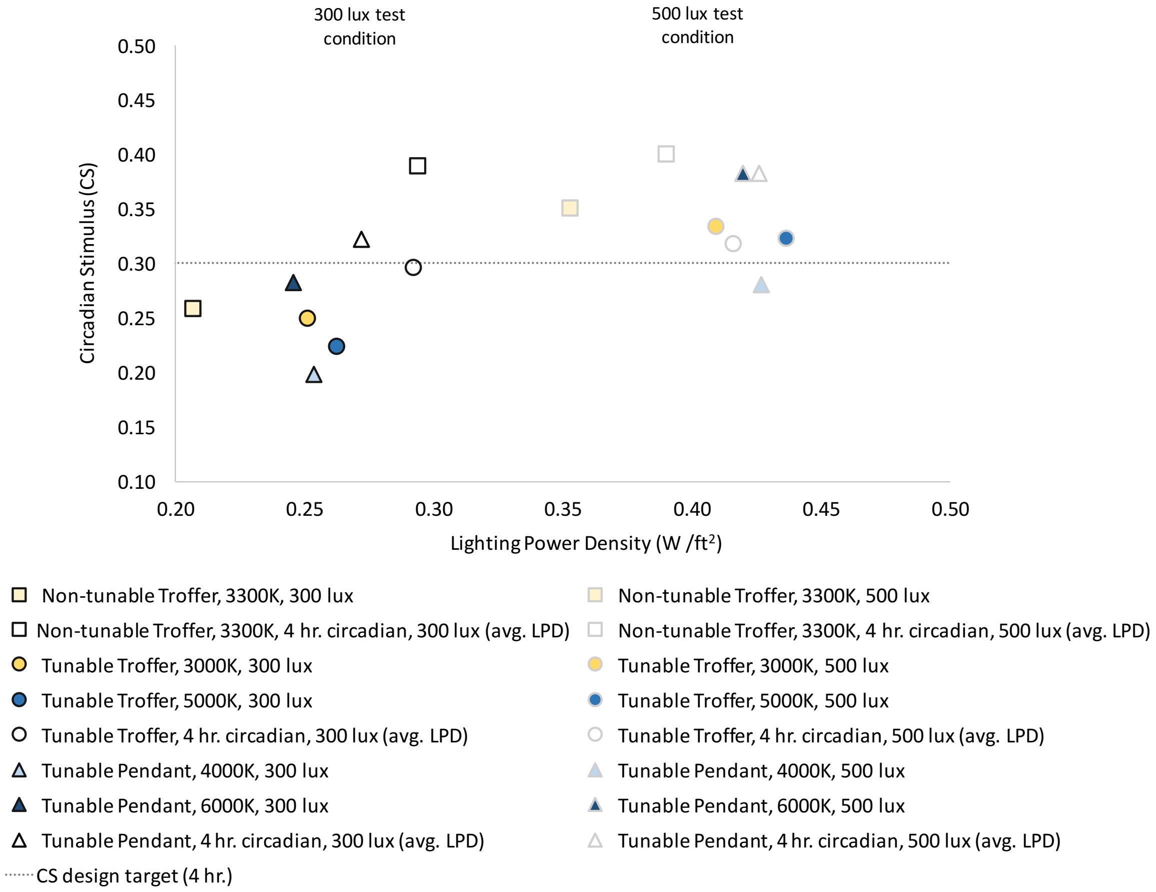


FIGURE 18. CIRCADIAN PERFORMANCE (CS) PER UNIT LIGHTING POWER DENSITY (LPD) FOR NON-TUNABLE AND TUNABLE LIGHTING

PERIMETER ZONE

For the daylit perimeter zone, we implemented the same non-tunable LED troffers and tunable troffers as in the interior zone, and enabled daylight controls so the light fixtures dimmed when sufficient light was sensed by luminaire-level photosensors. This closed-loop photopic illuminance control is typical for daylight dimming strategies; the fixtures dim and brighten automatically based on illuminance setpoints and photosensor readings, without respect to circadian criteria. In general, we found the perimeter zone saved significant energy relative to the interior zone based on the daylight dimming controls, while meeting illuminance criteria, though savings varied day to day depending on weather and available daylight. *As such, with the small number of test days for this experiment, it was not possible to estimate average annual savings; more test days through more seasons and weather conditions would be necessary*.

Importantly, we found the daylight-dimming perimeter zone also met circadian criteria during the 9 am to 1 pm performance period, requiring no extra lighting power during our tests. The perimeter zone for the FLEXLAB test had a large window aperture on the south-facing wall (about a 0.5 window-to-wall ratio), though standard venetian blinds were lowered across the windows, with louvers adjusted to block glare. Even so, for the conditions in which the tests were run, ranging from sunny to overcast (no rainy days occurred during the test periods), we found daylight in the perimeter zone allowed circadian criteria to be met at no additional energy cost.

The following plots illustrate this point, as well as the energy savings relative to the interior zone. The plotted timeframes were selected from the more overcast days in our dataset (*worst-case scenario* in terms of available daylight) in the non-tunable troffer test phase (B2) and in the tunable pendant test phase[4] (C2). The first set of plots shows interior and perimeter lighting system performance for the B2 non-tunable troffers, 500-lux test condition. Figure 19 shows the lighting power the system required to meet the criteria, and Figure 20 shows the resulting mEDI performance. In the interior zone (with the orange line) the lighting power increased for the 9 am to 1 pm period to meet the circadian criteria, but for the perimeter zone (with the blue line) fixtures dimmed according to daylight availability. Yet ample mEDI was present, even with the electric lights at low power.

---

[4] For the test period when tunable pendant lights were evaluated, due to material and time constraints, it was not possible to install the system in the perimeter zone. We were still able to evaluate that system's performance in the perimeter zone by setting up the furnishings and monitoring equipment in that zone, the same as in previous test phases, and collecting several days of illuminance and spectral data at the same measurement locations, but with no electric lighting system operation. Based on the measured daylight quantities, we calculated electric lighting system performance by adding at each time step the electric lighting quantities (illuminance, wattage) the tunable troffers needed (characterized in the interior zone tests) to meet the 300-lux or 500-lux daylighting setpoint.

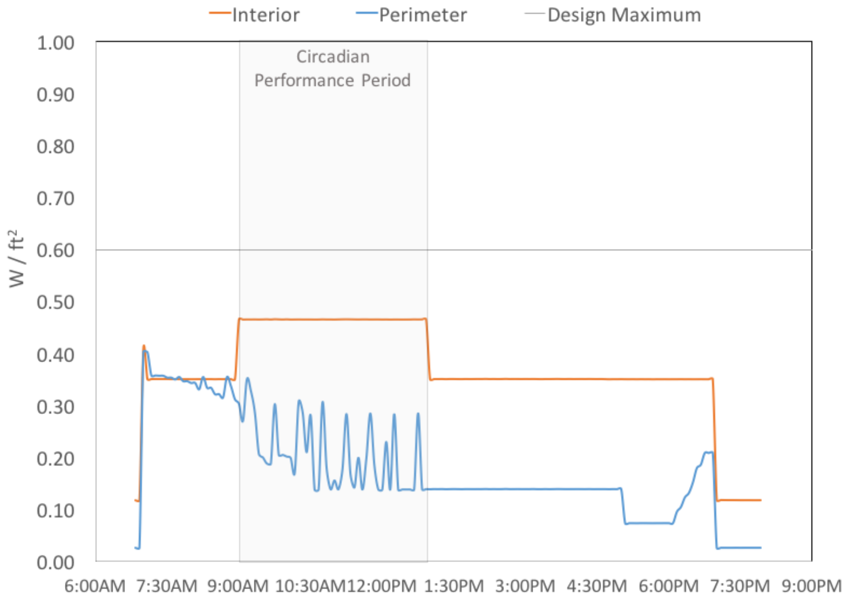


FIGURE 19. TIME SERIES OF LIGHTING POWER DENSITY DATA: B2 RETROFIT, 500 LUX TEST

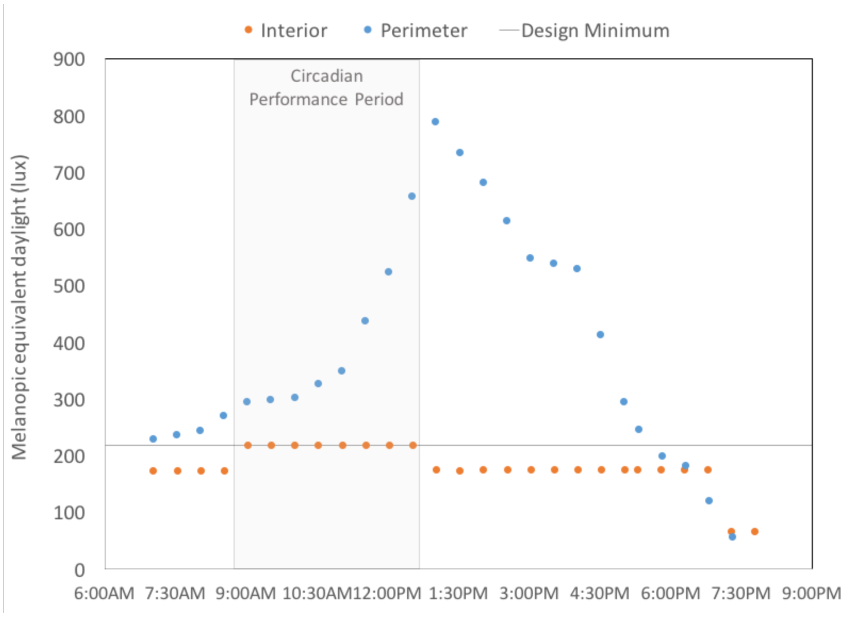


FIGURE 20. TIME SERIES OF MEDI DATA AT OCCUPANT-VIEW POSITION: B2 RETROFIT, 500 LUX TEST

For the tunable white LED pendants, the calculated daylight dimming results for the perimeter zone again indicated that with available daylight and standard photopic dimming, the four-hour circadian target required no additional lighting energy. Figure 21 shows time-series energy performance and mEDI results for the C2 retrofit using tunable pendants, 300 lux condition. Note that while the lights dimmed for much of the afternoon based on available daylight, the mEDI (Figure 22) and CS criteria (not shown) were met for the four-hour period.

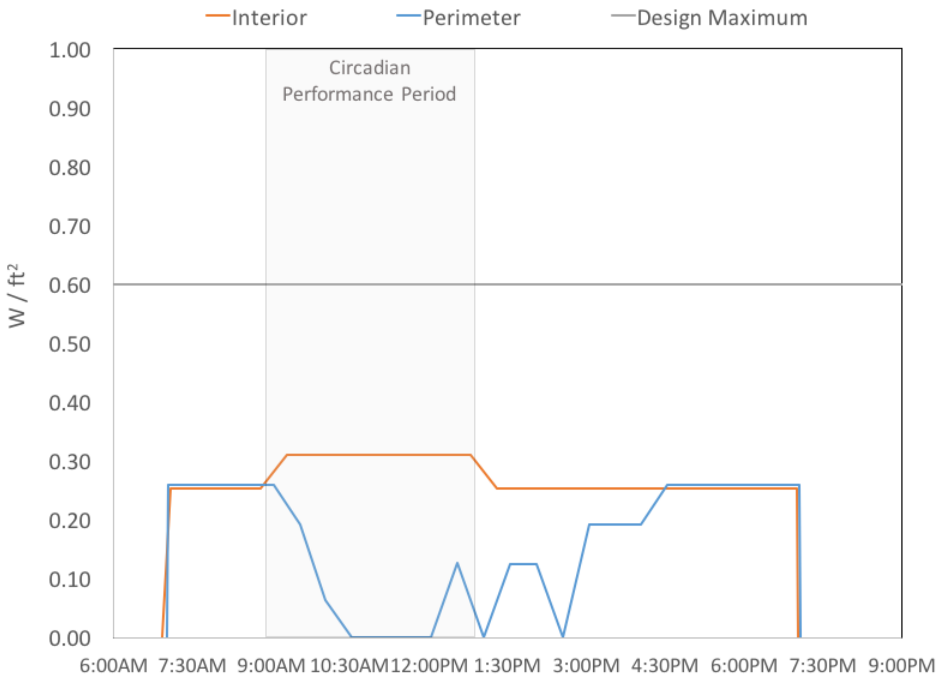


FIGURE 21. TIME SERIES OF LIGHTING POWER DENSITY DATA: C2 RETROFIT, 300 LUX TEST

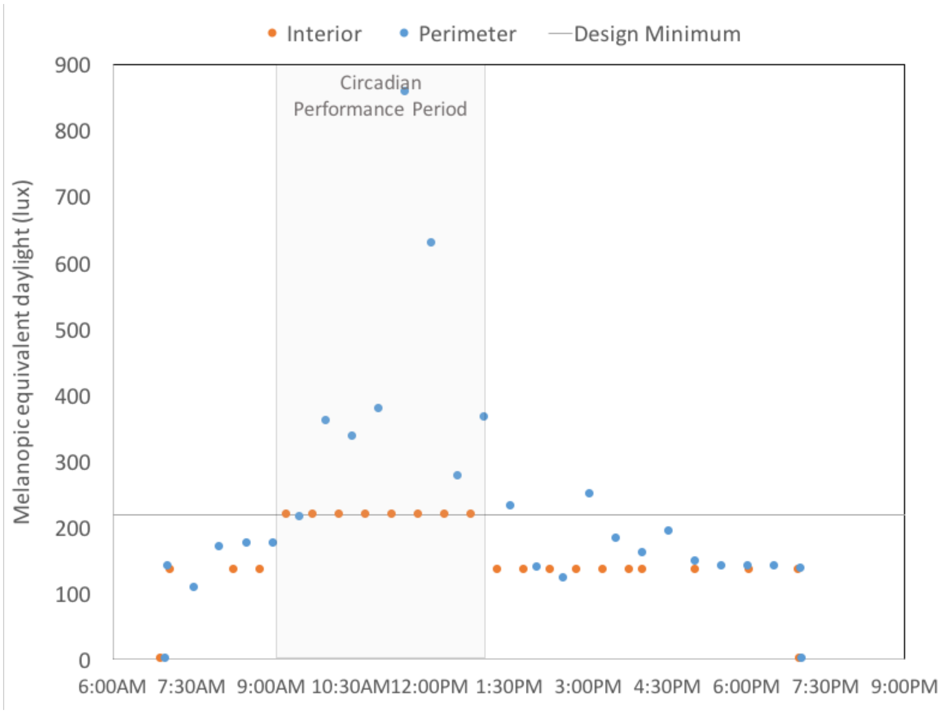


FIGURE 22. TIME SERIES OF MEDI DATA AT OCCUPANT-VIEW POSITION: C2 RETROFIT, 300 LUX TEST

SPECTRAL CONTENT, COLOR TEMPERATURE, AND MELANOPIC EQUIVALENT DAYLIGHT EFFICACY

We analyzed the lighting performance data collected during the experiments to identify trends and directions on how circadian performance is affected by key variables. The intention was to see whether the data indicate (a) any variables that do a good job of predicting circadian and energy performance, and (b) lighting solutions that deliver circadian performance at a lower relative energy intensity.

The premise of using tunable white LEDs for circadian lighting is that light sources with radiant flux more heavily weighted to shorter wavelengths should provide higher melanopic effect at equal power, because melanopsin sensitivity is higher in that range, peaking at 480–490 nm. This typically corresponds to higher-CCT, "cooler" lighting. The point is illustrated by plotting spectral irradiance data for our light sources, with melanopic and visual sensitive curves overlaid for reference (Figure 23). Relative spectral irradiance per wavelength at equal total radiant power is shown for the tunable troffers at the highest and lowest CCT settings, the tunable pendants at the highest and lowest CCT settings, and the baseline non-tunable LEDs at 3300 K. The tunable LEDs at the higher CCT settings emit a significantly-higher proportion of radiant flux in the melanopic range compared to the lower CCT sources. This carries over to a relatively-higher mEDI performance for those high CCT values.

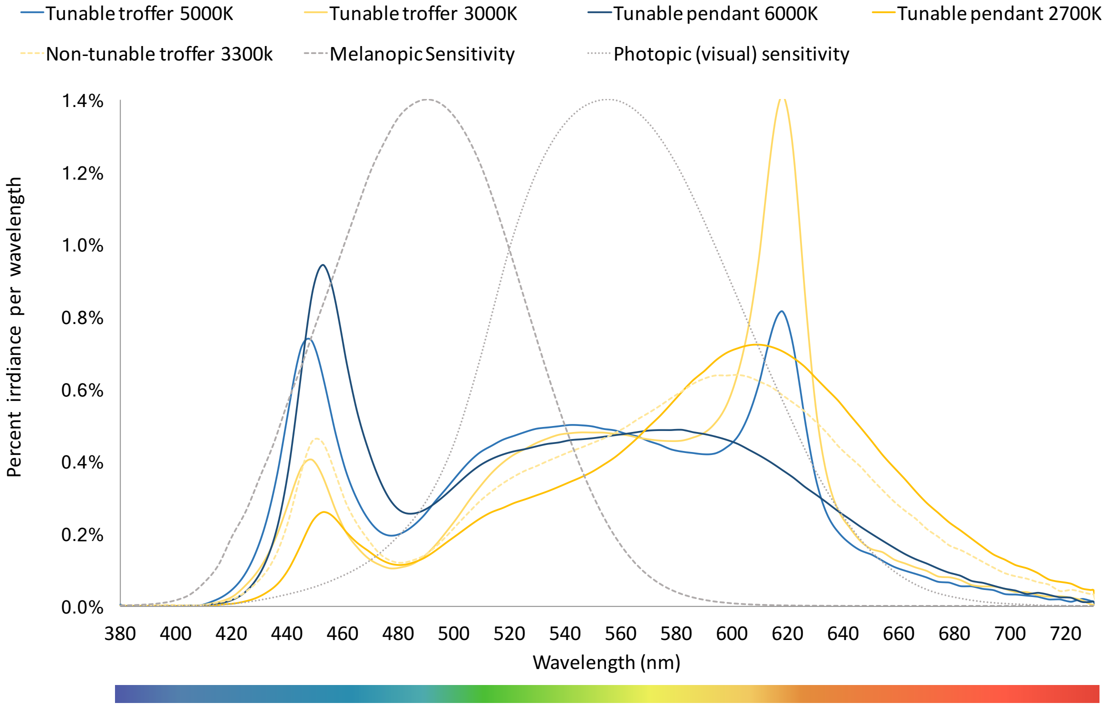


FIGURE 23. RELATIVE SPECTRAL IRRADIANCE COMPARED TO MELANOPIC AND VISUAL SENSITIVITY

RELATIONSHIP BETWEEN CCT, LIGHTING POWER, AND CIRCADIAN PERFORMANCE

The relationship between color temperature, lighting power, and circadian performance can be illustrated by plotting mEDI and CS against color temperature for different light levels. The following graphs are for the tunable LED pendant system, showing mEDI (Figure 24) and CS (Figure 25) for different color temperature settings (x-axis) and at different lighting power settings (isopleths labeled in the legend). Higher lighting power results in higher mEDI values, as more radiant flux is delivered to the space and reaches the sensor at the occupant-view position. Higher color temperatures at equal lighting power also correspond to higher mEDI.

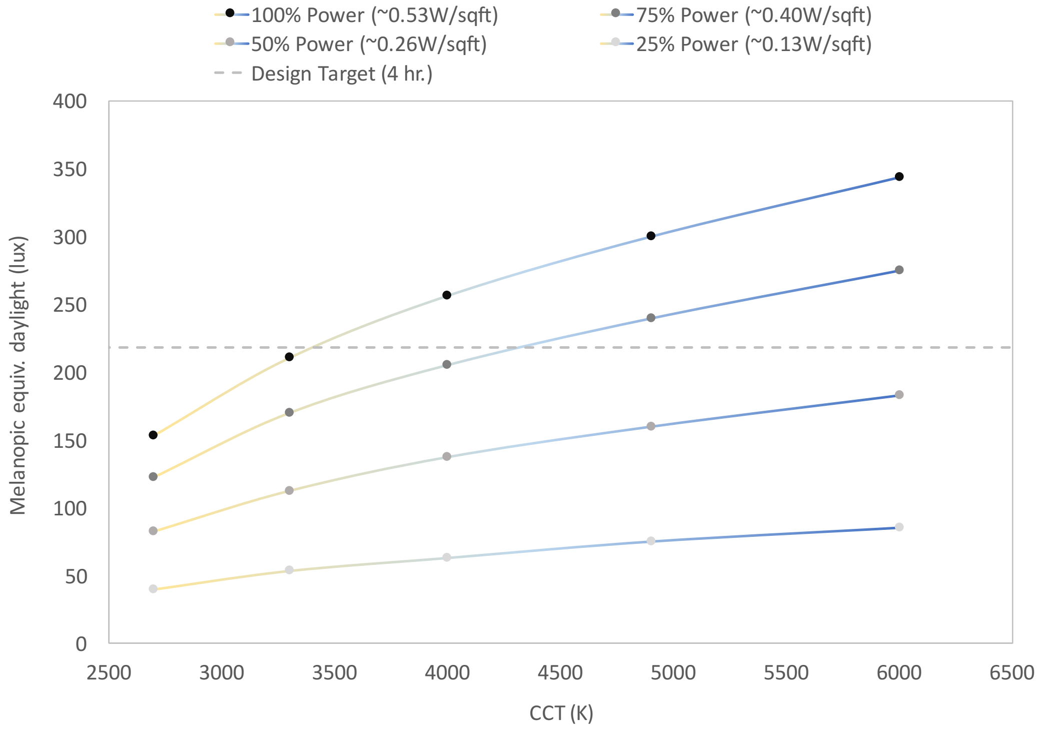


FIGURE 24. MEDI THROUGH A RANGE OF CCT AND INTENSITY SETTINGS FOR SYSTEM C2

Generally, the test data show that at equal lighting power, CS levels correlated positively to color temperatures as well, but only for the CCT range from 3,500 K up. In our measurements, the relationship reversed around values of 3,300 K to 3,500 K, depending on the tunable light source. This non-linearity is likely related to the CS model's inclusion of b-y spectral opponency and is consistent with other research, though a detailed causal explanation is beyond the scope of this project.

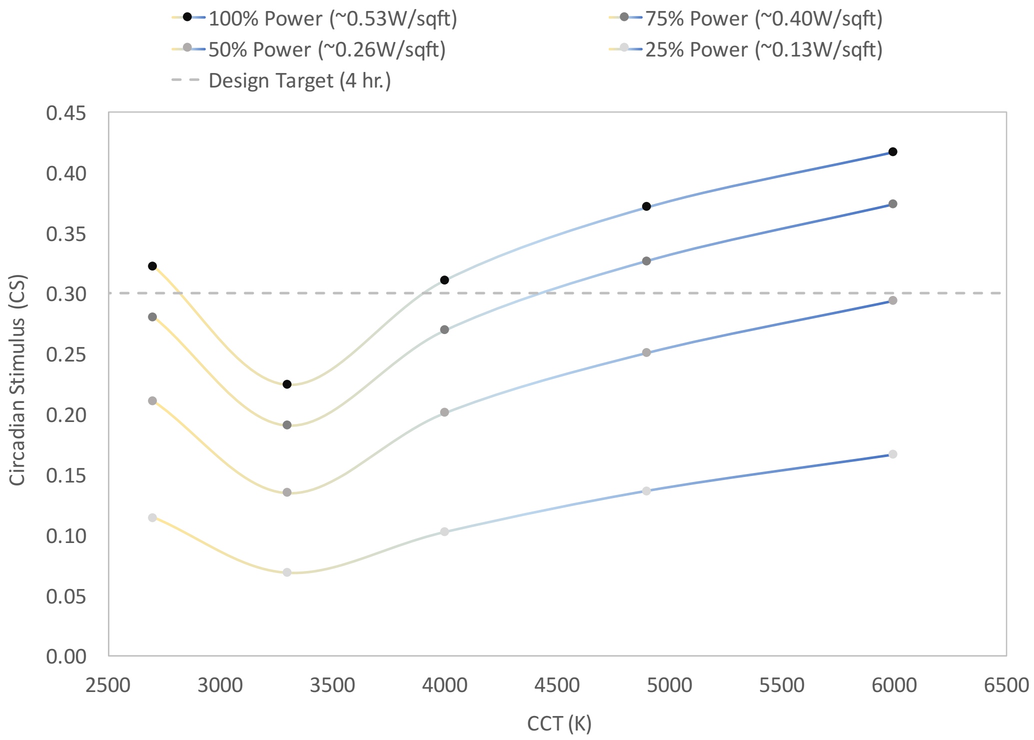


FIGURE 25. CS THROUGH A RANGE OF CCT AND INTENSITY SETTINGS FOR SYSTEM C2

We extended the analysis to look at the relationship between circadian performance and lighting power for the broader set of data collected during the experiment, including points for all of the lighting systems in one data set and tabulating mEDI and CS levels at different lighting power densities for color temperature bins (multiple fixture types per bin) as shown in Figure 26 and Figure 27. At a constant CCT, mEDI correlates positively with lighting power, and again higher CCTs were shown to produce higher mEDI. This held for CS as well for the color temperature bins from 4,000 K to 6,000 K, but for the lower color temperature bin of 3,300 K, which included the baseline troffer and the tunable troffer, the results vary considerably between light sources.

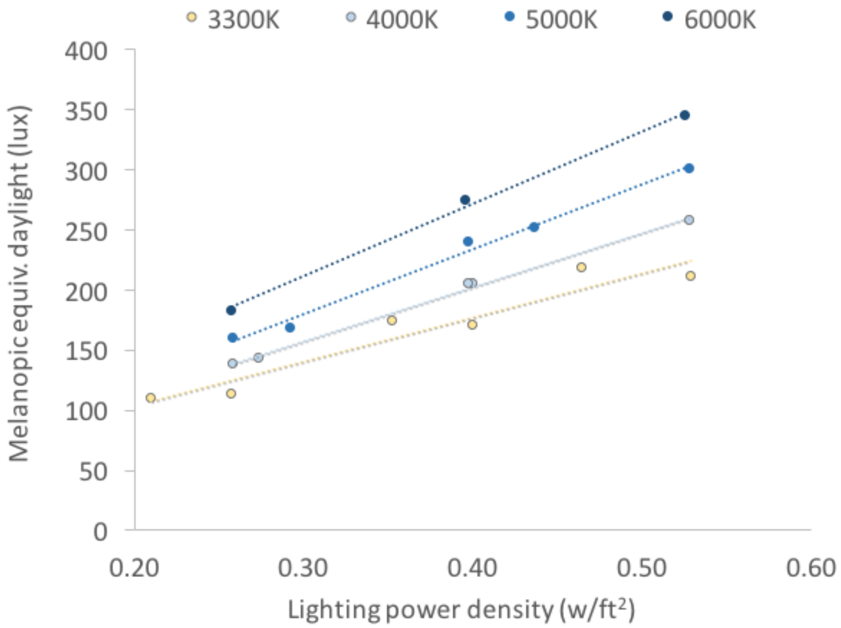


FIGURE 26. MEDI THROUGH RANGE OF LIGHTING POWER DENSITIES AND CCTS FOR ALL THREE LIGHTING SYSTEMS

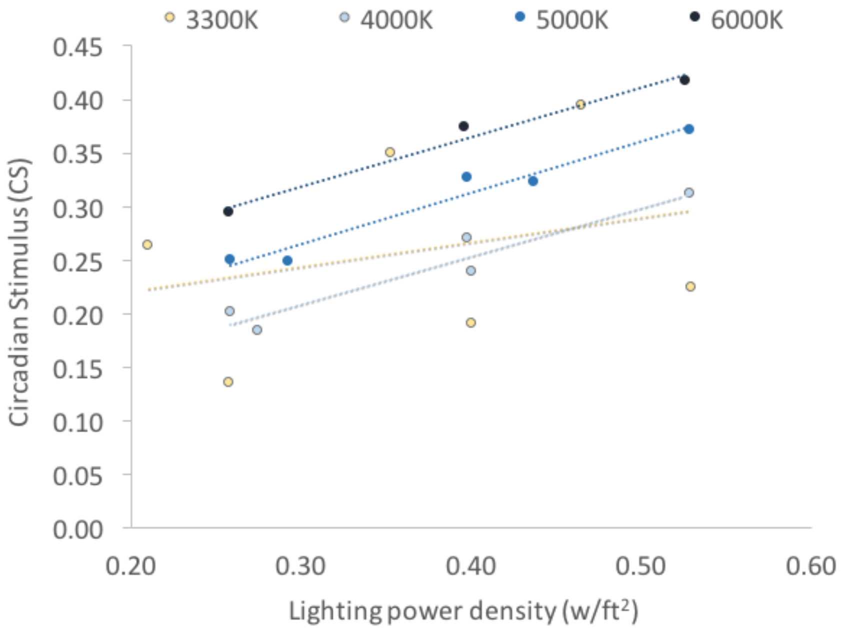


FIGURE 27. CS THROUGH RANGE OF LIGHTING POWER DENSITIES AND CCTS FOR ALL THREE LIGHTING SYSTEMS

RELATIONSHIP BETWEEN CCT AND M-DER

Graeber and von Erberich [26] studied the relationship between CRI and CCT, and melanopic efficacy (defined as melanopic flux/photopic flux) and found the highest efficacy for higher CCT and higher CRI sources. From our experimental data, we also wanted to analyze melanopic efficacy, but since we relied on the quantity mEDI, we used a different measure of efficacy for unit consistency. From our calculated mEDI values, we computed the CIE term m-DER, a quantity like melanopic efficacy but with melanopic equivalent daylight units in the numerator (melanopic equivalent daylight radiant flux divided by photopic radiant flux [11]). This is essentially a measure of the proportion of melanopic performance (in equivalent daylight units) to visible performance. Plotting this ratio against color temperature for a range of CCTs and lighting power levels for the three fixture types, we found a strong fit, as Figure 28 shows. There is no doubt that CCT, as an indicator of the relative spectral power distribution from the light source, is a good predictor of the proportion of melanopic equivalent daylight output to photopic output.

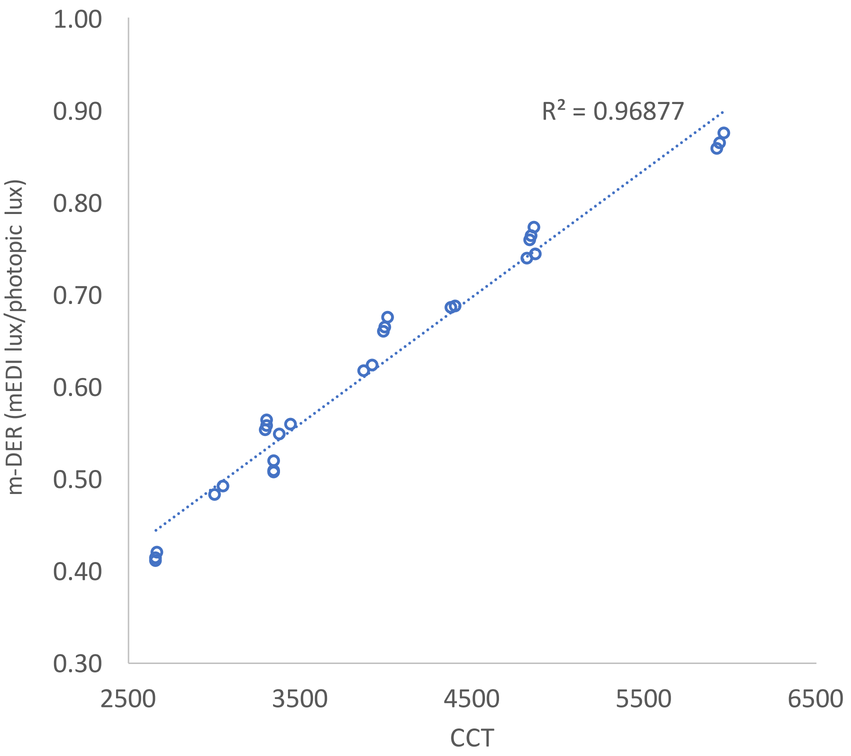


FIGURE 28. RELATIONSHIP BETWEEN M-DER AND CCT FOR ALL THREE LIGHTING SYSTEMS

MELANOPIC EQUIVALENT DAYLIGHT EFFICACY

For energy efficiency in visual design, lighting designers and specifiers typically think in terms of photopic, or luminous, efficacy (LPW). m-DER quantifies the proportion of melanopic equivalent daylight to photopic light, but reveals little about the system's energy efficiency. To judge energy efficiency for circadian design, m-DER can be multiplied by photopic efficacy to compute what we term "melanopic equivalent daylight efficacy," also in LPW. While we did not find a melanopic equivalent daylight efficacy metric referenced elsewhere in the literature, we found it useful for characterizing circadian energy efficiency. Just as high-photopic efficacy is a good predictor of visual performance (lux) for the least energy cost, melanopic equivalent daylight efficacy should be a good predictor of circadian performance (mEDI) for the least energy cost. To efficiently meet both visual and circadian criteria, the goal is to achieve the highest combination of photopic efficacy and melanopic equivalent daylight efficacy.

We computed approximate melanopic equivalent daylight efficacies for our light sources based on rated photopic efficacy and measured m-DER. These values were approximate, because the m-DER measurements included the combined effects of the direct radiant flux from the fixtures as well as reflected flux in the test environment. Table 9 shows the m-DER values for the light sources we tested, ranging from 0.50 for the nominal 3,500 K non-tunable troffer (measured at 3,300 K) to 0.74 for the tunable troffer at CCT of 5,000 K nominal (measured at 4,800 K) and 0.87 for the tunable pendant at 6,000 K. In the final column, we included the calculated melanopic equivalent daylight efficacy of each option at low and high CCT settings for the tunable sources.

TABLE 9. LIGHT SOURCE m-DER AND "MELANOPIC EQUIVALENT DAYLIGHT EFFICACY"

LIGHT SOURCE	RATED PHOTOPIC EFFICACY (LPW)	MELANOPIC DAYLIGHT EFFICACY RATIO (M-DER, UNITLESS)	APPROXIMATE MELANOPIC EQUIVALENT DAYLIGHT EFFICACY (LPW)
A1: Baseline LED troffers (3500 K rated / 3300 K measured)	125	0.50	62.5
C1: Tunable LED troffers (3000 K)	100	0.48	48.2
C1: Tunable LED troffers (5000 K rated / 4800 K measured)	100	0.74	73.8
C2: Tunable LED pendant (2700 K)	109	0.42	45.2
C2: Tunable LED pendant (6000 K)	120	0.87	104.8

The same data is plotted in Figure 29. The baseline non-tunable troffer with the highest photopic efficacy rating (the right-most data point) performed slightly better in terms of melanopic equivalent daylight efficacy than the tunable systems at equal or lower CCT, and even performed better than some higher CCT values. This shows high-photopic efficacy can benefit melanopic performance as well. However, the ability of the tunable pendants to adjust CCT to high levels for maximum m-DER performance, in combination with relatively-high photopic efficacy, can lead to even higher melanopic equivalent daylight efficacies, as the middle column shows.

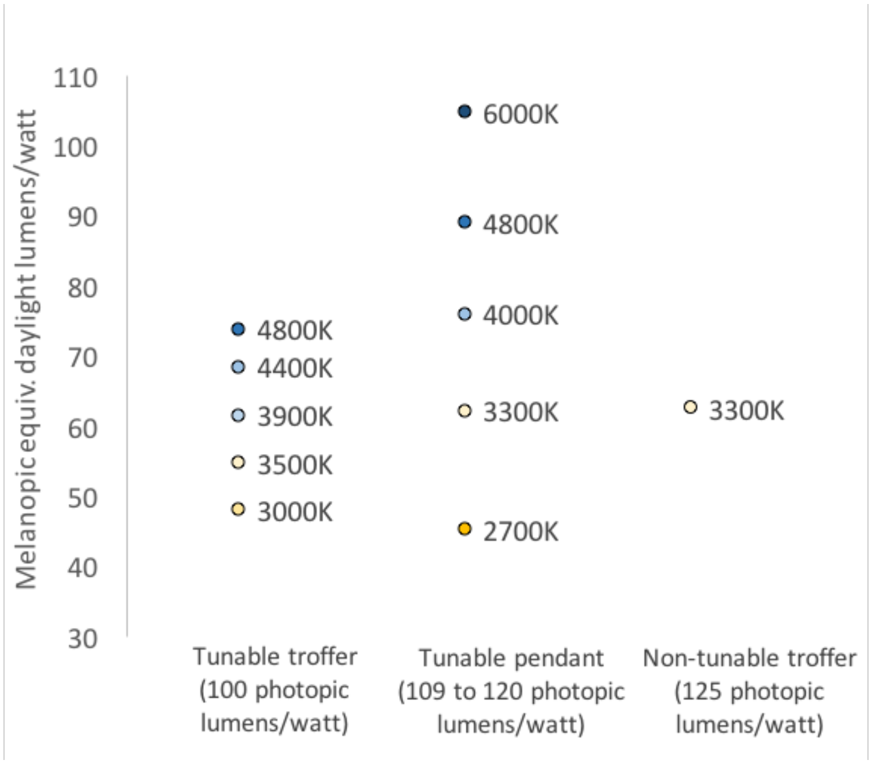


FIGURE 29. APPROXIMATE PHOTOPIC AND MELANOPIC EQUIVALENT DAYLIGHT EFFICACIES FOR THE TESTED SYSTEMS

If the circadian criteria only apply for four hours per day, photopic efficacy is the first concern for an efficient lighting system. The incremental energy cost of meeting circadian goals for a four-hour performance period depends on the light source’s m-DER. The intensity increase required for the circadian period is lower with high-efficacy light sources that also have higher m-DER values, which correspond to higher-melanopic equivalent daylight efficacies. A high-efficacy tunable source can achieve this, but a non-tunable source with high photopic efficacy and high m-DER (likely a high color temperature source) could also maximize system efficiency.

DISCUSSION

THE ENERGY "BIG PICTURE"

This study found for interior office environments without daylight, meeting circadian criteria may require increased light levels and power relative to the low illuminance prescriptions in modern recommended practice. On the other hand, in our perimeter zone experiments, we found standard daylight dimming saved energy compared to no daylight dimming in the interior zone, and the lighting systems met circadian criteria at no extra energy cost.

For the interior zone, the range of lighting energy increase was found to be 11% to 21% for a 500-lux task illuminance condition, and 31% to 42% for the modern 300-lux task illuminance condition. Simple strategies in which lighting power is raised all day to meet circadian criteria could carry an energy cost of more than 100% (300-lux condition) and such alarming energy increases have been cited as the potential cost of circadian lighting design. However, this seems to overstate the likely energy costs, with the availability of dimming controls that can schedule intensity increases only when necessary (during the circadian performance period).

Another important, rarely-mentioned point is even when LED systems are operated to meet circadian criteria, they still generally offer significant energy savings over standard non-LED systems common in existing buildings. In fact, compared to a fluorescent baseline, the difference in EUIs between LED systems designed for illuminance criteria or circadian criteria may be small. Consider a calculated baseline scenario (A0) with two-lamp T8 fluorescent troffers at the same fixture density and operating schedule as the LEDs we tested. Table 10 shows the high-efficacy, non-tunable LEDs at the 300-lux test condition saved 74% annual energy (no circadian criteria) over the A0 fluorescent baseline, and using those same LEDs at higher intensity to meet circadian criteria all day still saved 41% of energy over the fluorescent system, while the tunable pendants, including in the four-hour circadian performance period, saved 66% energy. If we were to add a layer of savings for modern controls such as luminaire-level, occupancy-based dimming, the savings would be even higher, and the difference between lighting systems with and without circadian criteria potentially even lower.

TABLE 10. INTERIOR ZONE ANNUAL LIGHTING ENERGY COMPARISON AGAINST FLUORESCENT BASELINE: 300-LUX TEST

LIGHTING SYSTEM, PERFORMANCE REQUIREMENTS, AND METHODS PER TEST PHASE	DAILY EUI (WH/FT^2/DAY)	EFFECTIVE LPD (AVG. W/FT^2 THROUGH DAY)	ANNUAL EUI (KWH/FT^2/YR) 12 HR/DAY * 261 DAYS/YR	ANNUAL EUI SAVINGS COMPARED TO T8 BASELINE (A0)
A0: Baseline two-lamp T8 troffers. 64 W each, installed at the same fixture density.	9.60	0.80	2.51	n/a
A1: Baseline LED troffers. 300 lux on desk at a CCT of 3500 K, did not meet circadian target.	2.48	0.21	0.65	74% savings
B1: Retrofit, using baseline LED troffers with intensity adjustment. Met circadian target all day.	5.63	0.47	1.47	41% savings
B2: Retrofit, using baseline LED troffers. With intensity increase for 4 hrs. to meet circadian target.	3.52	0.29	0.92	63% savings
C1: Retrofit tunable white LED troffers. 4 hr. intensity and CCT increase (5000 K) to meet circadian target.	3.51	0.29	0.92	63% savings
C2: Retrofit tunable white LED pendants. 4 hr. intensity and CCT increase (6000 K) to meet circadian target.	3.26	0.27	0.85	66% savings

BENEFITS AND LIMITATIONS OF LAB TESTING

There has been limited research on implementing circadian lighting strategies and tunable white LEDs in office environments and measuring energy impacts. Most recent research on this subject has relied on computer simulations and mathematical models. Our applied research in a mock office environment is an important contribution in terms of proving out and validating the performance of market-available technologies. Experimental data can also be useful for validating or refining simulation-based findings. We view the lab experiments as a bridge between simulation studies and more naturalistic field studies, of which there are relatively few in the office environment, and fewer still that directly measure energy impacts.

While the lab environment provides a realistic picture of how non-tunable and tunable white LED systems perform when operated for circadian criteria, there are limitations to the lab work that simulation studies are able to overcome. For example, in our daylit zone, the results are subject to the building orientation, location, window parameters, and prevailing weather during the time of the measurements, whereas all of these can be manipulated in simulations for more broadly-applicable results, including annualized daylight simulations. Similarly, while we are only able to measure spectral irradiance at select view positions, simulations can calculate results throughout the modeled environment. Likewise, the impacts of different finishes and spectral reflectances, furniture layouts, etc. can be interrogated through a computer simulation, which is not as practical in physical space.

There is a role for simulation as well as applied research in physical space, and projects that combine both might be the gold standard. Building a computer model of a given physical environment in which a lighting system is implemented and performance measured can allow for validation of simulations and feedback for model improvements, providing more confidence in model results.

POTENTIAL FOR DEMAND RESPONSE (DR)

While DR potential is an important consideration for all grid-connected electric loads, the potential for programmatic intervention, with respect to circadian lighting performance, appears to be limited. Similar to lighting for visual purposes, lighting for circadian benefit cannot be effectively "stored" or "shifted" per se. At the most, the period of higher lighting power intensity for circadian criteria as prescribed here, 9 am to 1 pm, may be shiftable by one or two hours in either direction. Fortunately, the circadian period is non-coincident with current grid peak demand, at least for the service areas of interest in this study. California peak demand has largely shifted to the late afternoon and evening hours, at which time most circadian recommendations promote lower light levels and avoidance of Light at Night (LAN). A blog article from *Lightshow West* on potential DR implications of circadian lighting suggests the frequent midday overabundance of photovoltaic electricity production in California could serve as an energy source to meet the higher energy intensities of the circadian performance period [37]. At this point, that may be more of a passive synergy between coincident available production and circadian lighting demand, at least in the California energy supply context, and not something coordinated by active communication pathways between the grid and lighting system.

CONCLUSIONS

Earlier research clearly points to the essential role of the lighting environment in human circadian health. Failing to address this phenomenon in commercial office lighting design could have adverse consequences for occupant wellbeing. Yet the lighting community is waiting for more clarity in terms of consensus-based standards and best practice. Indeed, the lack of "official" standards around circadian lighting design, such as would be provided by IES or CIE recommended practices, remains a serious hurdle. Additionally, the sources of guidance that do exist, like the WELL Building Standard and the UL Design Guideline, are somewhat contradictory in terms of proposed metrics and methodologies, potentially leaving practitioners confused about what to do. Nonetheless, at a time when low lighting energy intensities are achievable with LEDs, and when lighting energy is a diminishing fraction of building energy usage, prioritizing lighting energy savings over circadian performance may not be necessary.

We demonstrated performance and energy usage for a small sample of available LED sources, both non-tuning and tunable white. However, myriad solutions exist in the ever-expanding commercial LED lighting market. While tunable white solutions were shown to offer compelling melanopic equivalent daylight performance improvements at higher CCTs, the simplest and perhaps most efficient solution might be a non-tunable light source specified for the highest-possible luminous (photopic) efficacy and the highest m-DER value, which, if multiplied by photopic efficacy, gives "melanopic equivalent daylight efficacy."

With the efficacies and color temperatures available today, fixtures likely already exist that combine higher photopic efficacies than what we tested with high-m-DER and melanopic-equivalent daylight efficacies. Figure 30 illustrates two hypothetical sources by multiplying the highest luminous efficacy we tested (the baseline LED fixtures) by the highest m-DERs we tested (tunable LEDs at a high CCT). Even at these high combined efficacies, some increase in lighting intensity might be required during the circadian performance period. In our tests, the tunable pendants, at 120 LPW and with an m-DER of 0.87 at 6,000 K, required an approximate 22% increase in power during the circadian period. However, for even higher photopic efficacies at the high m-DER values, the incremental energy cost of meeting the circadian criteria might be small.

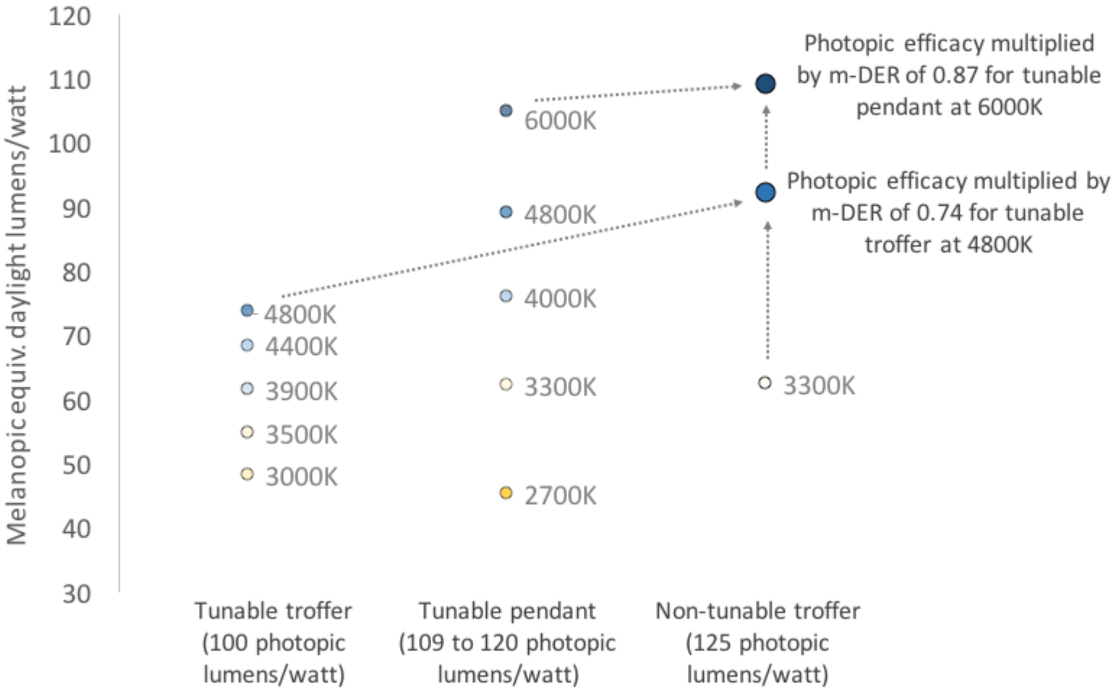


FIGURE 30. PHOTOPIC- AND MELANOPIC-EQUIVALENT DAYLIGHT EFFICACIES FOR HYPOTHETICAL LIGHT SOURCES

In the DLC Qualified Products List, we found more than 80,000 troffers and pendants with rated efficacies of 125 LPW or more. Of those high-efficacy models, nearly 23,000 are at rated CCTs of 4,800 K to 6,000 K. About 1,800 of the 125 LPW or greater models are tunable white [3]. We believe many of these listed fixtures could meet the hypothetical high performance we illustrate above.

While we were able to measure m-DER, ideally, LED systems on the market would provide m-DER ratings in product literature. This would give specifiers valuable information for translating photopic efficacy into circadian performance in units consistent with CIE guidance. We currently find limited evidence of lighting products listing performance metrics such as m-DER (also "MDER" in product literature) though there are some; for example, Signify's LEDALITE EyeLine series [38].

RECOMMENDATIONS

Early adopters who pursue circadian design goals based on available guidance should be encouraged to prioritize the lowest-possible incremental energy cost, and utilities and efficiency programs may be able to provide resources on best practices to promote this. As we have seen, lighting energy will be affected by circadian criteria, but solutions involving the highest-possible efficacies, potentially in combination with scheduled CCT tuning (and daylighting, where possible) can meet circadian goals while reducing incremental energy impacts. Also, while circadian criteria may lead to lighting energy increases compared to the lowest-possible EUI achievable with modern LED systems, the lighting power density and energy budget should still fall within current building energy code requirements.

Utilities, in the role of customers' trusted energy advisors, can help relay findings from this project to customers interested in implementing LED retrofits with circadian criteria in commercial offices. Recommendations for efficient circadian design at the lowest incremental energy cost could also be included in utility codes and standards development efforts. Additionally, education programs for installation and implementation contractors such as CALCTP could be updated to include curricula on energy-efficient circadian lighting equipment and strategies based on this study's findings.

RECOMMENDED SPECIFICATIONS AND STRATEGIES FOR EFFICIENT CIRCADIAN LIGHTING

In new construction or retrofit projects implementing circadian criteria, the aim should be to minimize incremental energy cost. Based on findings from our lab tests and data analysis, we have developed the following recommendations to help achieve this goal:

- Specify LED lighting with the highest photopic efficacy reasonably attainable (125 or 130 LPW or more) which benefits visual lighting energy performance as well as energy efficiency for circadian criteria.
- Specify LED lighting with the highest m-DER rating reasonably attainable (at least 0.69 to 0.80, depending on photopic efficacy – see Table 11). Because m-DER is a CIE-defined measure, its inclusion in a specification is preferred over our "melanopic equivalent daylight efficacy" term.
- To minimize the incremental energy costs of circadian criteria, use basic intensity ("dimming") controls to schedule an increase in light levels to meet circadian criteria only during the specified performance period (such as 9 am to 1 pm).
- Implement tunable white lighting or higher-CCT, non-tunable lighting to deliver high-melanopic equivalent daylight efficacy lighting during the circadian performance period.
- Prioritize daylighting wherever possible, since sufficient daylighting can minimize or eliminate the incremental energy costs of circadian lighting criteria.

- Specify LED fixtures with higher E_V/E_H ratios and surface finishes with higher reflectance values (these factors were essentially constant in our lab tests, but other research points to their importance).

Table 11 includes the type of performance criteria our research indicates for selecting energy-efficient circadian lighting options. A performance specification including these criteria could help lighting designers and specifiers select efficient equipment for office projects to meet circadian criteria. The rank order of the performance specification is photopic efficacy first, since the lighting system must always meet visual criteria. The second specification layer would then be the m-DER rating, a useful indicator of the system's melanopic equivalent daylight efficacy and important for the circadian performance period. We also include criteria for E_V/E_H and glare.

TABLE 11. DRAFT SPECIFICATION TO ILLUSTRATE PERFORMANCE CRITERIA FOR EFFICIENT CIRCADIAN LIGHTING

Parameter	**Tier I Requirement**		**Tier II Requirement**	
Minimum photopic efficacy*	125 LPW	130 LPW	125 LPW	130 LPW
Minimum m-DER (melanopic equivalent daylight/photopic light)*	0.72	0.69	0.80	0.77
E_V/E_H	0.65 or greater		0.65 or greater	
UGR (fixture glare rating)	Below 19		Below 19	
*The above corresponds to "melanopic equivalent daylight efficacy"	90 melanopic equivalent daylight LPW		100 melanopic equivalent daylight LPW	

FURTHER RESEARCH QUESTIONS AND OPPORTUNITIES

Based on the results of the lab tests and analysis, we identified several research veins related to circadian performance and energy efficiency. Subsections addressing some of the most compelling topics follow.

LAB, SIMULATION, AND FIELD STUDIES

It would be valuable to perform lab experiments similar to those conducted for this project, but with light sources specified for high photopic efficacy and m-DER values, essentially per our draft specification in Table 11. Since there are market-available LED troffers and pendants with rated performance consistent with our draft specification, this would be a relatively-straightforward next research step to potentially identify even more energy-efficient options. Is it possible with such lighting equipment to minimize or eliminate the incremental energy costs of circadian design? An alternative topic that also merits further investigation is light sources engineered with novel SPDs that specifically target the melanopic range, but maintain more traditional color temperatures for commercial lighting. Such LED sources are available on the market, including BIOS SkyBlue®, which provides 3,500 K light but with an SPD optimized for melanopic performance via an emissions peak corresponding to peak melanopsin sensitivity [39]. Research on such sources would be valuable to better understand whether these technologies can provide visual and circadian performance at a lower energy cost.

More research would be useful to identify innovative fixtures, and layouts and design schemes, that produce prescribed task illuminance values at low lighting power densities, but with luminous distributions more effective for circadian activation, including higher E_V/E_H ratios in the office environment. In such a study, glare criteria would be important to consider. Intuitively, there would seem to be an upper bound to the E_V/E_H ratio with respect to glare, above which glare limits would be violated; it would be worthwhile to try to define this boundary.

We recommend more comprehensive daylighting studies and simulations for perimeter zone circadian performance, including parametric analysis of the many variables affecting circadian performance (view positions, building orientations, depth into office space, window dimensions, shading strategies, typical meteorological year data for different geographic locations, etc.). For what range of conditions are our perimeter zone findings valid; namely, that circadian criteria require no additional lighting energy in the daylit zone?

Finally, we have determined field studies on tunable white office lighting, circadian design, and energy impacts are lacking. Finding office locations where such lighting systems and strategies have been (or will be) implemented, and conducting rigorous field evaluations (preferably including pre-and post-energy monitoring and photometric and spectral measurements, as well as occupant surveys), would be invaluable.

USER ACCEPTANCE

Higher CCT lighting in our tests corresponded to the highest melanopic equivalent daylight performance. Importantly, it still remains to be seen how the highest color temperatures would be accepted by office occupants. More research is needed on user acceptance of and adaptation to higher color temperatures, the upper limits for CCTs in offices, and any other potential negative (or positive) effects from high CCTs. More generally, research on office user acceptance of, and interest in, tunable white light sources would be useful. It is still not clear to what extent office occupants desire, would respond to, and would engage with such lighting systems.

MARKET

A market study on the prevalence of lighting retrofits and new construction including circadian design criteria would be helpful. How often are such installations taking place, and how many are currently in the United States in different building types, including commercial offices and others where there is an interest in circadian performance (such as health care, assisted living, and education)? And what circadian design guidance or criteria are being implemented in such installations?

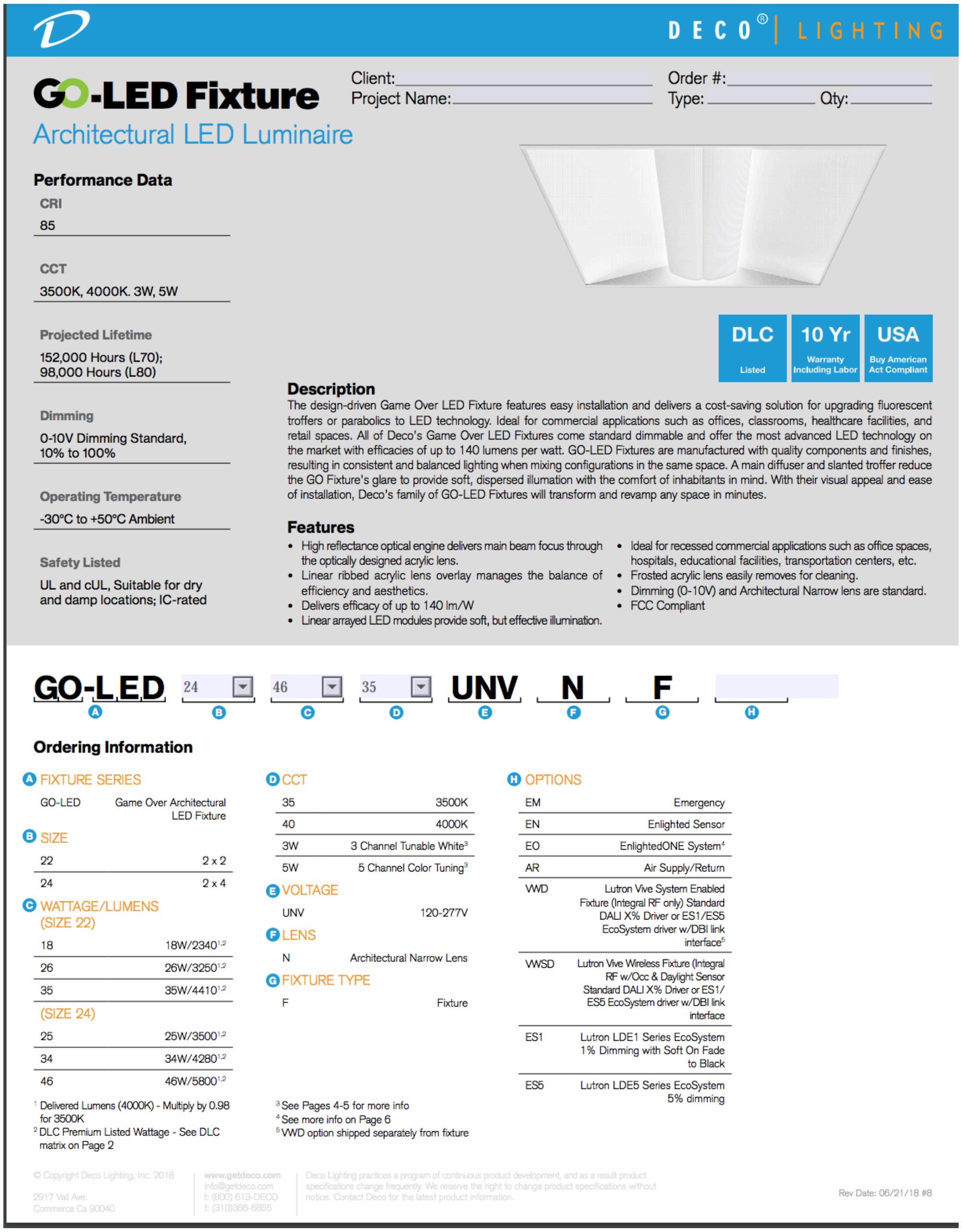
Additionally, we see a need for a market study on the prevalence of tunable white LED lighting in new lighting installations and the overlap between tunable white system and lighting installations for circadian performance criteria. Are the two closely related, or are other factors motivating the adoption of tunable white lighting? The same study would do well to consider the cost premium of tunable white fixtures and controls. Finally, data on the efficacy ranges of tunable white sources relative to non-tunable sources should be collected, to determine what, if any, energy penalty is associated with tunable technology.

NEW PRODUCTS AND CONTROLS INNOVATIONS

Because desk-based CL_A sources have shown high circadian efficacy for the lowest energy cost, it would be worthwhile to research, develop, and prototype this technology, and study user interaction and acceptance. It also would be valuable to explore integrating such devices with general overhead lighting system controls to orchestrate lighting timing and intensity from various sources for the different purposes they serve.

Also, with low-cost integrated circuits and chip sets now available, new spectral sensors to enable more sophisticated lighting controls are in development or entering the market; for example, the small form-factor Blue Iris Labs spectrometer [40]. Mini spectrometers or purpose-built mEDI sensors could be deployed alongside traditional photopic illuminance sensors and used as closed-loop control points for intensity and tunable white adjustments to meet circadian criteria. We recommend research, including bench testing, lab testing, or field testing small form-factor spectrometers or melanopic-equivalent daylight sensors, to identify new ways of controlling and monitoring the lighting environment.

APPENDIX A: LED FIXTURE SPECIFICATIONS



DECO® | LIGHTING

GO-LED Fixture

Architectural LED Luminaire

Client:
Project Name:
Order #:
Type: Qty:

Performance Data

CRI	85
CCT	3500K, 4000K. 3W, 5W
Projected Lifetime	152,000 Hours (L70); 98,000 Hours (L80)
Dimming	0-10V Dimming Standard, 10% to 100%
Operating Temperature	-30°C to +50°C Ambient
Safety Listed	UL and cUL, Suitable for dry and damp locations; IC-rated

DLC Listed | 10 Yr Warranty Including Labor | USA Buy American Act Compliant

Description

The design-driven Game Over LED Fixture features easy installation and delivers a cost-saving solution for upgrading fluorescent troffers or parabolics to LED technology. Ideal for commercial applications such as offices, classrooms, healthcare facilities, and retail spaces. All of Deco's Game Over LED Fixtures come standard dimmable and offer the most advanced LED technology on the market with efficacies of up to 140 lumens per watt. GO-LED Fixtures are manufactured with quality components and finishes, resulting in consistent and balanced lighting when mixing configurations in the same space. A main diffuser and slanted troffer reduce the GO Fixture's glare to provide soft, dispersed illumination with the comfort of inhabitants in mind. With their visual appeal and ease of installation, Deco's family of GO-LED Fixtures will transform and revamp any space in minutes.

Features

- High reflectance optical engine delivers main beam focus through the optically designed acrylic lens.
- Linear ribbed acrylic lens overlay manages the balance of efficiency and aesthetics.
- Delivers efficacy of up to 140 lm/W
- Linear arrayed LED modules provide soft, but effective illumination.
- Ideal for recessed commercial applications such as office spaces, hospitals, educational facilities, transportation centers, etc.
- Frosted acrylic lens easily removes for cleaning.
- Dimming (0-10V) and Architectural Narrow lens are standard.
- FCC Compliant

GO-LED	24	46	35	UNV	N	F	
A	B	C	D	E	F	G	H

Ordering Information

A FIXTURE SERIES

GO-LED	Game Over Architectural LED Fixture

B SIZE

22	2 x 2
24	2 x 4

C WATTAGE/LUMENS

(SIZE 22)	
18	18W/2340[1,2]
26	26W/3250[1,2]
35	35W/4410[1,2]
(SIZE 24)	
25	25W/3500[1,2]
34	34W/4280[1,2]
46	46W/5800[1,2]

D CCT

35	3500K
40	4000K
3W	3 Channel Tunable White[3]
5W	5 Channel Color Tuning[3]

E VOLTAGE

UNV	120-277V

F LENS

N	Architectural Narrow Lens

G FIXTURE TYPE

F	Fixture

H OPTIONS

EM	Emergency
EN	Enlighted Sensor
EO	EnlightedONE System[4]
AR	Air Supply/Return
VWD	Lutron Vive System Enabled Fixture (Integral RF only) Standard DALI X% Driver or ES1/ES5 EcoSystem driver w/DBI link interface[5]
VWSD	Lutron Vive Wireless Fixture (Integral RF w/Occ & Daylight Sensor Standard DALI X% Driver or ES1/ ES5 EcoSystem driver w/DBI link interface
ES1	Lutron LDE1 Series EcoSystem 1% Dimming with Soft On Fade to Black
ES5	Lutron LDE5 Series EcoSystem 5% dimming

[1] Delivered Lumens (4000K) - Multiply by 0.98 for 3500K
[2] DLC Premium Listed Wattage - See DLC matrix on Page 2
[3] See Pages 4-5 for more info
[4] See more info on Page 6
[5] VWD option shipped separately from fixture

© Copyright Deco Lighting, Inc. 2018
2917 Vail Ave.
Commerce Ca 90040

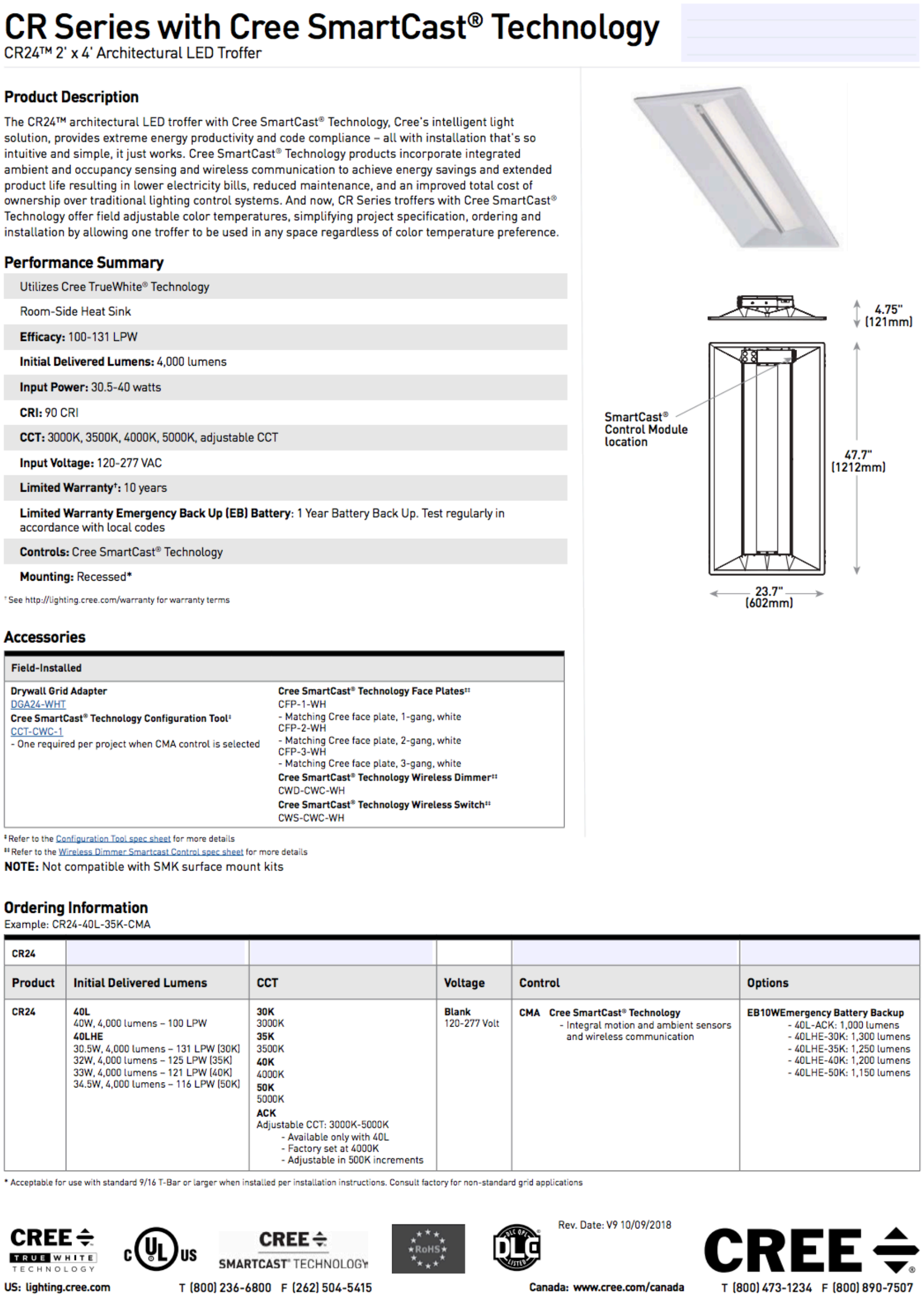
www.getdeco.com
info@getdeco.com
t: (800) 613-DECO
f: (310)366-6855

Deco Lighting practices a program of continuous product development, and as a result product specifications change frequently. We reserve the right to change product specifications without notice. Contact Deco for the latest product information.

Rev Date: 06/21/18 #8

FIGURE 31. BASELINE TROFFER (A1) CUT SHEET

Model: GO-LED-24-46-35-UNV (Enlighted controls, 125 LPW, 5684 lumens, 46 W)



CR Series with Cree SmartCast® Technology

CR24™ 2' x 4' Architectural LED Troffer

Product Description

The CR24™ architectural LED troffer with Cree SmartCast® Technology, Cree's intelligent light solution, provides extreme energy productivity and code compliance – all with installation that's so intuitive and simple, it just works. Cree SmartCast® Technology products incorporate integrated ambient and occupancy sensing and wireless communication to achieve energy savings and extended product life resulting in lower electricity bills, reduced maintenance, and an improved total cost of ownership over traditional lighting control systems. And now, CR Series troffers with Cree SmartCast® Technology offer field adjustable color temperatures, simplifying project specification, ordering and installation by allowing one troffer to be used in any space regardless of color temperature preference.

Performance Summary

Utilizes Cree TrueWhite® Technology

Room-Side Heat Sink

Efficacy: 100-131 LPW

Initial Delivered Lumens: 4,000 lumens

Input Power: 30.5-40 watts

CRI: 90 CRI

CCT: 3000K, 3500K, 4000K, 5000K, adjustable CCT

Input Voltage: 120-277 VAC

Limited Warranty†: 10 years

Limited Warranty Emergency Back Up (EB) Battery: 1 Year Battery Back Up. Test regularly in accordance with local codes

Controls: Cree SmartCast® Technology

Mounting: Recessed*

† See http://lighting.cree.com/warranty for warranty terms

Accessories

Field-Installed	
Drywall Grid Adapter DGA24-WHT **Cree SmartCast® Technology Configuration Tool‡** CCT-CWC-1 - One required per project when CMA control is selected	**Cree SmartCast® Technology Face Plates‡‡** CFP-1-WH - Matching Cree face plate, 1-gang, white CFP-2-WH - Matching Cree face plate, 2-gang, white CFP-3-WH - Matching Cree face plate, 3-gang, white **Cree SmartCast® Technology Wireless Dimmer‡‡** CWD-CWC-WH **Cree SmartCast® Technology Wireless Switch‡‡** CWS-CWC-WH

‡ Refer to the Configuration Tool spec sheet for more details

‡‡ Refer to the Wireless Dimmer Smartcast Control spec sheet for more details

NOTE: Not compatible with SMK surface mount kits

Ordering Information

Example: CR24-40L-35K-CMA

CR24					
Product	**Initial Delivered Lumens**	**CCT**	**Voltage**	**Control**	**Options**
CR24	**40L** 40W, 4,000 lumens – 100 LPW **40LHE** 30.5W, 4,000 lumens – 131 LPW (30K) 32W, 4,000 lumens – 125 LPW (35K) 33W, 4,000 lumens – 121 LPW (40K) 34.5W, 4,000 lumens – 116 LPW (50K)	**30K** 3000K **35K** 3500K **40K** 4000K **50K** 5000K **ACK** Adjustable CCT: 3000K-5000K - Available only with 40L - Factory set at 4000K - Adjustable in 500K increments	**Blank** 120-277 Volt	**CMA** **Cree SmartCast® Technology** - Integral motion and ambient sensors and wireless communication	**EB10WEmergency Battery Backup** - 40L-ACK: 1,000 lumens - 40LHE-30K: 1,300 lumens - 40LHE-35K: 1,250 lumens - 40LHE-40K: 1,200 lumens - 40LHE-50K: 1,150 lumens

* Acceptable for use with standard 9/16 T-Bar or larger when installed per installation instructions. Consult factory for non-standard grid applications

Rev. Date: V9 10/09/2018

US: lighting.cree.com T (800) 236-6800 F (262) 504-5415

Canada: www.cree.com/canada T (800) 473-1234 F (800) 890-7507

FIGURE 32. TUNABLE RETROFIT TROFFER (C1) CUT SHEET

Model: CREE CR24 40L ACK CMA (SmartCast controls, 100 LPW, 4000 lumen, 40 W)

ALW

SUPERPLANE 2.5

SP2.5 | CONTROLROLL OPTICS | SUSPENDED, WALL, SURFACE

STANDARD SIZES
2.5" Aperture
2ft - 8ft straight sections

LAMPING
LED - Direct & Indirect - 80/90 CRI - 2700K/3000K/3500K/4000K
ControlRoll Optics - Continuous lens up to 250ft.
Standard Lambertian | 60° Batwing/Flood | 25° Asy/Wall Wash (Direct Only)
120° Rigid Batwing Optic available (Indirect Only)
Output Options: MIN/LOW/MED/HI/MAX/BIOS/Tunable White/RGB/RGB+W
Dimming down to 0%

FINISH
18 standard finishes available at no extra charge
RAL classic colors, TCI / Tiger Drylac catalog colors, & custom color match

CONSTRUCTION
Extruded 6063-T6 Aluminum

SPECIFYING FOR WELL™?
See pages 8-9 for recommended options that contribute to meeting the WELL Building Standard™.

QuickShip Eligible
Intertek ETL Listed 1598
ControlRoll Optics
bios ILLUMINATED
enlighted
vive by LUTRON

SP2.5 – SPECIFICATIONS
SUSPENDED, WALL, SURFACE
ALWUSA.COM

FIGURE 33. TUNABLE RETROFIT PENDANT (C2) CUT SHEET

Model: ALW 4' SP2.5S-S4-TUNE PENDANTS (diffuse downward / batwing flood upward, 109 to 120 LPW, 1,050 lumen/ft, 9W/ft)

APPENDIX B: SUPPLEMENTAL DATA PLOTS

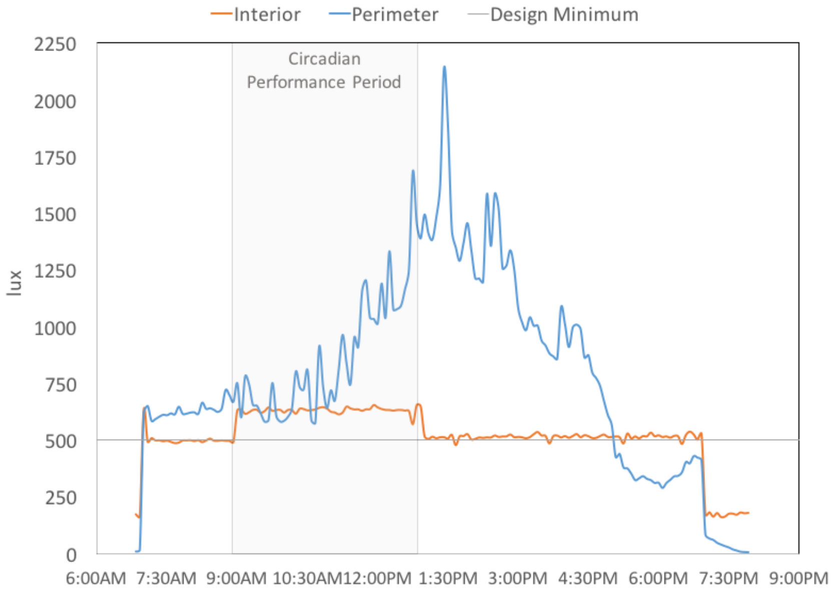


FIGURE 34. TIME SERIES OF TASK PLANE ILLUMINANCE DATA: B2 RETROFIT, 500-LUX TEST

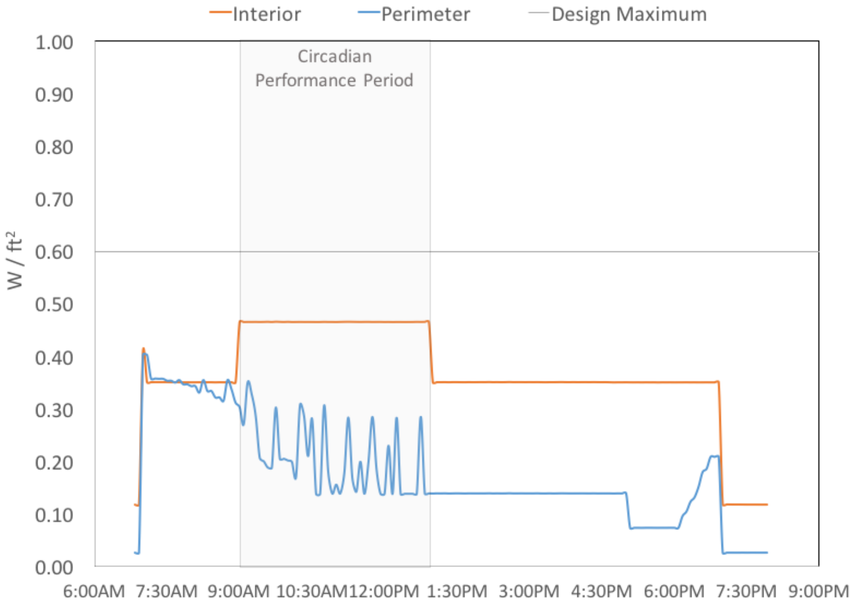


FIGURE 35. TIME SERIES OF LIGHTING POWER DENSITY DATA: B2 RETROFIT, 500-LUX TEST

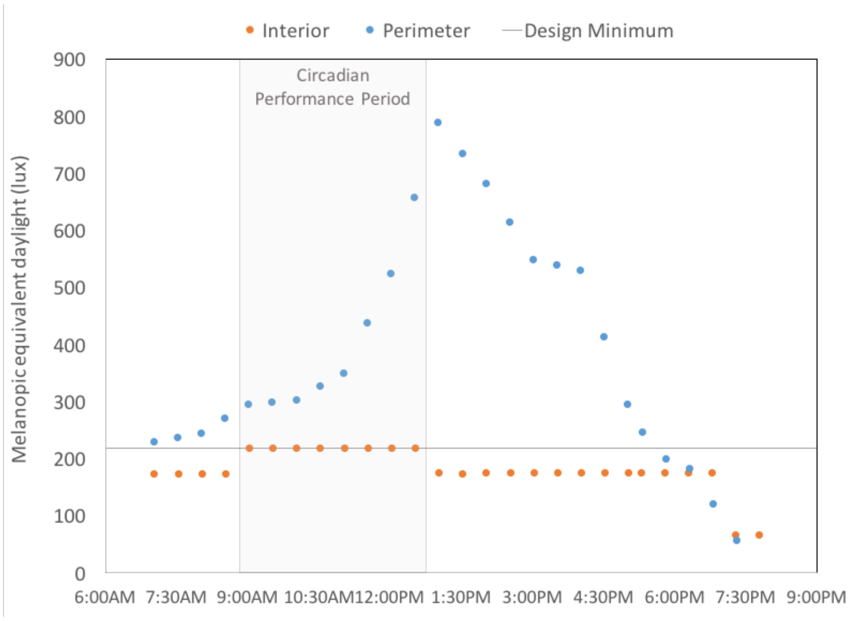


FIGURE 36. TIME SERIES OF MEDI DATA AT OCCUPANT-VIEW POSITION: B2 RETROFIT, 500-LUX TEST

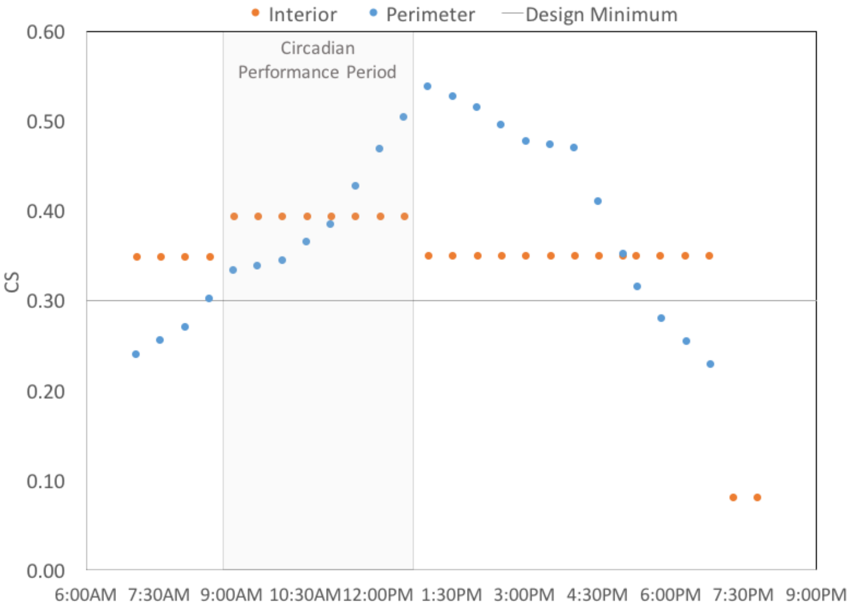


FIGURE 37. TIME SERIES OF CS DATA AT OCCUPANT-VIEW POSITION: B2 RETROFIT, 500-LUX TEST

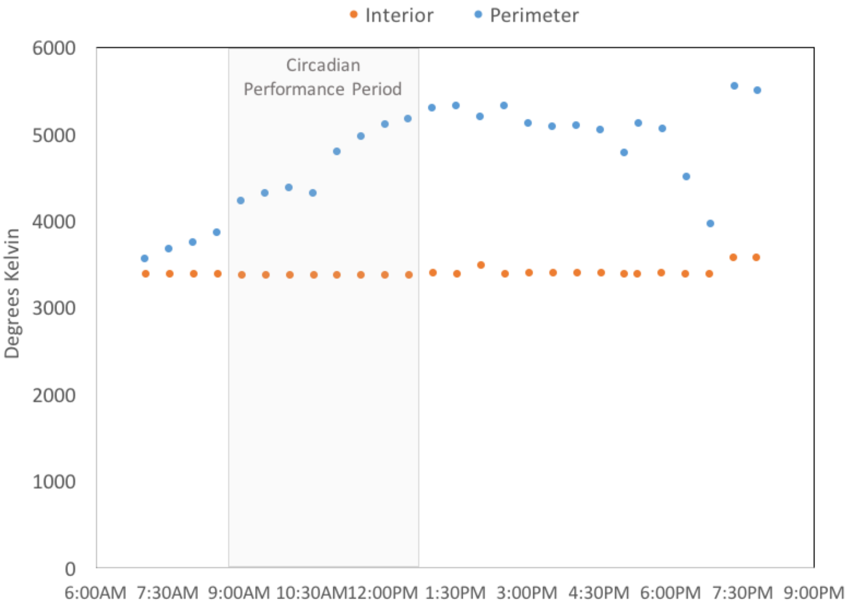


FIGURE 38. TIME SERIES OF CCT DATA AT OCCUPANT-VIEW POSITION: B2 RETROFIT, 500-LUX TEST

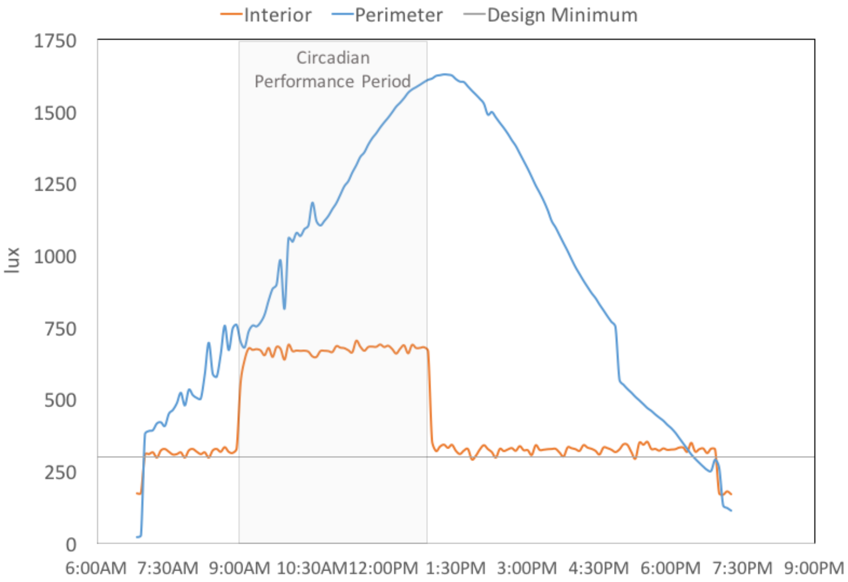


FIGURE 39. TIME SERIES OF TASK PLANE ILLUMINANCE DATA: B2 RETROFIT, 300-LUX TEST

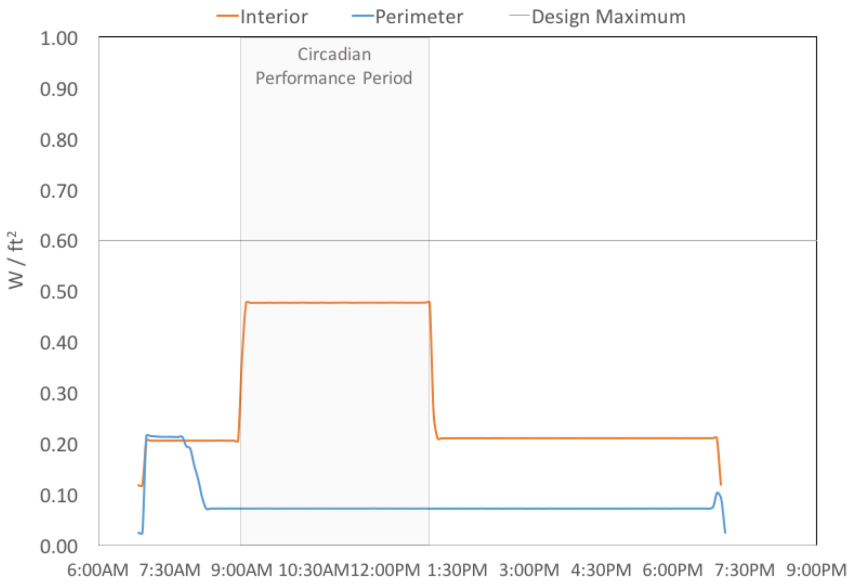


FIGURE 40. TIME SERIES OF LIGHTING POWER DENSITY DATA: B2 RETROFIT, 300-LUX TEST

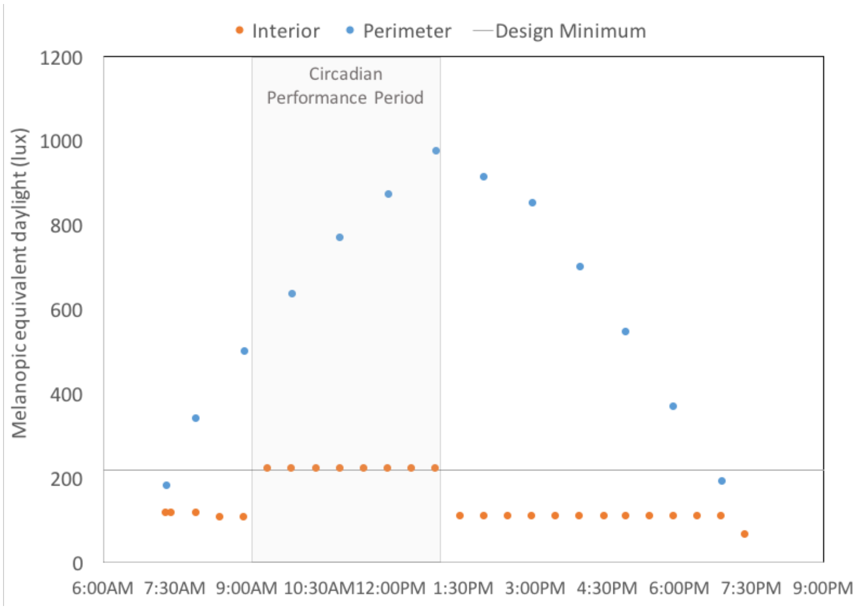


FIGURE 41. TIME SERIES OF MEDI DATA AT OCCUPANT-VIEW POSITION: B2 RETROFIT, 300-LUX TEST

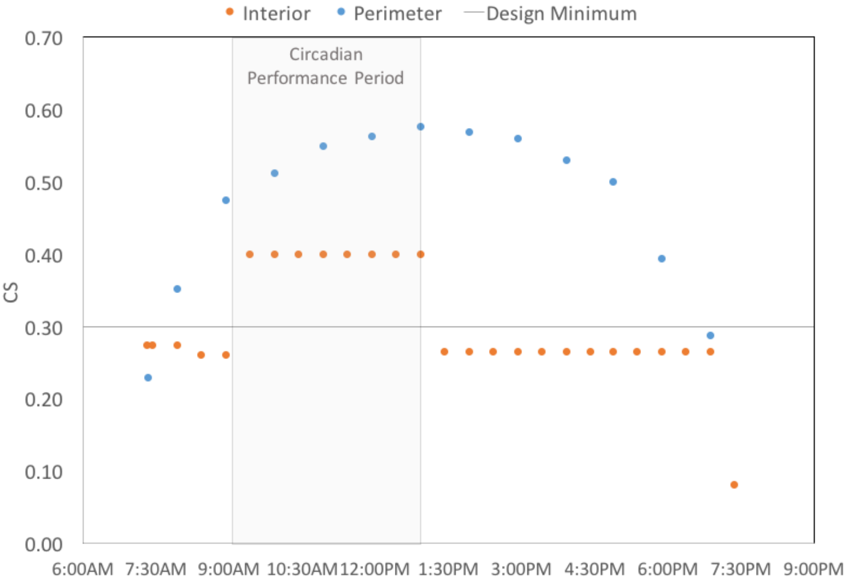


FIGURE 42. TIME SERIES OF CS DATA AT OCCUPANT-VIEW POSITION: B2 RETROFIT, 300-LUX TEST

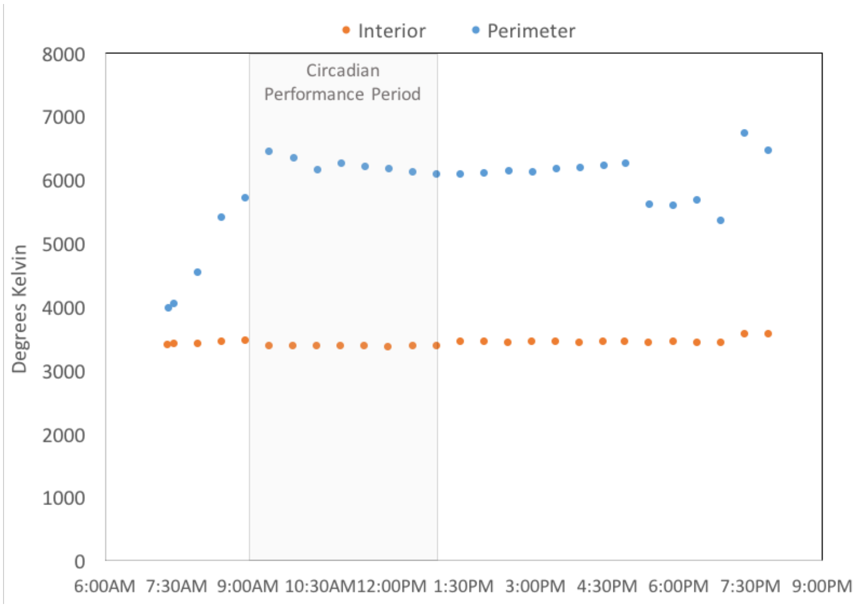


Figure 43. Time Series of CCT Data at Occupant-View Position: B2 Retrofit, 300-Lux Test

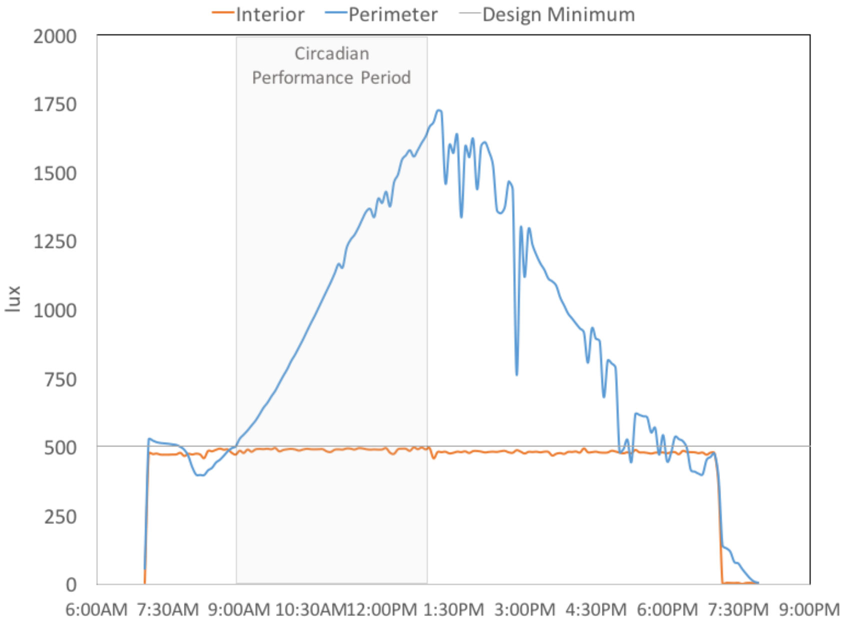


FIGURE 44. TIME SERIES OF TASK PLANE ILLUMINANCE DATA: C1 RETROFIT, 500-LUX TEST

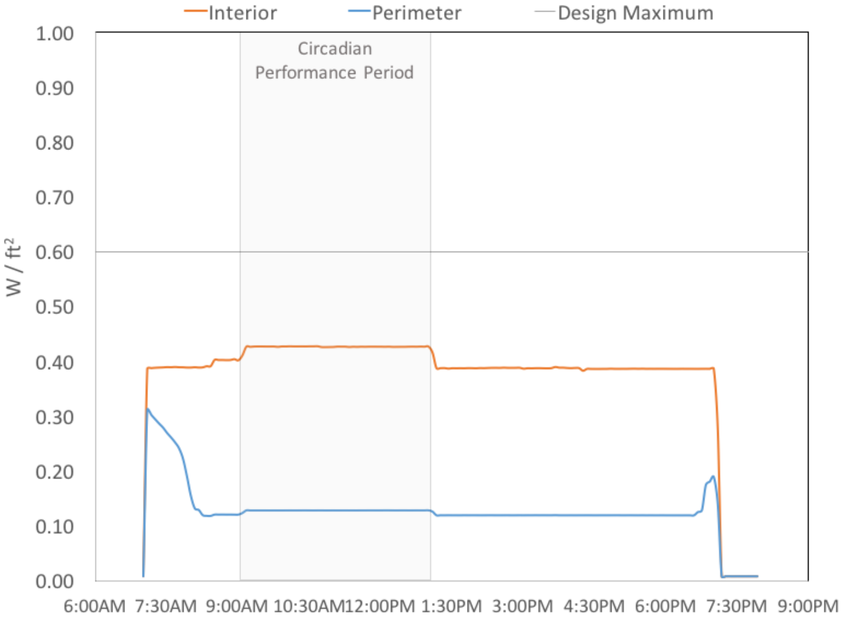


FIGURE 45. TIME SERIES OF LIGHTING POWER DENSITY DATA: C1 RETROFIT, 500-LUX TEST

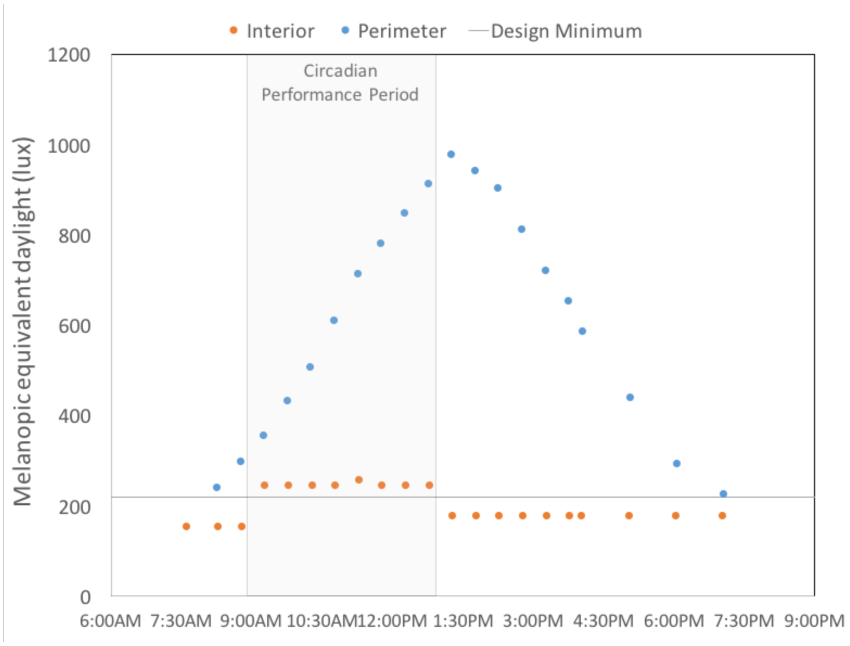


FIGURE 46. TIME SERIES OF MEDI DATA AT OCCUPANT-VIEW POSITION: C1 RETROFIT, 500-LUX TEST

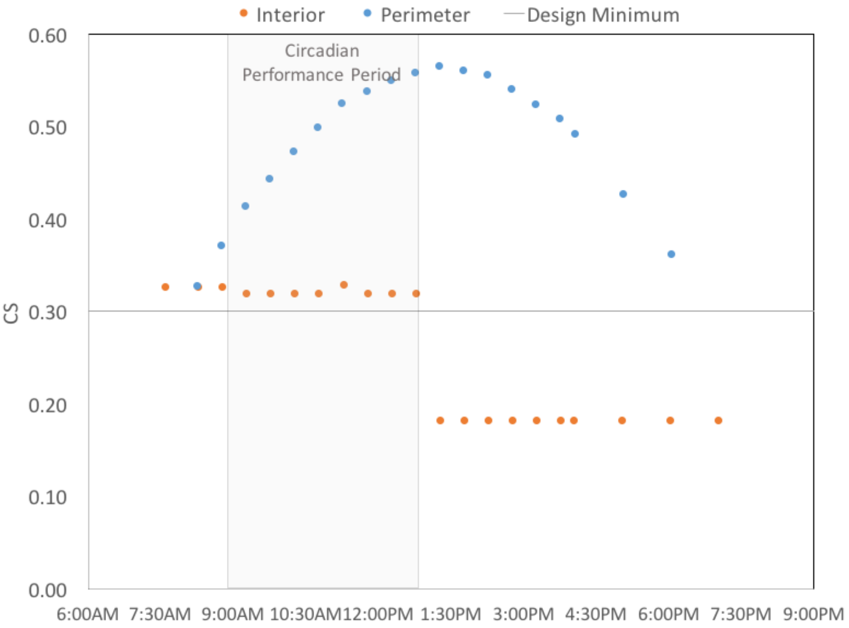


FIGURE 47. TIME SERIES OF CS DATA AT OCCUPANT-VIEW POSITION: C1 RETROFIT, 500-LUX TEST

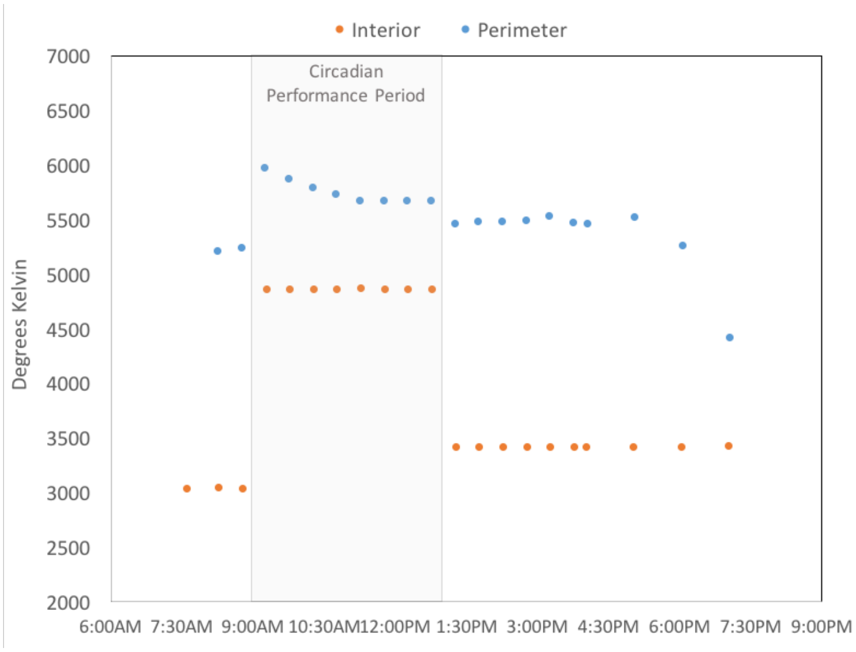


FIGURE 48. TIME SERIES OF CCT DATA AT OCCUPANT-VIEW POSITION: C1 RETROFIT, 500-LUX TEST

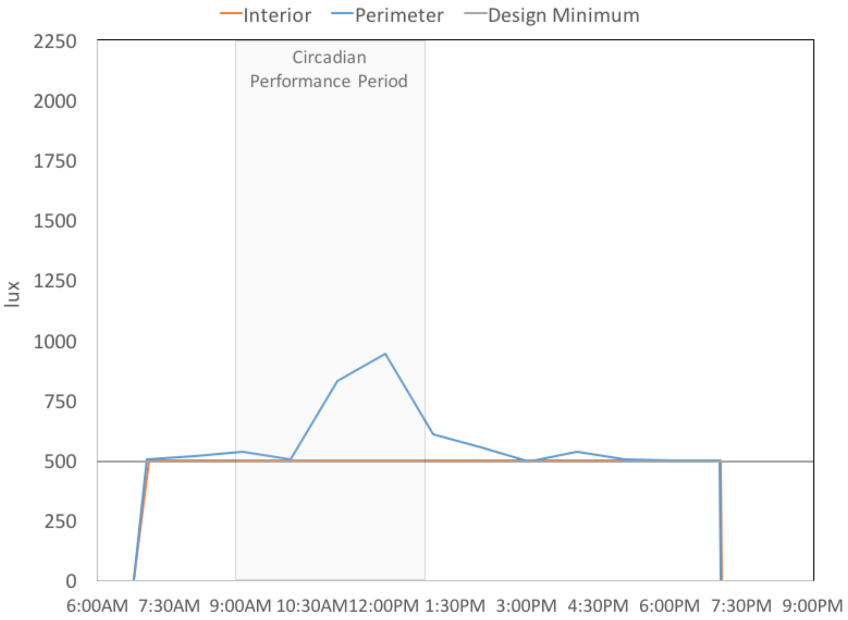


FIGURE 49. TIME SERIES OF TASK PLANE ILLUMINANCE DATA: C2 RETROFIT, 500-LUX TEST

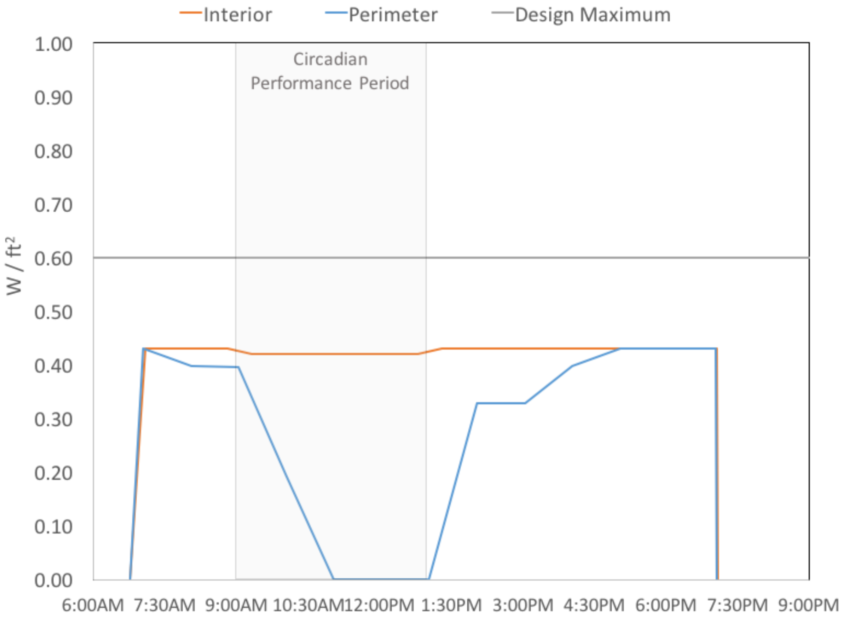


FIGURE 50. TIME SERIES OF LIGHTING POWER DENSITY DATA: C2 RETROFIT, 500-LUX TEST

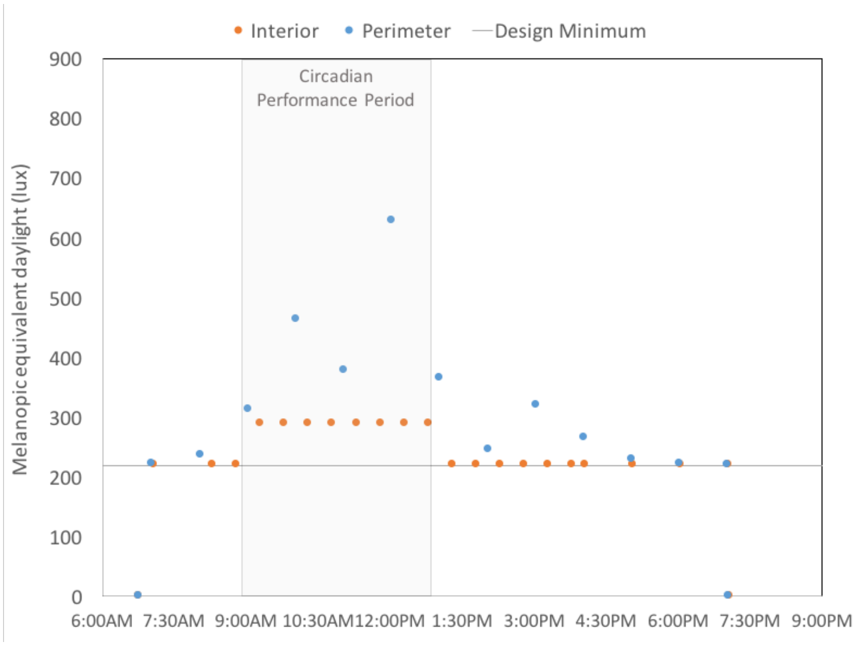


FIGURE 51. TIME SERIES OF MEDI DATA AT OCCUPANT-VIEW POSITION: C2 RETROFIT, 500-LUX TEST

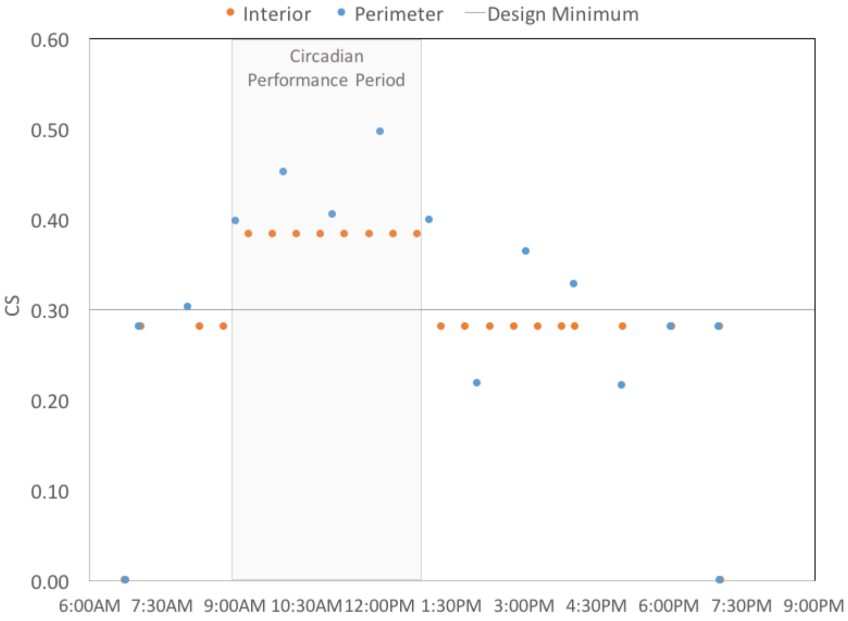


FIGURE 52. TIME SERIES OF CS DATA AT OCCUPANT-VIEW POSITION: C2 RETROFIT, 500-LUX TEST

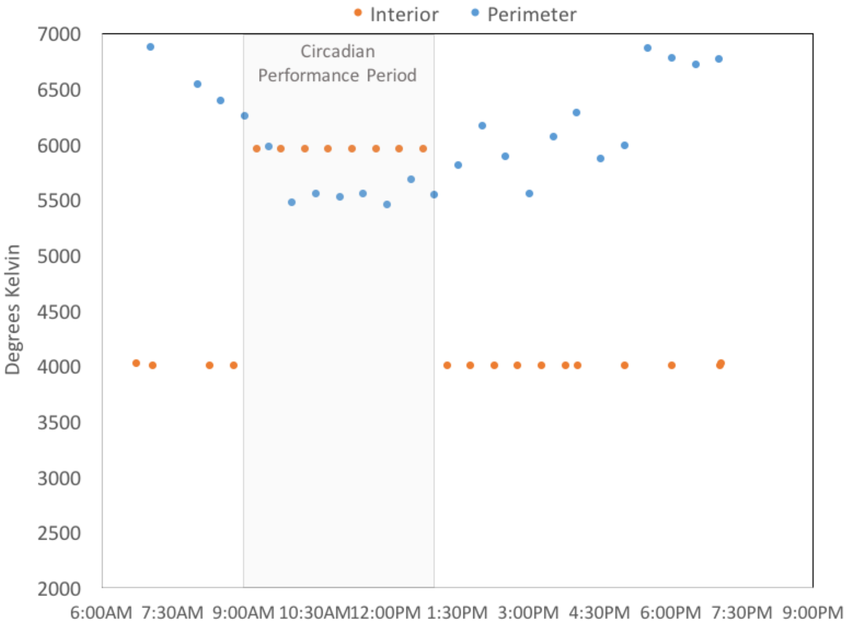


FIGURE 53. TIME SERIES OF CCT DATA AT OCCUPANT-VIEW POSITION: C2 RETROFIT, 500-LUX TEST

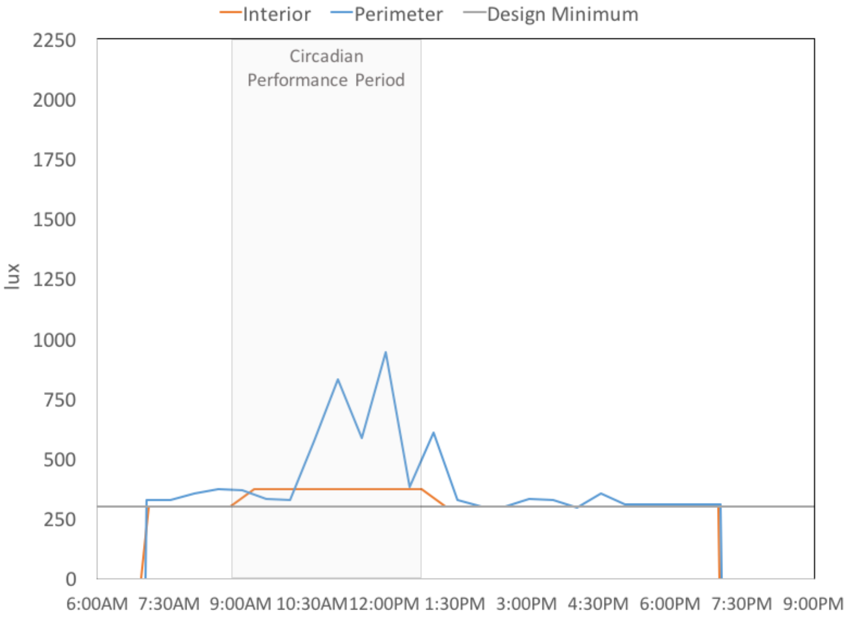


FIGURE 54. TIME SERIES OF TASK PLANE ILLUMINANCE DATA: C2 RETROFIT, 300-LUX TEST

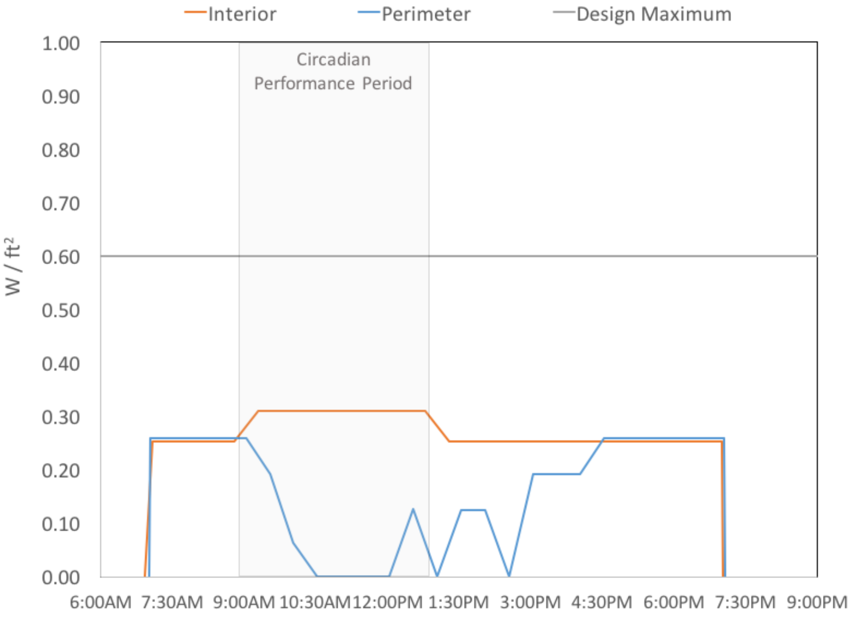


FIGURE 55. TIME SERIES OF LIGHTING POWER DENSITY DATA: C2 RETROFIT, 300-LUX TEST

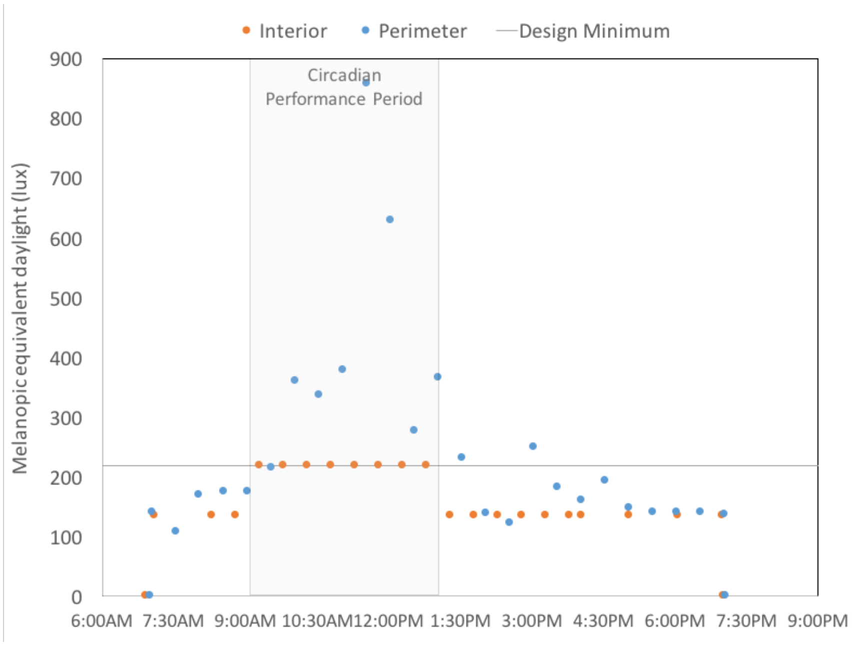


FIGURE 56. TIME SERIES OF MEDI DATA AT OCCUPANT-VIEW POSITION: C2 RETROFIT, 300-LUX TEST

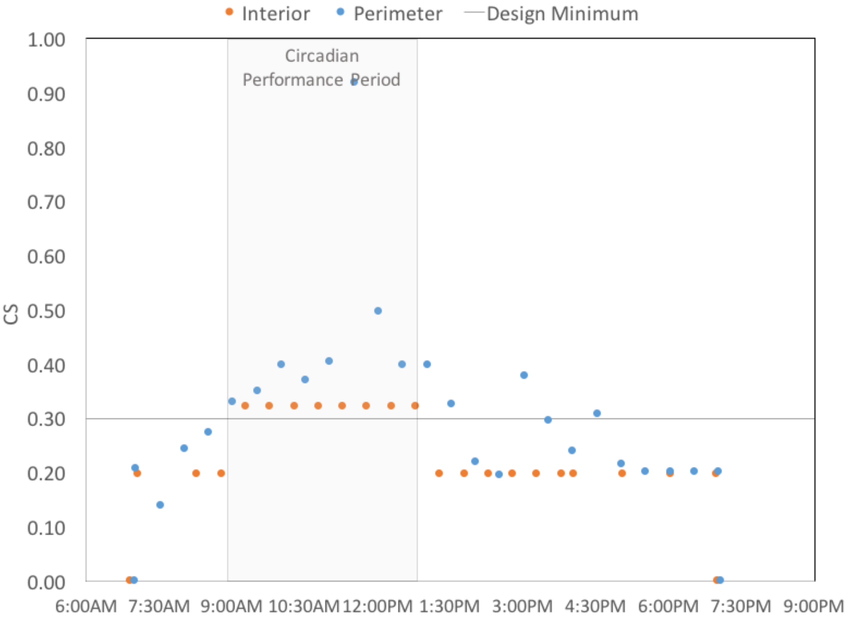


FIGURE 57. TIME SERIES OF CS DATA AT OCCUPANT-VIEW POSITION: C2 RETROFIT, 300-LUX TEST

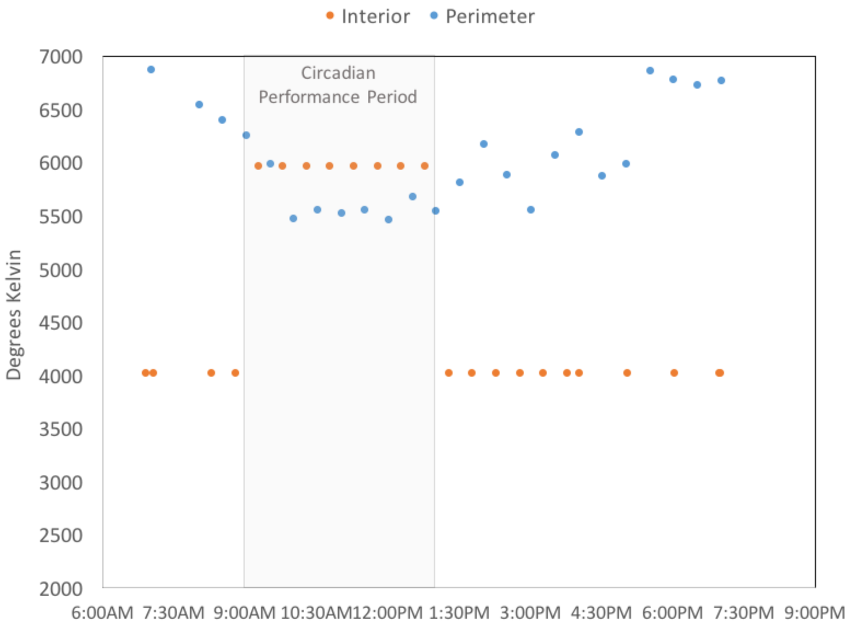


FIGURE 58. TIME SERIES OF CCT DATA AT OCCUPANT-VIEW POSITION: C2 RETROFIT, 300-LUX TEST

REFERENCES

1. I. Provencio, I. R. Rodriguez, G. Jiang, W. P. Hayes, E. F. Moreira, and M. D. Rollag (2000), "A novel human opsin in the inner retina." *Journal of Neuroscience.* Vol. 20, No. 2, pp. 600–605.
2. Design Lights Consortium (2018), Testing and Reporting Requirements for Color-Tunable Products. https://www.designlights.org/solid-state-lighting/testing-reporting-requirements/color-tunable-products/.
3. Design Lights Consortium (No date), Solid State Lighting Qualified Products List. https://www.designlights.org/search/.
4. George C. Brainard, John P. Hanifin, Jeffrey M. Greeson, Brenda Byrne, Gena Glickman, Edward Gerner, and Mark D. Rollag (2001), "Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor." *Journal of Neuroscience.* 15 August. Vol. 21, No. 16, pp. 6405–6412.
5. K. Thapan, J. Arendt, and D. J. Skene (2001), "An action spectrum for melatonin suppression: Evidence for a novel non-rod, non-cone photoreceptor system in humans." *The Journal of Physiology.* Vol. 535 (Pt 1), pp. 261–267. doi:10.1111/j.1469-7793.2001.t01-1-00261.x.
6. M. S. Rea, M. G. Figueiro, J. D. Bullough, and A. Bierman (2005), "A model of phototransduction by the human circadian system." *Brain Research Reviews.* December. Vol. 50, No. 2, pp. 213–228. DOI: 10.1016/j.brainresrev.2005.07.002.
7. P. J. Sollars, C. A. Smeraski, J. D. Kaufman, M. D. Ogilvie, I. Provencio, and G. E. Pickard (2003), "Melanopsin and non-melanopsin expressing retinal ganglion cells innervate the hypothalamic suprachiasmatic nucleus." *Visual Neuroscience.* Nov–Dec. Vol. 20, No. 6, pp. 601–610. doi: 10.1017/s0952523803206027.
8. Robert J. Lucas, Stuart N. Peirson, David M. Berson, Timothy M. Brown, Howard M. Cooper, Charles A. Czeisler, Mariana G. Figueiro, Paul D. Gamlin, Steven W. Lockley, John B. O'Hagan, Luke L. A. Price, Ignacio Provencio, Debra J. Skene, and George C. Brainard (2014), "Measuring and using light in the melanopsin age." *Journal for Trends in Neurosciences.* Vol. 37, No. 1, pp.1–9.
9. Commission Internationale de l'E´ clairage, Pincipales de´cisions (6e Session, 1924), CIE Sixie`me Session, Gene`ve, Juillet, 1924. Recueil des Travaux et Compte Rendu de Se´ances, Cambridge, the University Press, 1926. pp. 67–69.
10. M. G. Figueiro (2017), "Disruption of Circadian Rhythms by Light During Day and Night." *Current Sleep Medicine Reports.* Vol. 3, No. 2, pp. 76–84. doi:10.1007/s40675-017-0069-0.
11. S 026:2018 (2018), "CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light." DOI: 10.25039/S026.2018. CIE Central Bureau. Vienna, Austria.
12. Mark S. Rea, Mariana G. Figueiro, Andrew Bierman, and John D. Bullough (2010), "Circadian light." *Journal of Circadian Rhythms.* Vol. 8, p. 2.
13. Lighting Research Center. Calculator. No date. https://www.lrc.rpi.edu/cscalculator.
14. IES TM-18-08 (2018), Light and Human Health: An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses. Illuminating Engineering Society, 120 Wall Street, New York, New York 10005. ISBN 978-0-87995-228-0.

15. IES PS-12-19 (September 9, 2019 and Amended August 10, 2020), IES Position On UL RP 24480 Regarding Light and Circadian Entrainment.
16. CIE (2013), Report on the First International Workshop on Circadian and Neurophysiological Photometry. Luke Price, CIE TN003:2015.
17. CIE (October 2019), CIE Position Statement on Non-Visual Effects of Light – Recommending Proper Light at the Proper Time, 2nd Edition. http://cie.co.at/publications/position-statement-non-visual-effects-light-recommending-proper-light-proper-time-2nd.
18. International WELL Building Institute (2020), WELL Building Standard version 2 (WELL v2). https://www.wellcertified.com/certification/v2/.
19. Underwriters Laboratories (2019), UL Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People. UL Inc. Design Guideline 24480, Edition 1. December 19.
20. Collaborative for High Performance Schools (CHPS) (2020), 2020 US CHPS standard, version 2.0. October. https://chps.net/us-chps-online.
21. DIN SPEC 67600:2013-04 (English translation) (2013), Biologically effective illumination – Design guidelines. ICS 17.180.20; 91.160.01. *Deutsches Institut für Normung*. Berlin, Germany.
22. Mariana G. Figueiro, Kassandra Gonzales, and David Pedler (2016), "Designing with Circadian Stimulus." *LD+A,* October. pp. 31–34.
23. C. Jarboe, J. Snyder, and Mariana Figueiro (2019), "The effectiveness of light-emitting diode lighting for providing circadian stimulus in office spaces while minimizing energy use." *Lighting Research & Technology.* Vol. 52, No. 2, pp. 167–188.
24. S. Safranek, J. M. Collier, A. Wilkerson, and R. G. Davis (2020), "Energy impact of human health and wellness lighting recommendations for office and classroom applications." *Energy & Buildings.* doi: 10.1016/j.enbuild.2020.110365.
25. Q. Dai, W. Cai Barch, L. Hao, W. Shi, and Z. Wang, (2017), "Spectral optimisation and a novel lighting-design space based on circadian stimulus." *Lighting Research & Technology.* Vol. 50, pp. 1198–1211.
26. Philip von Erberich, and Keith Graeber (2019), "Circadian Lighting Design: Leveraging the Melanopic Efficacy of Luminous Radiation Metric." *LD+A* Research section. May. pp. 76–80.
27. Sacramento Municipal Utility District (2018), Gold Ridge Elementary School Lighting Study. Dave Bisbee. CEM. October.
28. Sarah F. Safranek, and Robert G. Davis (2018), Evaluating Tunable Lighting in Classrooms: Trial LED lighting systems in three classrooms in the Folsom Cordova Unified School District. September. https://www.energy.gov/eere/ssl/downloads/evaluating-tunable-lighting-classrooms.
29. General Service Administration (2021), Circadian Light for Your Health. https://www.gsa.gov/governmentwide-initiatives/federal-highperformance-buildings/resource-library/health/circadian-light-for-your-health.
30. U.S. General Services Administration (2020), *A Case for Circadian Lighting in Federal Buildings.* Office of Federal High-Performance Green Buildings. https://www.gsa.gov/cdnstatic/AcaseforCircadianLightinginFederalBuildings.pdf.

31. M. G. Figueiro, B. Steverson, J. Heerwagen, R. Yucel, C. Roohan, L. Sahin, K. Kampschroer, and M. S. Rea (2020), "Light, entrainment and alertness: A case study in offices." *Lighting Research & Technology.* Vol. 52, pp. 736–750.
32. ANSI/IES RP-1-20 (2020), Recommended Practice: Lighting Office Spaces.
33. Jan Wienold, and Jens Christoffersen (2006), "Evaluation Methods and Development of a New Glare Prediction Model for Daylight Environments with the Use of CCD Cameras," *Energy and Buildings, Special Issue on Daylighting Buildings.* Vol. 38, No. 7, pp. 743–757. doi:10.1016/j.enbuild.2006.03.017.
34. European Committee for Standardization (CEN) (2011), EN 12464-1 Light and lighting – Lighting of work places – Part 1: Indoor work places.
35. California Energy Commission (2018), California Title 24 2019 Building Energy Efficiency Standards Part 6 Section 140.6. Area Category Method – Lighting Power Density Values.
36. Lighting Research Center, Rensselaer Polytechnic Institute (2018), *Lighting for Health and Energy Savings: Photometric Calculations.* Troy, New York.
37. Schwartz, Peter M. (2018), Circadian Lighting and Demand Response Synergy. West Coast Lighting Insider Blog. Lightshow West. May 16. https://www.lightshowwest.com/circadian-lighting-and-demand-response-synergy.
38. Signify (No date), LEDALITE EyeLine by Signify (formerly Philips). Product specifications. https://www.signify.com/en-us/brands/product-highlights/eyeline.
39. BIOS (2021), Circadian Solutions For Your Home. https://bioslighting.com/circadian-lighting-solutions/.
40. Blue Iris Labs (2020), Products. https://blueirislabs.com/products/.