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An Investigation of the Operational and Design Characteristics of Circadian Lighting Systems - Report

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UCARE: Undergraduate Creative Activities and Research Experience at Nebraska

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1. Abstract

This report investigates the operation of circadian lighting systems to gain an understanding of the main design and control characteristics and to promote different objectives for use. Research is guided by asking how color intensity, color temperature and their temporal characteristics are related to the circadian response, and how this knowledge can be utilized when designing and operating lighting systems for indoor environments. This report consists of an extensive literature review and case study application cut short by the impact of the novel coronavirus. The case study takes place in an office space housed on the UNMC campus featuring an installed circadian lighting system capable of changing color temperature and intensity independently. The results of the literature review lead to the understanding of biological impacts of suggested operational patterns for the lighting system. Specifically, the interaction between human physical characteristics as they relate to the current lighting technologies has helped to develop the rational for use of these systems. These biological impacts ultimately aim towards improved occupant attention and well-being in the space. Future investigation and implementation are encouraged to continue advanced analysis of occupant response to varied patterns of operation for this circadian lighting system.

2. Introduction

Circadian rhythms are biological responses driven by our internal biological clocks that operate on a 24-hour day/night schedule [2]. These rhythms are endogenously generated and persist when environmental conditions are kept constant. This allows humans to anticipate and predict daily changes in the environment they commonly occupy [10]. Circadian light is light that acts as a stimulus for the human circadian system [6]. Similarly, circadian lighting design is design of lighting systems that intends to work in harmony with the circadian rhythm of our internal clocks, doing so through access to daylight or modulation of the intensity and spectrum of electric light in symbiosis with the natural lighting cycle [2].

Since a greater understanding of the biological effects of light has been gathered over time, designers, manufacturers, and engineers are going into greater detail when defining what it means to have a circadian lighting system. While “tunable white” and “circadian lighting” are often oversaturated marketing terms for popular new technologies available for both consumer and commercial lighting systems, understanding the fundamentals, the technology limitations, and how everything should be used is critical to achieving the desired lighting effects in their full potential.

3. Human Physical Characteristics

Now more than ever, light is understood to be more complex than simply a stimulus for visual functions. The traditional recommendations for horizontal illuminance on the work plane are being supplemented by additional requirements for biological responses in humans. Nonvisual stimulus related to circadian rhythm in humans is a newfound effect of the biological impact of light and has great value in evaluation towards application in the work environment [1]. Integration between daylight and electric lighting is on the leading edge of design as we begin to integrate the two. Focusing on human centric design is a key factor when balancing daylight and electric lighting in a way that supports human circadian adapted design [2]. To better understand the effects of natural and artificial light on human circadian rhythms, we must first detail the physical characteristics of lighting as well as the circadian response in humans.

a) Lighting Physical Characteristics

i) Define Light

It is important to understand light in a classical sense, in addition to the newly described circadian light. Fundamentally, *light* is defined specifically as optical radiation capable of producing a visual sensation in humans [3]. *Circadian light* considers the non-visual response in optical irradiance that stimulates the human circadian system [4]. Therefore, the fundamental definition of light falls short when encompassing the "non-visual" circadian response of circadian lighting, pertaining to impacts on relative day-night timing and melanopic response which will be addressed later in the report. Ordinarily, light refers to the optical radiation with a *spectral power distribution* (SPD) within the "visible region" of the electromagnetic spectrum, lacking consideration for biological effects. The visible region ranges from approximately 380 nm to 730 nm [4]. Issues arise when using light to describe *the stimulus to* rather than *the response from* a biological system due to the circularity of the definition. For this definition to be accurate for circadian light as well, it must be dependent on a measured response from the circadian system as an effect of a stimulus from this defined "circadian light". This tricky circularity of the definition of light should be considered as formal definitions and investigations of circadian light ensue [4].

ii) Spectral Vision

Photoreceptors in the eye, like rods and cones, are not equally sensitive to all wavelengths of visible light. Because of this, the biological effectiveness of light sources of equivalent power can vary due to the spectral composition of the light. This concept is referred to as the *spectral sensitivity* of humans [4][5]. Data from experimentation in the early 1900's was combined to form $V(\lambda)$, the *photopic luminous efficiency* function, and formally define light experienced by humans [4]. Luminous efficiency functions can focus on different forms of vision due to inherent biological features of the eye.

Photopic vision refers to our daytime vision or vision under light conditions of a well-lit space and is typically the standard when defining lighting metrics for humans. The photopic spectral sensitivity function peaks at 555 nm, around the green-yellow color wavelength of the visual spectrum. This function was adopted in 1924 and was incorrectly assumed to be the only measure of spectral sensitivity for human vision. Conversely, *scotopic vision* occurs under low light conditions under darkness. Typically, at night this scotopic response is characterized by a loss of color discernment and sensitivity peaks at 498 nm near the blue-green color [1][6]. Beyond visual perception, however, lies the biological impact of light, addressed through the concept of *melanopic vision*. Similar in function to photopic and scotopic vision, melanopic vision has a peak sensitivity between 480 nm to 490 nm, a deep blue color, as a blue light stimulus related to the suppression of melatonin [1][7]. Graphs of these spectral sensitivity functions are visible below in **Figure 1** and **Figure 2.** Melatonin functions as the sleep hormone produced in the pineal gland and contributs to regulation of the circadian rhythms.

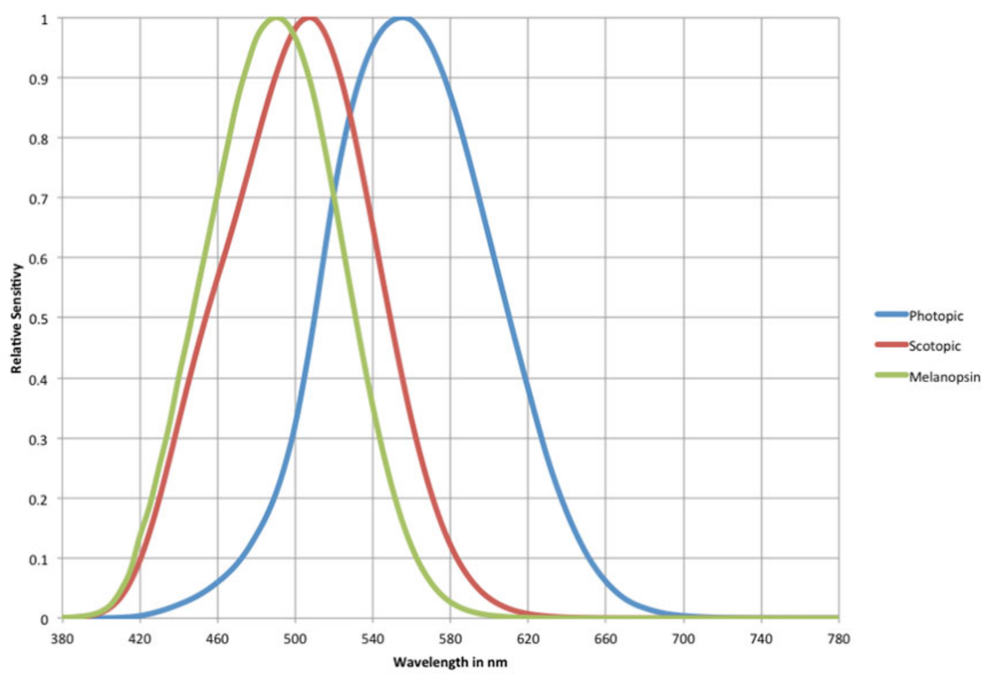


Figure 1. Spectral sensitivity curve for melanopsin, photopic, and scotopic response [7]

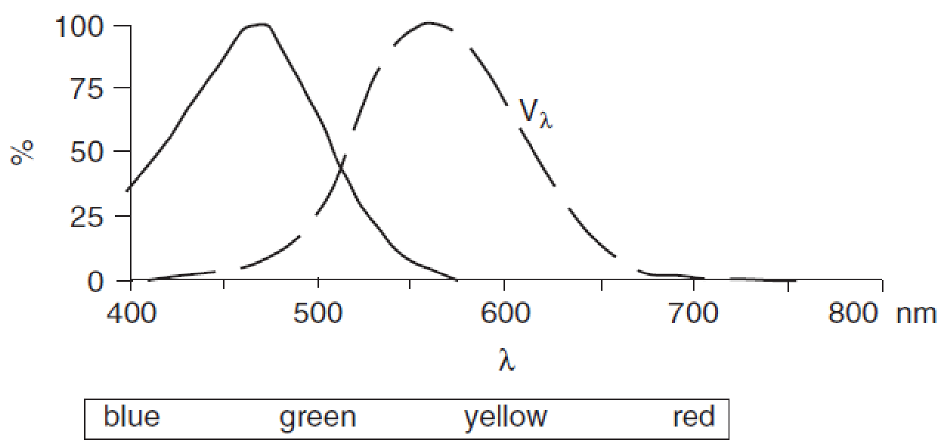


Figure 2. Spectral sensitivity curve of the eye, V(λ) for the photopic system (dotted line) and spectral biological action curve based on melatonin suppression (full drawn line) [8]

iii) Sensitivity Functions

Based on this understanding of varying spectral sensitivity curves, standard metrics for light measurement have been developed. V(λ) is the developed link between *radiometry*, the measurement of radiant energy, and *photometry*, the measurement of light [4]. Radiometry characterizes light wavelength and energy by quantifying radiant power over a defined bandwidth of electromagnetic energy [9]. Photometry considers the challenge of weighing the biological effectiveness of spectral power across wavelengths, specific to the biological system under consideration and its inherent

perceptive qualities [5]. Ultimately, V(λ) describes the relationship between perceived illuminance and wavelength for human cone-based (photopic) vision, normalized to 1 at the peak of 555 nm. Similarly, the scotopic spectral sensitivity function V'(λ) normalized to 1 at a peak of ~505 nm exists to describe scotopic vision in humans [5]. Integrating across wavelength for photopic vision can then quantify light as a one-dimensional parameter in a biological meaningful manner. This simple methodology allows for comparisons among various light sources and lighting scenarios in the field of lighting [5]. For example, see **Table 1** below for reference to derived units for light measurement. Radiant flux (radiant energy per unit time) can be weighted by V(λ) for the fundamental definitions of luminous intensity, illuminance, and luminance.

Table 1. Lighting Metrics Derived from Radiant Flux and V(λ) Weighting [4][5]

METRIC	SIG.	DESCRIPTION	UNIT(S)
Illuminance	(I)	The most popular metric used by circadian lighting researchers, *lux* is used to quantify the total power of light falling on a surface from all directions	Footcandle, lum/ft^2 Lux, lm/m^2
Luminous Intensity	(E)	The V(λ) weighted radiant flux within a solid angle, where a solid angle is a three-dimensional field of view from a reference point measured in steradians	Candela, cd
Luminance	(L)	The V(λ) weighted luminous intensity per unit area of a surface	cd/ft^2, cd/m^2

These metrics allow for the understanding and further measurement of various quantitative metrics pertaining to lighting. Following this concept, circadian light could then form a connection between radiometry and circadian photometry to suggest parallel definitions to those used for visible light [4]. This concept does come with problems, however, as will be discussed later in this report.

iv) Eye-Brain Physiology

Rods and cones had been believed to be the only photoreceptor cells in the eye for over 150 years of study. These photoreceptors are responsible for sending visual signals via nerve connection from the retina of the eye to the visual cortex of the brain. The varied sensitivity of this eye-brain system is described by the V(λ) luminous efficiency function for photopic vision [19]. However, a novel third type of photoreceptor cell in the retina of mammals has been identified as the intrinsic photosensitive retinal ganglion cell (ipRGC). This newfound photoreceptor is in part responsible for the regulation of many non-visual biological effects including melatonin production and alertness related to circadian timing [8].

While rods and cones exist in the millions in humans, ipRGCs are estimated to be 4,000 to 8,000 in number. IpRGCs can respond to light even without communication with the rods and cones due to the presence of melanopsin, an opsin photopigment that responds to ambient light for primarily non-image forming effects [7]. Photopigments are photoreceptor proteins that convert light into neural signals in the retina [6]. These ipRGCs form the main neural pathway from the retina to the suprachiasmatic nuclei (SCN), providing a direct connection between the eye and the brain for photosensitive neural response as visible in **Figure 7**. The SCN is the region in the brain where circadian rhythms are regulated as well as control of the master clock is held [6]. This path is visible in **Figure 8** below. Further nerve connections from the SCN to the pineal gland transfers regulation for certain hormones as well, such as cortisol and melatonin – both important for governing alertness and sleep.

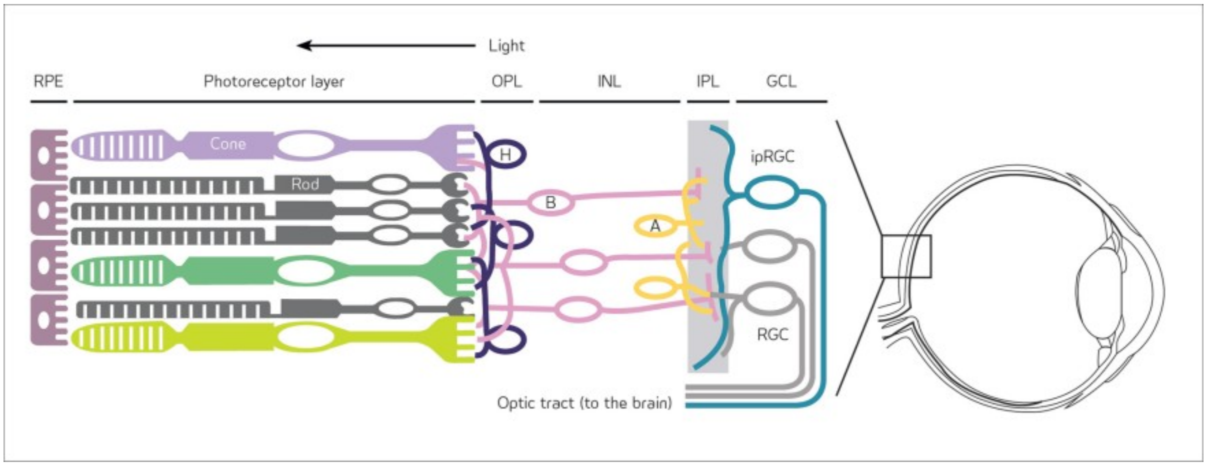


Figure 7. ipRGC orientation relative to photoreceptors in the human eye [6]

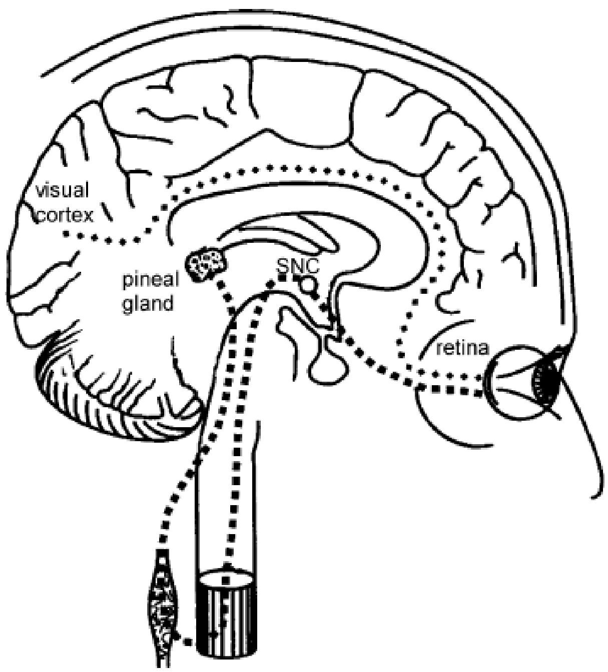


Figure 8. Physical and biological eye-brain connection related to the SCN [8]

b) Circadian Response and Human Physiology Interaction

i) Circadian Rhythm Adjustment

While humans have an intrinsically generated circadian rhythm, adjustment from the environment is still needed to continually correct the response for a 24-hour cycle. This correction has been developed by the temporal pattern of dark-light alteration on the retina as a product of the earth's rotation [4][11] over the span of human civilization development. Synchronization/entrainment to the 24-hour dark-light cycle allows for optimization of daily activities like sleeping and eating while also enabling disorders related to the desynchronization of internal and external time [10].

Studies have found an average intrinsic period length for humans to be close to 24.2 hours, although the period length tends to be highly individual and may have slight variance. These variances help to differentiate "morning-type" and "evening-type" humans depending on the exact length of the period, with "morning-type" periods slightly shorter than 24 hours and "evening-type" periods slightly longer than 24 hours [8]. Studies in completely blind people have even found longer intrinsic period lengths of up to 24.5 hours [10], again suggesting the need for the regulation of the circadian cycle with visual light as an inhibitor of melatonin secretion.

ii) Timing and Frequency for Response

Light and dark both act as a timing device within the SCN, the master clock in the brain, with negative effects on health outcomes from disruption of it [6]. The pineal gland secretion of melatonin corresponds with the dark-light cycle and defines biological night, terming melatonin the 'darkness hormone'. For example, rapid time zone shifts and rotating shift work can have negative effects on health due to this concept through the irregularity of the light and dark stimulus over a period of time [10]. Studies have determined that monochromatic short-wavelength "blue" light as well as blue-enriched polychromatic light have a stronger effect on melatonin suppression than longer wavelength light. This is an example of the non-image forming (NIF) responses of the ipRGC's, in addition to circadian clock adjustment, enhanced alertness and cognitive function, and pupil constriction [5][12].

Although, enough empirical evidence shows that while the spectral sensitivity of the SCN peaks around 460 nm, the action spectrum for melanopsin peaks around 480 nm. This discontinuity shows that the spectral sensitivity related to the SCN cannot be based on melanopsin alone. Here, the action spectrum refers to the rate of physiological activity plotted against the wavelength of light. There seems to be an important contribution from the photopigments within the rods and cones that shift the spectral sensitivity of the input to the SCN [6]. While axons stemming from the ipRGCs are the main conduit for light signals to reach the SCN, melanopic photoreceptors are not the only source of input in this system. The influence of the more distal rods and cones, while indirect, is important to completely understanding a successful model for human circadian transduction [13].

Additionally, the action spectrum for melanopsin does not account for the amount of light, rather only the spectral distribution. For melanopic lux to be an accurate and impactful metric portraying the effect on the human circadian system, the amount of light must be considered as it has an impact on circadian response. Any metric based on melanopsin alone would be inaccurate in that regard [6].

iii) Circadian Stimulus

Related to physical lighting characteristics, *circadian light* can be defined as "the irradiance at the cornea weighted by the sensitivity of the human circadian system as measured by acute melatonin suppression after a one-hour exposure" [6]. Relatedly, *circadian stimulus* refers to the "calculated effectiveness of the spectrally weighted irradiance at the cornea from threshold to saturation" [6]. A mathematical model proposed by Figueiro et al. [14] based on the neurophysiology of the retina, in addition to psychophysical studies of nocturnal melatonin suppression related to various spectral power distributions, has contributed to the definition of circadian light. This model provides values of circadian light for a light source based on SPD, accounting for reactions of ipRGCs in addition to rods and cones participating in phototransduction [4]. The spectral sensitivity of the circadian system is modeled below in **Figure 9** for narrowband and polychromatic light stimuli, with supporting data from Brainard and Thapan [15][16]. From this, a graph of circadian stimulus as a function of normalized circadian light can be generated relative to melatonin suppression to further understanding of apparent effects of typical lighting scenarios, as seen in **Figure 10** [4][6].

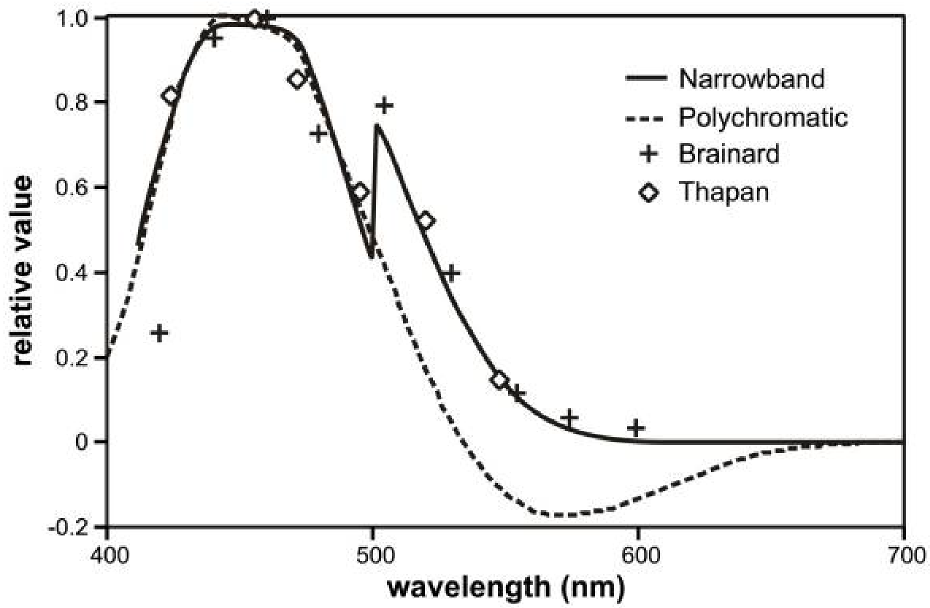


Figure 9. Nocturnal human melatonin suppression for narrowband spectra (symbols) and a spectral sensitivity function resulting from exposure to narrowband stimuli (solid curve) [4]

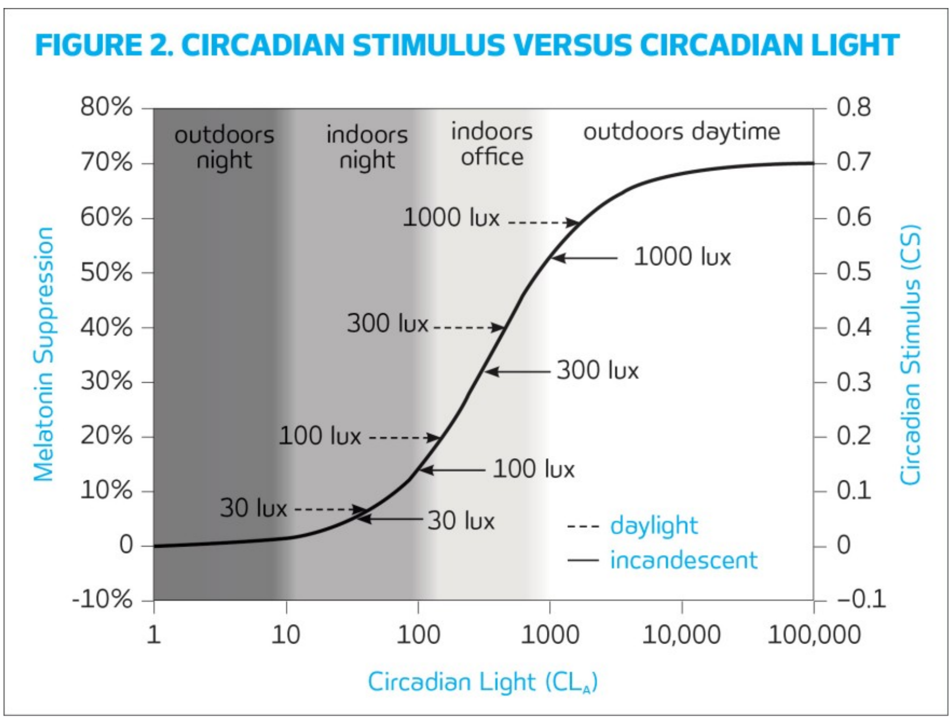


Figure 10. Measurements of nocturnal melatonin suppression including circadian stimulus levels at different photopic illuminance levels [6]

iv) Proposed Term Melanopic Lux and Criticisms

Continuing, the biophysical mechanisms responsible for phototransduction (how the retina converts light into neural signals [13]) among both the visual and circadian system are similar, yet just different enough, to warrant careful consideration as metrics and further definition of circadian light evolve. There are fundamental differences between measuring the response from the visual system opposed to the circadian system when describing optical radiation on the retina [4]. If a lighting metric were to be based on melanopsin alone, say melanopic lux, there would be a disconnect from the fundamental understanding of photopic lux, known as the flux density weighted by the photopic luminous efficiency function $V(\lambda)$. $V(\lambda)$, based on the response of foveal long wavelength and middle wavelength sensitive cones, peaks at 555 nm [6] and provides humans with high spatial resolution [4]. It would follow that a circadian luminous efficiency function ($C(\lambda)$, perhaps) would be based on the action spectrum of melanopsin and peak at 480 nm. However, this way of thinking could be problematic when defining metrics related to circadian lighting [6].

While it would be beneficial to use a spectral sensitivity function, like $V(\lambda)$, to predict the sensitivity of melanopsin to broad-spectrum white light, there may be a more complex relationship between spectral quality and photoreceptor response with circadian lighting [5]. It has been found that melanopsin is a bistable pigment containing an intrinsic light-dependent bleach recovery mechanism, suggesting a less direct relation between incident wavelengths and photoreceptor response. There is the possibility for wavelengths that individually lack the ability to activate melanopsin to still influence the response of melanopsin as a photoreceptor as an effect of this bistability [5]. The contribution from rods and cones, additionally, cause a broadening shift of the spectral sensitivity of the SCN, which peaks around 460 nm compared to the action spectrum for melanopsin peaking around 480 nm [6].

Additionally, definition of a circadian luminous efficiency function would be fundamentally incomparable to the current photopic luminous efficiency function. While ipRGCs have been shown to provide direct input to the SCN, due to support for color vision there are multiple photoreceptors that contribute to human circadian phototransduction from color opponent processes among the ipRGCs [4]. Formed from spectral opponent mechanisms in the retina, this subadditive response to polychromatic light by the circadian system varies fundamentally from the additive response to optical radiation for photopic vision [17]. Brightness is an important characteristic in measuring the response of the SCN in relation to melatonin suppression, although the action spectrum of melanopsin is incapable of describing responses to brightness. The apparent brightness of a scene cannot be predicted by an achromatic channel response such as the action spectrum of melanopsin. In photopic vision, the two spectral-opponent channels of blue-yellow versus red-green stimulus are required to accurately create conscious perceptions of luminosity from neural channel responses, as they provide opposing color information to the brain [6]. This lack of continuity across luminous efficiency functions would prevent a direct comparison of metrics, rendering a proposed metrology of circadian luminous efficiency useless in this regard [4]. Because of this, researchers lack a constancy for comparison among findings or when replicating experimental conditions, while creating a barrier between research and already established lighting industry regulations [9]. **Table 2** below outlines current metrics and their relative differentiations below, based on non-visual spectral effectiveness of light.

Table 2. Overview of categorization of existing proposed quantities for evaluating non-visual spectral effectiveness of light [12]

	RADIOMETRIC	PHOTOMETRIC
CIE System	*Not possible*	Circadian illuminance Melanopic illuminance
Relative Quantities	Circadian Efficiency	Relative ratio of circadian to photopic lumens
Spectrally Weighted	Circadian effective irradiance Circadian light α-opic irradiance	α-opic equivalent illuminance
Biologically Scaled	*None existing*	Circadian equivalent illuminance

4. **Current Lighting Technology**

a) **Design**

i) **Introduction to Characteristics**

Design characteristics play a key role in framing the discussion for the controlled operation of both natural and artificial light and are important for understanding the design strategies of current lighting systems. When evaluating output characteristics of a light source, intensity and color temperature are often the primary factors influencing how a source appears to the observer. In addition to the already defined metrics pertaining to intensity, metrics such as Correlated Color Temperature (CCT) and Color Rendering Index (CRI) are imperative to understand within the context of circadian lighting. CCT in lighting describes the hue of a light source compared to the idealized blackbody radiator, represented by a curve on the CIE Color Space chart published in 1931. This Color Space chart shows perceived colors as a ratio of red, green, and blue and lets us measure CCT based on corresponding Kelvin (K) temperatures [18] and can be seen below in **Figure 11**.

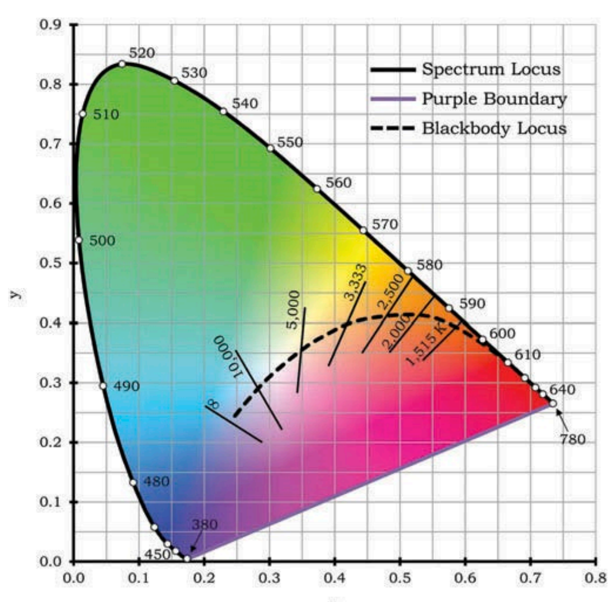


Figure 11. The CIE 1931 chromaticity diagram illustrating the location of the spectrum locus in addition to many lines of constant CCT [19]

ii) Color Variables of Interest

The blackbody locus is represented as an ideal curve on the CIE Color Space, with deviations from the curve corresponding to Color Rendering Index (CRI) values less than the maximum value of 100. This curve shows chromaticity coordinates for blackbody radiators of varying temperatures. While CCT relates a source to the nearest blackbody locus for a given temperature, CRI exemplifies the variation between the source and the reference locus through chromaticity coordinates – a result of the luminous efficiency function V(λ) and tristimulus values for perceived light [19]. The overall spectrum locus of the CIE Color Space describes the bounds of all possible chromaticity coordinates for light visible to humans. On this chart, the *x* and *y* chromaticity coordinates give a precise value for the chromaticity of a lamp, although CCT is often used due to common practice. Color Rendering therefore compares the color appearance of objects in a scene to the human conscious or subconscious comparison to a reference light source [19]. These distinctions are important to understanding the current technology of tunable white LED sources and their controls.

iii) Melanopic Sensitivity

It is valuable to revisit spectral distribution as it relates to the Melanopic-Photopic ratio (M/P). Unique to humans, ipRGCs have a greater concentration from two degrees to four degrees of eccentricity in the retina while being absent in the fovea, the location of photopic response. Yet, the photopigment melanopsin is still active at photopic and scotopic light levels, further suggesting the importance of input from non-melanopic photoreceptors on circadian response as triggered by melanopsin. Figure # in Section 3 again references the spectral sensitivity curves for photopic, scotopic and melanopic sensitivity functions, normalized to unity [7]. Historically, calibration of light meters has been based on our understanding of photopic and scotopic spectral sensitivity functions. For V(λ), the peak wavelength at 555nm is normalized to a lumen value of 683 lumens per watt of physical light power at this 555nm value. This normalization has been determined from lab testing by several psychophysical methods. Similarly, the influence of scotopic rod receptors on lower-level natural visual scenes has been found to allow for a shift of this normalization to a value of 1700 lumens per watt of physical light power at 507nm, the peak value for the scotopic sensitivity function [7].

With that, a proper melanopic normalization to the human spectral sensitivity function has been achieved through a similar shift to 490nm. From this, *melanopic effective watts* can be defined in conjunction with photopic lumens, with V(λ) substituted with the melanopic sensitivity function normalized to peak unity at 490nm. This intuitive approach has been worked out to fit the data for human perception [7]. This simple procedure has an easily interpreted intrinsic meaning that is a direct measure of relative biological efficiency. This allows for direct measures of relative values enabling congruent comparisons due to a comparable maximum efficiency. The International Commission on Illumination (CIE) has recommended the use of *effective watts* for measurement of nonvisual ocular radiation [7]. **Equation 1** below defines M(S), or *melanopic effective watts,* where S(λ) is the SPD of the source and M(λ) is the melanopic sensitivity function.

$$M(S) = \int S(\lambda)M(\lambda)d\lambda \qquad \textbf{(1)}$$

The melanopic spectral factor associated with any SPD can be represented by the ratio M/P. The numerator M can be calculated from **Equation 1** above, where P is the net lumens for the same SPD. P can be calculated in the same manner as M by replacing M(λ) with V(λ) normalized to 683 at 555nm [7]. **Table 3** below shows representative values for M/P for a few well-known sources based on known SPDs and the M(λ) values obtained from Lucas et al (2014) [9] and CIE S 026:2018 [20].

This ratio is defined with units of effective milliwatts per photopic lumen and is numerically identical to values for *melanopic efficacy of luminous radiation* defined in CIE S 026:2018 [7].

Table 3. Representative Source M/P (Effective Milliwatts per Lumen) Values based on Lucas et al (2014) Values for M(λ) [7]

SOURCE	CCT (K)	M/P
High Pressure Sodium	1960	0.24
Incandescent Lamp, 100 W	2810	0.64
LED	3855	0.82
Metal Halide	4000	0.73
Sunlight	4889	1.12
Equal Energy White	5460	1.20
CIE Illuminant D65	6500	1.33

iv) LED Technology

In the modern day, LED technology has increased the ability for humans to create more diverse and dynamic lighting environments. Not only does color appearance have a major impact on how people perceive spaces, it also is proven to have an impact on the circadian system and our overall productivity and wellbeing. Specifically, tunable white and full color-tunable LED products allow users to fine-tune the color spectrum, hue, and tint through various possible manual or automatic control strategies [18]. Since CCT is closely related to the blue light component of the source, CCT can lead to varied effects on circadian rhythms as a result. Appropriate resulting CCTs for different activity types and time of day can be modulated through controls to simulate natural conditions. This control approach is referred to as *biodynamic lighting* [20]. See **Figure 12** below for the results of testing done by Bálský, Bayer, Zálešák, and Panská [20], showing the spectral progresses of relative radiant flux for different CCT settings on an LED fixture. This concept has helped influence development of tunable white LED lighting fixtures with variable color temperature settings for human use [20].

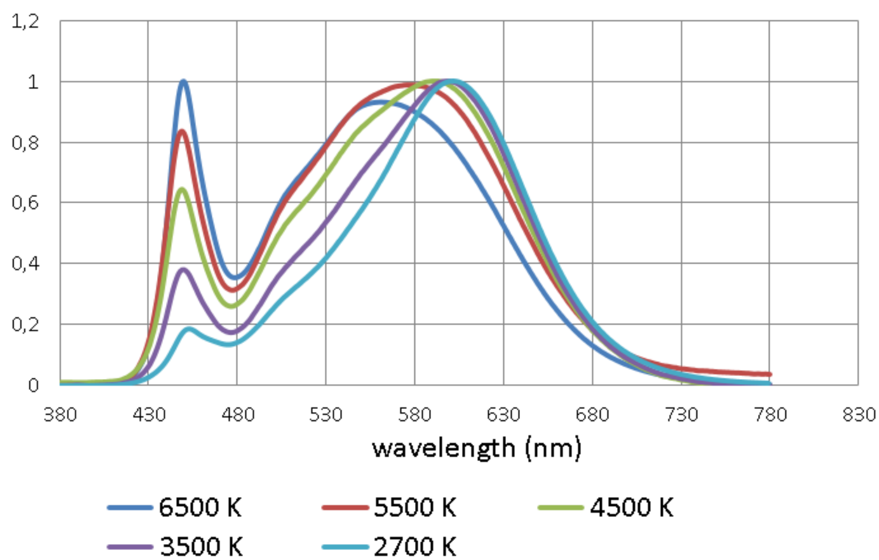


Figure 12. Progression of spectral relative radiant flux for different settings of a CCT tunable white luminaire [20]

v) LED Chromaticity Deviation

With the CIE Color Space blackbody locus, significant deviation from this ideal curve can cause potentially unwanted tint in the overall perception of the light spectrum. This matters as one of the common approaches for color tuning within LED fixtures involves a linear gamut for proportional mixing between a “warm” and “cool” color temperature LEDs to achieve a desired CCT [18]. That is to say, the upper and lower bounds of these “warm” and “cool” color temperatures may be on the blackbody locus, although once linear dimming is applied between the two different diodes the chromaticity values likely shift from the locus, reducing CRI and adding an overall tint to the targeted CCT. This method can be wasteful in cost, as on average only half of the LEDs in the system can be biased due to the linear control relationship, meaning double the LEDs needed for a desired light output compared to non-tuning [22]. For small tuning ranges this CRI deviation may be acceptable but is worth noting for larger scales of tunable white operation. Triangular or multi-angular gamut approaches through additional LEDs in the source can reduce this tinting effect, keeping the source chromaticity closer to that of the blackbody locus [18]. In fact, when looking specifically at LEDs for healthy and smart lighting pertaining to humans, full color RGBW (red green blue white) LED chip systems show great potential for providing great CCT and CRI relevance in architectural lighting [23]. However, there exists a need for a more optimized construction technique for producing LED fixtures that provide varied levels of circadian stimulation and desirable CCT without sacrificing CRI from a linear modulation along the color gamut [24].

b) Operation

i) Introduction

During the industrial revolution, working people made the shift from an outdoor daytime environment to an indoor daytime environment. With this transition comes a decrease in task lighting by 40-200 times less compared to outdoor daylighting, unless nearby a window [8]. This has led to negative impacts on health and well-being of workers in these indoor environments. In the work environment, stimulus for both action and relaxation are necessary for productivity among employees [8]. With advances in technology, specifically color-tunable LED fixtures and accompanying control systems, employers can leverage the impact of layout, intensity, and color temperature of these novel lighting systems. In addition, there exists a greater understanding of the melanopic spectral sensitivity in humans from daylighting concepts and the difference between natural and artificial light in a space. These operational characteristics all work to provide improved circadian response from employees in a work environment.

ii) Design Objectives

It has been realized that stimulation of a circadian light cycle similar to the natural occurrence of sunlight action over the day shows positive benefits to the users of the space. That is, bright illumination with a high “blue” spectral component in the mornings and midday coupled with lower, reduced “blue” content in the evenings mimics the natural patterns of daylight and brings positive benefits while avoiding deleterious effects [24]. While the architect enables the possibility for daylight penetration through building orientation and shape, the lighting designer determines the link between the natural and artificial light that exists in a space [8]. When doing so, the quality of the artificial lighting has great relevance to circadian response. Operational characteristics of lighting design in this regard may include overall fixture layout and spatial awareness, controls for intensity and color temperature, as well as the impact of daylight in the space.

iii) Natural vs. Artificial Light

When considering daylighting, there is a general awareness that the sun is above in the sky during the day and much more intense than typical artificial task lighting indoors [25]. As circadian lighting design develops, these qualities of natural lighting are making their way into artificial designs in order to better provide humans with the visual stimulus desired for productivity and overall wellbeing. With that, it is important to note that the non-visual effect of light, including both glare and circadian response to light, is dependent more so on the light entering the eye than the illuminance on the work plane [8]. Beyond the disproportionality between intensity of daylight and artificial light, the relative sun position can be predicted throughout the day as an operational characteristic related to the layout of fixtures. This effect can be seen when observing the spatial distribution of artificial lighting while considering intensity and color temperature [26]. The point here is to create biologically brighter days and darker nights through spatial distribution of light as it relates to the symbolic horizon line within a space. This can be achieved through high levels of photopic and vertical lux with a rich melanopic spectrum during the day (ideally from overhead light sources), while allowing for low vertical lux and melanopic depleted spectrum at night (ideally from lower, horizontally focused sources) [26]. Recent research indicates that light incident on the upper retina is less biologically important than light on the lower retina. That is to say that light reaching the lower retina from above has a greater effect on the biological response compared to light reaching the upper retina from below [27]. This notion aligns with the orientation of the sources of light that existed before artificial light was discovered, such as natural daylight during the day and campfire during the night.

iv) Operational Characteristics

The core elements for successful architectural lighting development include controlled manipulation of light quantity, spectrum, distribution, timing, and exposure duration [10][25]. Lighting sources and standards have evolved over a century of research of human vision and the needs of our circadian functions exclusively. Pertaining to quantity of light, it is obvious that daylight is most often more intense than electric lighting for buildings. Windows are helpful in this regard, although they present issues with glare and thermal gains or losses, depending on location and sky conditions. Additionally, exposure duration of sources with increased melanopic response has an impact on the circadian stimulus of humans. Circadian disruption is possible if lighting patterns are misaligned with the human response characteristics [25]. **Table 4** and **Table 5** below outline the photopic and 'circadian' luminous efficacies relative to luminous efficiency functions, as well as a framework for the characteristics of lighting and their circadian functions, respectively.

Table 4. Photopic and circadian luminous efficacies according to the empirical function [25]

Light source	Photopic luminous efficacy (lm/W)	'Circadian' luminous efficacy (lm/W)	Relative ratio of 'circadian' to photopic lumens
3000 K rare earth fluorescent	87 (1.00)	149 (1.00)	1.00
4100 K rare earth fluorescent	87 (1.00)	275 (1.85)	1.85
7500 K rare earth fluorescent	65 (0.75)	285 (1.91)	2.56
Sodium-scandium metal halide	108 (1.24)	300 (2.02)	1.63
High-pressure sodium	127 (1.46)	115 (0.77)	0.53
Incandescent	15 (0.17)	32 (0.21)	1.25
Red LED (630 nm)	44 (0.51)	2 (0.02)	0.03
Yellow LED (590 nm)	36 (0.41)	10 (0.07)	0.17
Green LED (520 nm)	25 (0.29)	88 (0.59)	2.06
Blue LED (460 nm)	11 (0.13)	681 (4.58)	36.2
White LED (460 nm + phosphor)	18 (0.21)	90 (0.60)	2.91
Daylight (6500 K)	—	—	2.78

Also shown are relative ratios of 'circadian' lumens for equal photopic lumens, normalized to 3000 K fluorescent. In other words, 500 photopic lux of HPS illumination will produce only about half (0.53) the 'circadian' lux as 500 photopic lux of 3000 K fluorescent.

Table 5. Framework for considering the characteristics of lighting for application and research supporting circadian functioning [25]

Lighting characteristics	Application Vision	Circadian—day shift work	Circadian—night shift work
Quantity	Low (300–500 lux on task: ~100 lux at eye)[24]	High (~1000 lux at eye)[29,30]	High (~1000 lux at eye)[29,30]
Spectrum	Photopic (peak sensitivity 555 nm)[36,37]	Short-wavelength (peak sensitivity 420–480 nm)[21–23]	Short-wavelength (peak sensitivity 420–480 nm)[21–23]
Spatial distribution	Distribution important (task luminance, contrast and size determine visibility)[31,32]	Independent of distribution (illuminance at eye)[25]	Independent of distribution (illuminance at eye)[25]
Timing	Any time[24]	Subjective morning[28]	Periodically throughout shift[8,40]
Duration	Very short (less than 1 s)[43]	Long (1–2 h)[28,33]	Short (15 min) pulses[40]

For areas that are shaded, evidence is less certain, and the results of future research will be needed to refine and corroborate these preliminary guidelines.

Many studies indicate lighting levels of at least 1000 lux on the eye are required for biological stimulation. Where daylighting alone cannot achieve this, artificial lighting is able to supplement these requirements. In addition, higher blue sensitivity of the ipRGCs can allow for lower equivalent

lux levels with higher CCT light [8]. This concept relates to the color tuning opportunities present in circadian lighting systems and the advantages that exist for circadian stimulation of humans. See **Figure 13** below for a suggested lighting scenario for color tuning control.

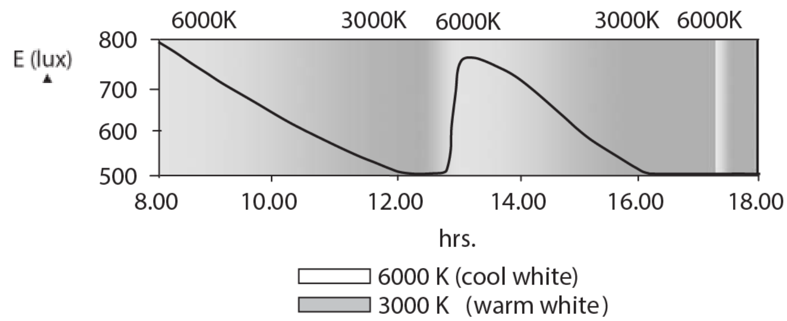


Figure 13. Suggested illuminance and CCT manipulation for optimal circadian influence throughout the workday [8]

Looking into controls for color tuning, there are two different system structures present: (i) dual channel and (ii) multichannel systems. The first option involves mixing cool CCT LEDs with warm CCT LEDs, proportionally, to combine them into the desired CCT. This method uses two channels for a linear distribution of input. Alternatively, multichannel systems utilize three or more CCT LEDs for higher color rendering accuracy [22]. Color tuning control is desirable in circadian lighting systems to elicit a sense of day/night rhythm within the space, especially when daylight is insufficient. For example, high circadian-action lighting in the morning can aid awakening and increase alertness and work efficiency while low circadian-action lighting could help improve sleep quality through melatonin secretion [28]. Overall, dimming two channels can be accomplished through varied power or current sent to each of the two LED channels. Multichannel solutions are more complex, usually involving digital feedback control and independent channel control to combine channels additively and produce an output stable in time and temperature [22]. Either way, color stability and light quality should be balanced characteristics of the control of circadian lighting systems. To obtain more advanced color quality and visual performance, four package white LEDs utilizing a RGBA configuration (red, green, blue, amber chips) have shown great potential. This configuration responds strongly when comparing CCT, CRI and vertical illuminance possibilities as shown beneficial to circadian impact [23].

5. Implementation

a) Overall Successful Utilization

Looking at the current state of circadian lighting systems, it is important to understand how technology and the concepts of design and operation are utilized through design standards and control strategies. The current implementation of these concepts allows for flexibility in design while still providing a strong framework for design recommendations. From an academic perspective, it has been argued that there exists enough knowledge on circadian lighting to be able to translate this knowledge to practice through code standards and recommended practices. However, further investigation will prove beneficial to calculation methods and measurement of metrics [29].

i) Optimized Control Patterns for Work Environment

Circadian lighting systems are being implemented in many workspaces such as offices and educational facilities due to the potential impact that circadian lighting can have on mood,

productivity, and the overall health of the occupants. Light inside interior environments is quite often adequate for visual purposes, but without strong control over circadian responses in humans [30]. In addition, these benefits may not be seen without proper strategies for operation, specifically the control pattern for intensity and color temperature variation.

Again, it is important to specify that the right combination of light intensity and color temperature at the right moments with the right duration can stimulate the natural cycle of melatonin secretion in humans [27]. However, understanding what is the "right combination" at what "right moment" and for what "right duration" is the next step in implementation of these circadian lighting systems. The intent is to provide the same natural effects as was once delivered through daylight during times of outdoor work in human history. Better workplace performance as a factor of the lighting can only be attained through optimization of visual performance in addition to health and well-being optimization [27]. See **Figure 14** below for a breakdown of the interaction between lighting and the human response.

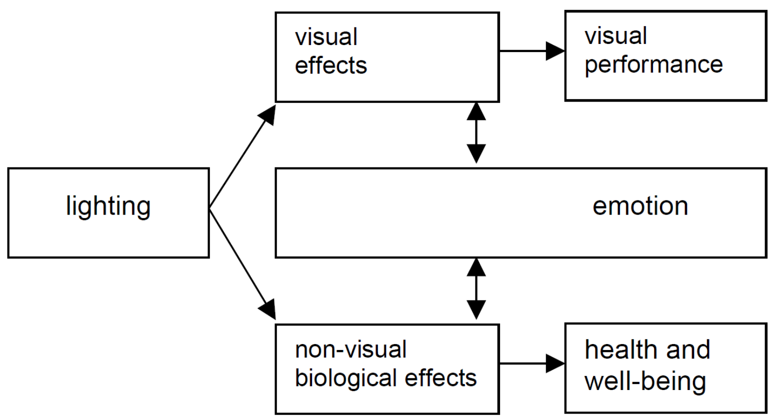


Figure 14. Interrelations between lighting and the possible human effects [27]

In the work environment, relaxation and stimulation are both necessary to supply workers with adequate environments for productivity. A possible lighting scenario in sync with the human rhythm derived from the congruent effects of daylighting as observed pre-industrial revolution and displayed below in **Figure 15** [27], which is very similar to the proposed **Figure 13** [8] earlier in this report. Following, **Figure 16** displays typical effects produced by outdoor daylight in parallel with indoor artificial lighting as described to create similar effects [27].

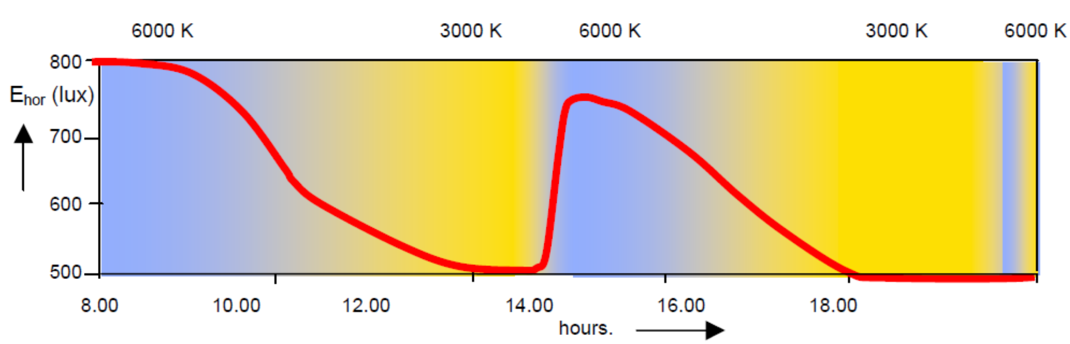


Figure 15. Lighting scenario for dynamic intensity level (red line) and color temperature (gradient shift) according to "human rhythm" [27]

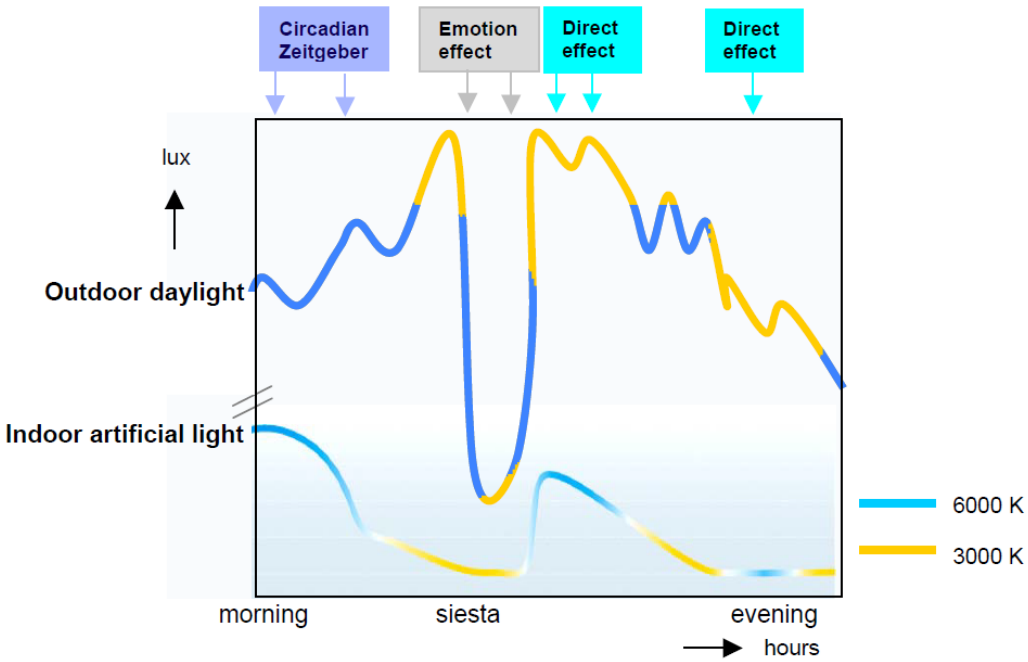


Figure 16. Example of how outdoor daylight can create different effects through the day compared with suggested "human rhythm" dynamic lighting [27]

ii) Daylighting Influence on Control Parameters

Daylighting is naturally dynamic in color temperature and intensity. Artificial lighting can be manipulated in such a way that resembles and provides the benefits associated with such variation. Where daylighting is not fully able to penetrate a space, artificial lighting plays a key role in filling the gaps while still entertaining the circadian response [27]. As seen above in Figure #, random variation in daylight color temperature is depicted on the upper curve along with dynamic intensity. The lower curve projects a suggested artificial lighting scenario corresponding to the action effects listed in the upper portion of the figure [27].

Starting with stimulating, cool-white light around 6000 K at a relatively high level helps to maintain and set our circadian rhythm cycle for the day, especially in the winter months where many people arrive to work before sunrise. Following, the light level can drop to conserve energy in accordance with available daylighting opportunities during the day. A shift to warmer color temperature around 3000 K provides and emotionally relaxing atmosphere, which is important due the benefits associated with a mid-day rest period [17][31]. From here, a spike to cooler color temperatures enables reactivation of the body for work after lunch, while the afternoon again recedes to a lower color temperature and intensity for a sort of emotional and architectural energy saving. Finally, a spike in color temperature only is given without the need for increasing intensity, as a boost for the trip home from work [27]. This sequence is illustrated above in Figure #.

Similarly, Arup engineers are utilizing circadian lighting through color tuning and intensity modulation, both in hospital work and their own offices. While dynamic patterns of daylighting will very from locations across the US, the color temperature recommendation in relation to human circadian rhythm can be seen below in **Figure 17**. This pattern strays from the ideas presented by

Brommet [23] above and are still being implemented and monitored as a case study among their employees [2].

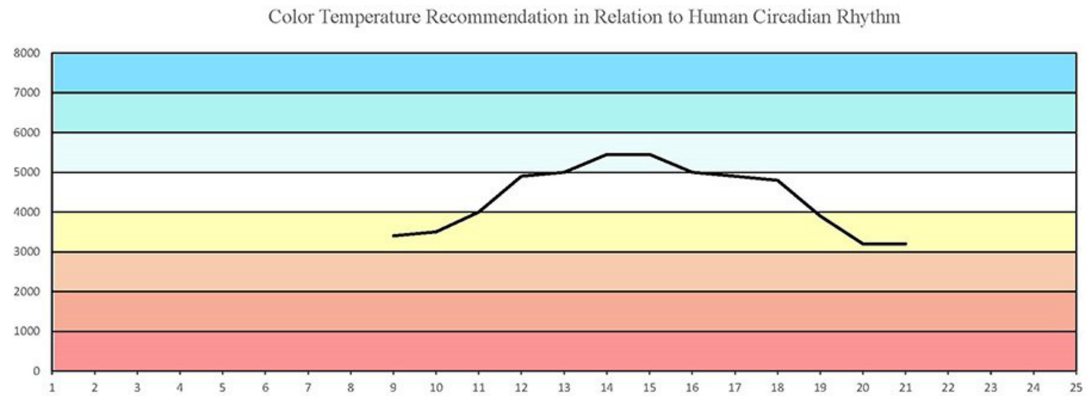


Figure 17. Color temperature recommendations in degrees kelvin across the y axis and hours of the day on the x axis [2]

iii) CIE, WELL Building Standards for Circadian Lighting

Continuing, both the International Commission on Illumination (CIE) and the Well Building Standard (WELL), among other entities, have adapted to the novel discovery of the impact of circadian lighting in the built environment. As of 01 Nov, 2018, 13 amendments have been made to WELL Feature 54 showing the importance of this topic and its development as research continues [32]. As lighting engineers and practitioners are increasingly asked to quantify melanopic illuminance for compliance analysis with WELL Building Standard, Equivalent Melanopic Lux (EML) is one metric used to depict the spectral qualities of daylight and electric light as it relates to melanopic response, taking into account the impact of variables like climate, color temperature, space colors and orientations. Installations are even spot checked in the field during operation with spectrometer measurements, meaning the SPD for glazing, materials, daylight, and electric light all need to be taken into consideration [31]. Design requirements are outlined based on the EML incident on the vertical plane at the eye level of the occupant [29]. Specifically focusing on work areas, requirements are as follows:

1. 200 EML (including present daylight) at four feet above the floor between 9:00 am and 1:00 pm every day of the year for 75 percent or more of workstations
2. Maintained illuminance of 150 EML on the vertical plane for all workstations

Within WELL, similar requirements exist for space types other than work areas and can be referenced in the WELL Feature 54 [32]. While many common lighting design programs like AGi32 and DIAL Evo do not directly predict EML, the WELL outlines a means for converting calculated photopic vertical illuminance values to EML [29]. Understanding the applicability and validity of this conversion factor, among other fundamental understandings of circadian response to lighting in humans is the future of circadian lighting from the engineer’s perspective. It is interesting to note that it has been shown that higher CCT sources (4000K to 6500K) exhibit a significant jump in EML when calculating. This can be valuable when designing artificial lighting systems in an absence of daylighting [31].

Conversely, pertaining to the M/P ratios introduced earlier, there exist fundamental concerns with the CIE S 026:2018 System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light as a method valid in comparison to standard analysis of illuminance. This International Standard defines the spectral sensitivity functions, quantities, and metrics appropriate for describing optical radiation stimulus contributing to the ipRGCs [20]. By merging traditional approaches for illuminance calculation with modern calculations based on the relative relationship between the spectral sensitivity of the non-visual system and the photopic visual system, a misalignment between comparable metrics and their fundamental understandings is present.

While this standard provides useful information about the evaluation and reporting of non-visual spectral sensitivity to light, care must be taken when comparing across differing approaches for analysis [12]. Within this CIE S 026:2018, equivalent illuminance values for reference sources are described as quantities expressed in lux, although not in the standard sense of the current understanding of lux as a unit. This "equivalent lux" is more so a ratio of the melanopic effective radiation at a given wavelength divided by the melanopic D65 efficacy ratio. While the melanopic equivalent lux can be calculated based on this understanding, it does not directly align with the interpretation of a photopic illuminance value in lux [7]. While these derived M/P values can make sense within context, again, a unified framework for comparison between evolving metrics is key in establishing the measurability and validity of circadian lighting moving forward in research and practice [12].

b) Case Study – UNMC Application

In the final stage of this investigation of circadian lighting design in the built environment, a case study was conducted at the 4230 Building at UNMC campus. This open plan office space hosts multiple workstations for University staff and features the installation of a novel circadian lighting system as well as daylight penetration. This new system, compared to conventional lighting systems, has the added capacity of changing both intensity and color temperature of the light emitting from the fixtures and is termed a *circadian lighting system*.

While these systems can provide great benefit to the occupants of the space through discovered influences on human satisfaction, alertness, health, and productivity through circadian rhythm stimulation, all of this is only possible with salient understanding of the control strategy and its accessibility. An understanding of the link between the biological effects of modern lighting and the physical characteristics of these systems is pertinent for system optimization and therefore maximum benefit to the building occupants. This UNMC case study aims to provide application of the concepts addressed previously in this report for system characteristics and control strategies.

i) Background

(1) Space Type

To begin, the space under consideration is the 4230 Building at UNMC campus in Omaha, NE. This space features an open plan office environment with arranged workstations and external windows to the N, E, and W directions. Primary work here is done on computer monitors or on horizontal work planes with artificial lighting overhead. Typical operational hours for the space are 7:00 am to 6:00 pm on weekdays. Windows feature twist-open shades for glare mitigation.

(2) Fixtures and Control System

Artificial lighting is supplied from an array of suspended LED linear fixtures with variable light intensity and CCT from 2700K to 6500K. Specification sheets for this fixture can be found in **Appendix A** with the model number 2 -J2-WL-30L82765-1D-UNV-W2A-W-AC48-T1-44'. Dual

linear slider switches are accessible for independent control of dimming and color temperature shift. Standard operation for this system was set to adjustable dimming based on occupant control, with a fixed CCT of 4000K. This strategy allows for familiar lighting conditions for a typical office space while still allowing occupant input for comfortable light levels.

(3) Motivation for Use

The opportunity for a case study in the UNMC office space was determined to be a great basis for this report as it allows for extensive literature review as a base for supplemental investigation of the space. Current system operations can be measured through data collection and then suggested modifications to the control strategy can be implemented based on the literature review. Occupants of the space can then be surveyed in addition to further measurements of corresponding light levels in the space to determine the effectiveness of the changes. This process can be repeated until system optimization occurs for the space, benefitting both the occupants and the researchers in understanding the impact of circadian lighting in the workplace.

ii) Data Collection

Taking place over the course of three weeks in November, initial data collection produced a baseline for the controlled state of operation as it exists in the space. The objectives of this data collection are to gain an understanding of the current light levels at various working planes throughout the space, in addition to the impact of daylight penetration into the space. From here, changes could be applied, and occupants' reactions observed, ultimately to determine effectiveness of the modified control strategy in terms of circadian response through subjective measures.

(1) Illuminance and Spectral Intensity Measurement

To begin, a plan view of the office space has been created and can be seen below in **Figure 18.** This view shows the data points for spectral intensity measurements across wavelength as well as measurements of illuminance. Additional illuminance measurements were taken throughout the space but are not pertinent at this point in discussion.

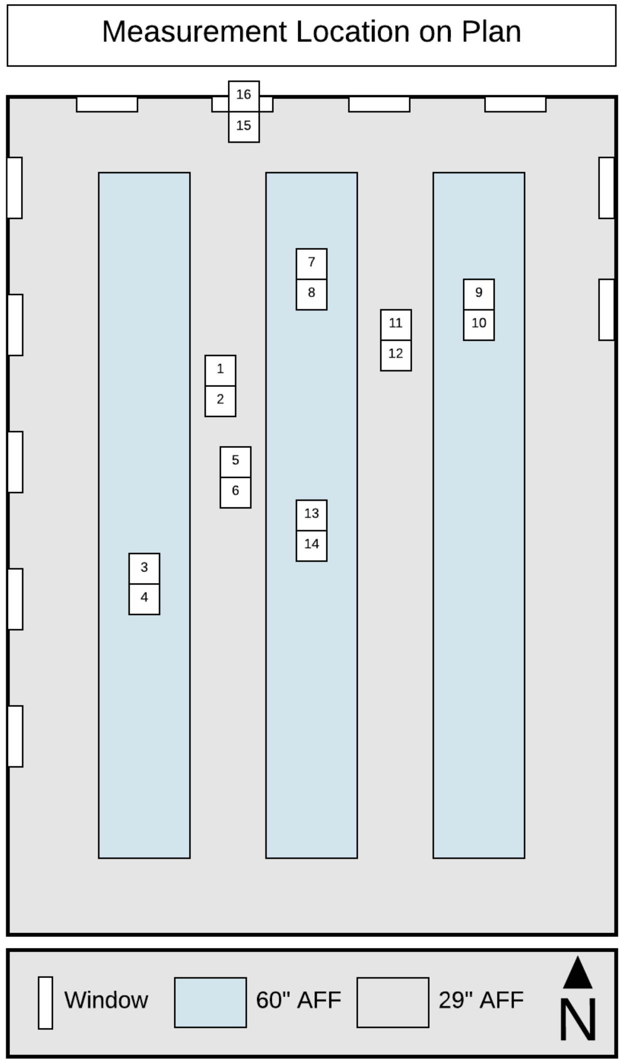


Figure 18. Plan view of Illuminance and Spectral Intensity measurement locations

For these measurements, HOBO Meters were used to obtain illuminance measurements (lum/ft^2, cd) over a span of two weeks, while a Gigahertz-Optik Spectral Illuminance Meters provide a graph of intensity across wavelength (W/m^2/nm), which can be used to calculate illuminance values (lx). It is valuable to gain an understanding of the daylight penetration into the office space. In doing so, the position of the meters formed a pseudo-grid allowing an analysis of the perimeter meters and the inner meters, based on the influence of daylight which can be seen from analysis of the raw data. For example, looking at the spectral intensity graphs, the difference between a daylight-prominent window scene (Point 15) and an artificial lighting-prominent interior scene (Point 14) is rather evident in the amplitude and overall distribution of the spectral intensity function. These plots can be seen below in **Figure 19** and **Figure 20** for a typical weekday with standard office occupancy. The measurements were taken at approximately 11:00 am with partly sunny weather conditions.

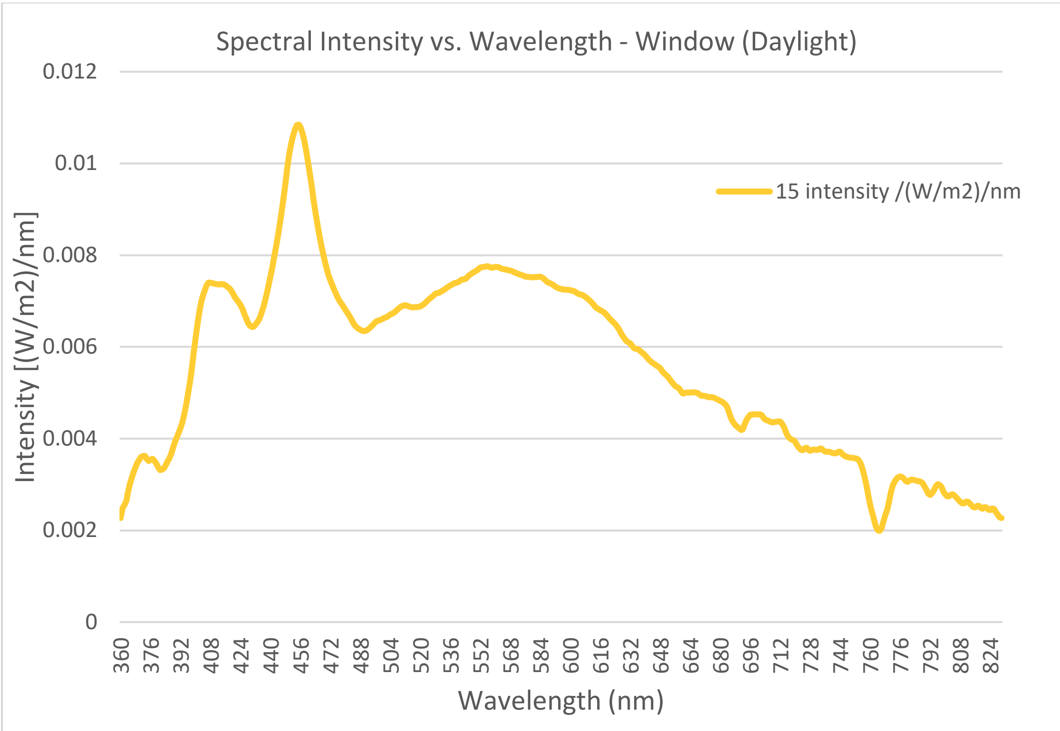


Figure 19. Spectral Intensity distribution for window scene (Point 15)

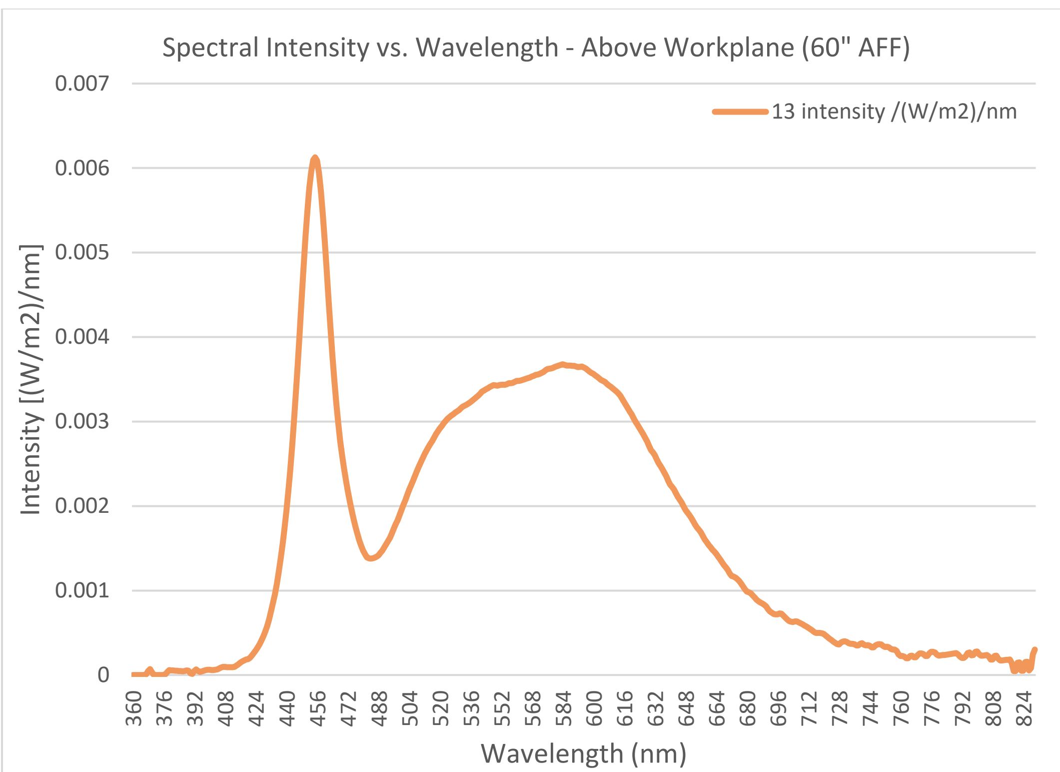


Figure 20. Spectral Intensity distribution at interior work shelf (Point 13)

Additionally, non-spectral illuminance meters were implemented to help understand daylight penetration into the space, rather than the spectral contribution of daylight. Overall, the goal of this preliminary data collection is to understand not only outside conditions of daylight influence, but also the impact of daylighting on the already prevalent electric lighting. As can be seen below in **Figure 21** and **Figure 22**, the difference between direct, north-facing daylight contribution from Point 16 and the lack of daylight penetration at Point 2 on the plan view in **Figure 18** above. These plots span the duration of a full day during the work week, using the standard 24-hour time scale.

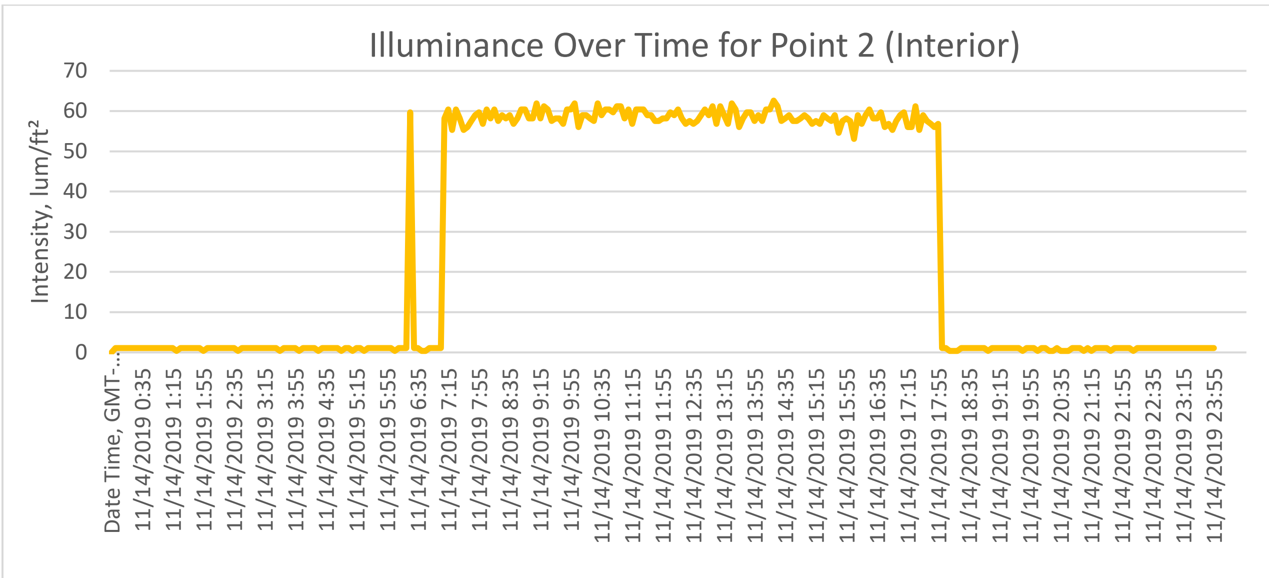


Figure 21. Illuminance (cd) for a typical workday for Point 2

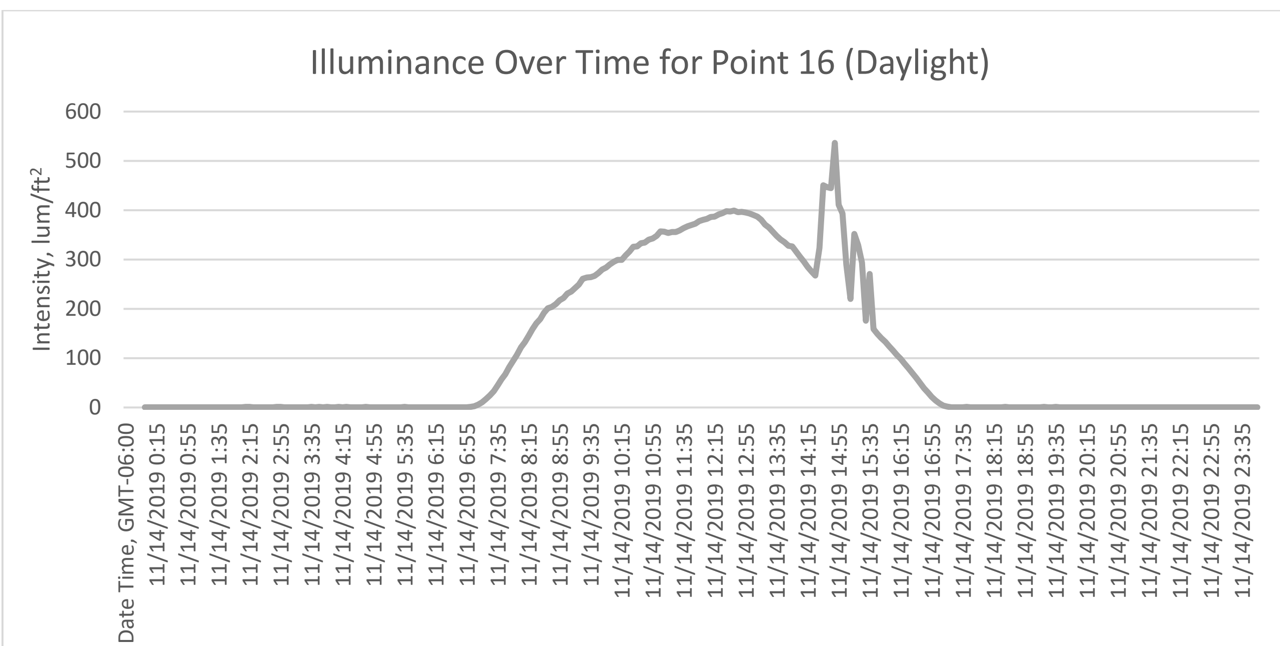


Figure 22. Illuminance (cd) for a typical workday for Point 16

(2) Occupant Responses

Next, following successful baseline measurement and control strategy implementation, occupant feedback regarding overall space feel and lighting quality is desired. A short survey is to be administered voluntarily upon the completion of each workday for a series of days, likely 3-5 days, of constant system operation at a new control sequencing. Responses pertaining to the overall experience of the occupants are valuable – examining characteristics such as perceived brightness, promoted focus or performance, and observed steps for periods of CCT shifts. These responses can provide firsthand evidence for or against suggested control strategies based on human perception and can ultimately influence design decisions for these circadian lighting systems. This occupant response survey can be seen in **Appendix B.**

iii) Modified Mode of Operation Data Collection

Unfortunately, any suggested modifications to system operational characteristics were not able to be implemented due to the outbreak of the novel COVID-19 virus across the US. Although, surveys to gather occupants' perceptions on changes to the lighting in the space were prepared prior to the outbreak and can be viewed in **Appendix B** following the report. These surveys intended to gain insight to the anecdotal responses of the occupants as system operation became more in tune with the circadian response of humans as determined through the literature review. These surveys, along with the modified control strategy, are a great point of continuation for further research with this case study.

iv) Analysis – Discussion

As can be seen through comparison of **Figure 19** and **Figure 20** above, the addition of daylight in the measurement for Point 15 not only adds increased amplitude response throughout the graph, but also adds in spectral intensity components less than 424 nm and greater than 616 nm, approximately. This alters the shape of the curve and helps to describe the rich spectral distribution of sunlight compared to typical artificial LED lighting. This concept is one that is beginning to be addressed within the lighting community in search for an artificial source that can provide the spectral distribution advantages of daylight in the form factor of an LED fixture [24][25].

Looking at **Figure 21** and **Figure 22** above, the difference in distribution and amplitude of the illuminance measurements is quite apparent. Point 2 represents an interior space with very little influence from daylight penetration into the space, while Point 16 was mounted vertically on a north facing windowpane for direct daylight measurement. That being said, the magnitude of illuminance values for direct daylight on the vertical surface is over 5x greater than that of the desk surface towards the interior of the office plan for most operational hours. This helps to suggest a shallow influence of daylight penetration in the space and less opportunity for daylighting as a circadian lighting solution. This means that the artificial electric lighting can have greater potential in influencing the circadian response of occupants in the space, if the desired design criteria are met as outlined in earlier sections of this report. Conversely, as circadian lighting solutions are meant to provide stimulus like those of the natural pattern of the sun through daylight, the inherent lack of daylight penetration leads to greater challenges with intensity variation in the space while still maintaining desirable illumination targets as recommended by the IESNA. In addition, color tuning must be carefully considered for positive effects on occupants in this office space.

6. Conclusion and Recommendations

Upon completion of this study, a few entities remain unaddressed due to the unforeseen circumstances of the novel coronavirus outbreak. This study was able to successfully identify and review pertinent literature in order to gain a well-rounded understanding of circadian lighting systems and their properties. This knowledge was then applied to the local case study with the UNMC office space primarily through relevant data collection and processing, specifically measuring spectral intensity and illuminance values across the space. After gathering initial data for spectral intensity and illuminance measurements throughout the space, interruption of the control strategy manipulation by the spread of Covid-19 put a halt on continuation of the case study. Future implementation of control strategy concepts has also been suggested if this investigation is to continue.

An understanding of daylight penetration into the space can be leveraged in future work and control strategy implementation pertaining to light intensity through a compiled daylight intensity mapping presented in the report. Suggested control strategy for intensity and CCT variation as presented in other literature has been documented and is the next step for continuation of this case study. Additionally, the inability to implement the occupant survey as well as the suggested control strategy is less than ideal for the investigation of the value of circadian lighting in modern design. Preliminary measurements of light in the space, with contributions from natural and artificial light sources, are valuable for understanding current state characteristics of the space and for addressing areas of improvement. From here, observing the interaction between CCT and intensity manipulation related to occupant well-being can pave the way for advanced data analysis. Comparison of measured values to empirical metrics developed for understanding circadian lighting can add to a growing knowledge base of the field, potentially influencing lighting standards and recommendations for design.

7. Appendix

Appendix A. Product Specification Sheets

Corelite

DESCRIPTION

The Jaylum LED is a timeless direct/indirect pendant featuring crisp modern lines and the latest solid state lighting and driver technology. This highly efficient luminaire will accompany almost any décor while meeting today's increasingly stringent energy requirements. The Jaylum series may be mounted individually or continuously with 4 and 8 foot modular sections and is suited for open offices, private offices, conference rooms, reception areas, and educational facilities. Companion wall mount and sconce fixtures are also available to create cohesive architectural spaces.

Catalog #		Type
Project		
Comments		Date
Prepared by		

SPECIFICATION FEATURES

Construction
Low profile housing and integral high reflectance gear tray constructed from die-formed 20 gauge cold rolled steel forming a 8-1/2" x 1-1/2" profile.

End Caps
Standard endcaps are rounded die cast aluminum and mechanically attached flush to end of fixture without exposed fasteners. End cap adds 1/2" at each end.

Light Engine
LED's are available in 3000K, 3500K or 4000K with CRI options of either ≥80CRI or ≥90CRI. Lumen output will be affected - please refer to the lumen adjustment factor table.

Electrical
Long-Life LED system coupled with integral electronic drivers to deliver optimal performance. Standard with 120-277V 0-10V dimming drivers (1% standard). 347V 0-10V drivers are available. Dimming wires come standard but can be capped in the field for standard switched operation. A single power feed drop supplied as standard.

Controls
Options compatible with Eaton's Connected Lighting Systems:
- WaveLinx sensor
- LumaWatt Pro sensor
- Fifth Light DALI driver

Refer to the Connected Lighting options page and ordering information for more details.

Mounting
Aircraft cable mounts on 4'-0" and 8'-0" centers. Fixture is balanced with cross cable to allow for minimal leveling and simple installation. Minimum mounting height from ceiling to top of fixture is 8". All sections are continuously wired with push-in connectors for fast installation. Fixtures can be joined for straight continuous runs. Refer to installation instructions for various ceiling interface details.

Finish
Electrostatically applied polyester powder coat paint in white, silver, or black. RAL custom colors are available.

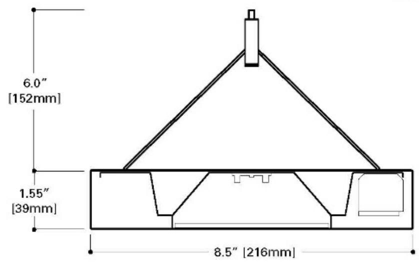
JAYLUM - J2

LED

Suspended
Direct / Indirect

cULus – 1598
Damp Location Listed
LM79/LM80 Compliant
ROHS Compliant

VividTune



ORDERING INFORMATION

Sample Number: J2-WL-40L835-1D-UNV-STD-SWPD1-W-AC48-T1-16

Series	Shielding	Lumen Package Nominal per 4' section	CRI	Color Temperature	Number of Circuits	Additional Circuiting	Input Voltage
J2 - Jaylum Suspended Direct/Indirect	**WL** - Frosted Lens (25% Up / 75% Dn)	**20L** - 2,000 Lms (500 lms/ft) **30L** - 3,000 Lms (750 lms/ft) **40L** - 4,000 Lms (1,000 lms/ft) **50L** - 5,000 Lms (1,250 lms/ft)	**8** - 80 CRI **9** - 90 CRI	**30** - 3000K **35** - 3500K **40** - 4000K **3050** - Tunable White 3000K-5000K **2765** - Tunable White 2700K-6500K	**1** - Single Circuit	**D** - None (Default Dimming) **E** - Emergency Circuit **S** - Secondary Circuit **N** - Emergency + Secondary Circuit	**120** - 120V **277** - 277V **UNV** - Universal (120V-277V) **347** - 347V
	More distributions are available. See Jaylum J3 series.	Refer to performance table on Page 3 for more detail.	Tunable White options to be used with W2A driver only. Must be used with two (2) 10V dimming control channels, 1 color, 1 intensity. Not compatible with other control or sensor options.		Refers to wiring in cross section.	Select "D" wiring for individual fixtures. Secondary circuit not available with integrated sensor options.	Integral 347V driver with STD 0-10V option only. Factory supplied 347V remote transformer for all other driver options.

Driver/Dimming Options	Integral Sensor	Integral Emergency	Top Cover (Optional)	Finish	Suspension Length	Ceiling Type	Run Length
STD - Standard 0-10V (1%-100%) **SR** - Sensor Ready (5%-100%) **5LT** - Fifth Light DALI (5%-100%) **LH** - Lutron HiLume 1% EcoSystems **L5** - Lutron 5-Series 5% EcoSystems **W2A** - Tunable White, 2ch, 0-10V Intensity and CCT Control	**SWPD1** - WaveLinx Wireless Integrated Sensor **LWIPD1** - LumaWatt Pro Wireless Integrated Sensor **SVPD1** - 0-10V Stand-alone Integrated Sensor	**ILB12** - 12-watt, 120V-277V Iota ILB-SL-CP12	**DC** - Dust Cover **DLED** - Downlight Kit (85% DOWN)	**W** - White **S** - Silver **B** - Black **CC** - Custom Color	**Adj. Cable** **AC48** - 48" **AC120** - 120" **AC240** - 240" **AC300** - 300" **AC360** - 360"	**T1** - 1" T-Bar **T9** - 9/16" T-Bar **TS** - Slotted T-Bar **ST** - Structure **JB** - 4" Octagonal J-Box	**4** - 4 ft **8** - 8 ft **XX** - Specify Row Length
One driver per 4' section unless otherwise noted.	SW sensor must be used with "STD" driver. LW sensor must be used with "SR" sensor ready driver. Consult factory for emergency circuit option with integrated sensor option.		Dust Cover cannot be combined with DLED kit.		White mounting hardware standard; for black mounting hardware, add "-B" after ceiling type.		Standard row configurations over 8' consist of 4' and 8' luminaires.

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SPECIFICATION FEATURES CONTINUED

Lengths
Available in 4-ft and 8-ft sections. All sections are modular eliminating the need for starter, joiner and end sections. Standard row configurations over 8-ft consist of 4-ft and 8-ft luminaires unless otherwise specified.

Shielding
Bottom lens is a high light transmission 0.08″ thick frosted acrylic material.

Lumen Maintenance
Projected lumen maintenance based on TM-21 standards is L93 > 60,000 hours at 25°C ambient conditions.

Emergency Options
Optional 120V-277V integral emergency battery pack is 12W maximum, 90 minute output, and powers a 4-foot section. Test switch/indicator button located on the top side of the luminaire. For approximate delivered lumens multiply the lumens per watt of the desired fixture by the wattage of the emergency battery pack (100 lm/W x 12 = 1200 lumens). Emergency section wiring and UL 924 emergency/generator transfer options available – see ordering information for details.

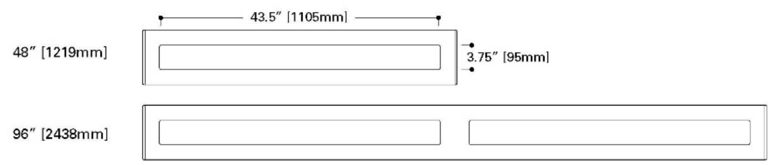
Integrated Sensing and Control Systems
Integrated options must be used in conjunction with the associated system and may not be compatible with other options or accessories. Please consult WaveLinx and LumaWatt Pro system pages for additional details and compatibility. Consult Marketplace Options - Lutron system pages for additional details and compatibility. Requires field commissioning to operate or dim. Contact Lutron at www.lutron.com.

Weight
3.5 lbs per foot.

Compliance
Modules are UL recognized components and indoor luminaires are cULus listed for 25°C ambient environments, damp location listed, and RoHS compliant. LED modules comply with IESNA LM-79 and LM-80 standards. DesignLights Consortium™ Qualified and classified for DLC Standard and DLC Premium, refer to www.designlights.org for details.

Warranty
Five year warranty.

FIXTURE LENGTHS



SENSOR INTEGRATION

Integrated sensors are located at the end of each 4′ unit and in the middle of each 8′ unit for individual and continuous runs. Each unit can be individually controllable or grouped together with the integrated sensors.

QUICK-TAB ALIGNMENT

Corelite's patented quick-tab alignment system creates a seamless and simple installation every time. Simply align the tabs into the corresponding slots. The fixture can then hang freely while a single contractor makes the final connections; it all slides back together and is securely fastened in place.

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ENERGY AND PERFORMANCE DATA

J2 LED Light Level Outputs and Distributions (3500K, 80 CRI)								
Series	Lumen Package	Delivered Lumens		Wattage		Efficacy LPW	Distribution	
		4FT	Per FT	4FT	Per FT		% Up	% Down
J2-WL	20L	1977	494	14.9	3.7	133	25%	75%
	30L	3012	753	23.1	5.8	130		
	40L	4075	1019	32.6	8.2	125		
	50L	4961	1240	42.9	10.7	116		
J2-WL w/ DLED	20L	1820	455	14.9	3.7	122	13%	87%
	30L	2773	693	23.1	5.8	120		
	40L	3752	938	32.6	8.2	115		
	50L	4567	1142	42.9	10.7	106		

LUMEN ADJUSTMENT FACTORS

CCT	80 CRI	90 CRI
3000K	0.961	0.830
3500K	1.000	0.861
4000K	1.019	0.883

Example Calculation:
40L / 3500K / 80 CRI
Lumen Output selected = 1019 lms/ft

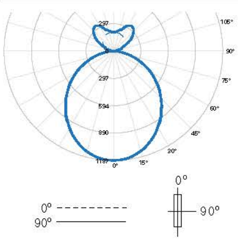
3500K / 90 CRI Desired
Lumen Adjustment Factor = 0.861

Adjusted Lumen Output = 1019 lms/ft x 0.861 = 877 lms/ft

LUMEN MAINTENANCE

Ambient Temperature	TM-21 Lumen Maintenance (60,000 hours)	Theoretical L70 (Hours)
25°C	>93%	331,000

PHOTOMETRICS



FILE NAME: J2-WL-40L835-1D-UNV-4.IES
LAMP: (LD5) LED 3500K
LUMENS: 4075 Lm
WATTS: 32.6 W
LPW: 125 Lm/W
TEST NO.: P253284
25% UP / 75% DOWN

ZONAL LUMENS SUMMARY

Zone	Lumens	% Fixture
0°-30°	890	21.8
0°-90°	3060	75.1
90°-130°	488	12.0
90°-180°	1016	24.9
0°-180°	4075	100

LUMINANCE DATA (CD/M²)

Vertical Angle	0°	45°	90°
45°	8181	8063	7946
55°	7679	7621	7361
65°	7000	6884	6687
75°	5908	5843	5653
85°	3813	4007	3813

COLOR DATA (3500K)

		80CRI	90CRI
TM-30-15	R_f	82.5	92.4
	R_g	96.0	100.6
CRI/CIE	R_a	83.1	96.1
	R_9	14.0	72.1

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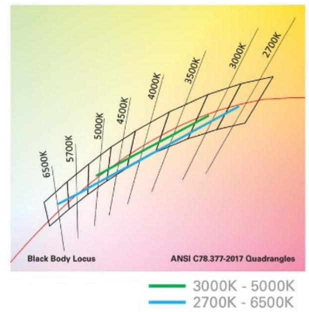
VividTune
color tuning solutions

Jaylum (J2) with VividTune Tunable White

VividTune tunable white luminaires from Eaton deliver high-quality light in a broad range of continuously variable color temperatures and intensities. Create a dynamic environment by adjusting the ambient light warmer or cooler to influence mood, support the task at hand, or create a dramatic ambience. The ability to control correlated color temperature and intensity separately using simple controls is the next evolution of LED lighting for the commercial, educational, healthcare and hospitality space. The unparalleled flexibility and number of available lighting environments enable users to find the right light with tunable white.



Energy and Performance Data

Tunable White - J2 LED Light Level Outputs (3500K, 80 CRI)						
Series	Lumen Package	Delivered Lumens		Wattage		Efficacy LPW
		4FT	Per FT	4FT	Per FT	
J2-WL	20L	2043	511	17	4.3	120
	30L	2974	744	25.8	6.5	115
	40L	3959	990	36.7	9.2	108
	50L	5009	1252	50.7	12.7	99
J2-WL w/ DLED	20L	1881	470	17	4.3	111
	30L	2739	685	25.8	6.5	106
	40L	3645	911	36.7	9.2	99
	50L	4612	1153	50.7	12.7	91

Tunable White - Lumen Adjustment Factors				
CCT	3000K-5000K		2700K-6500K	
	80 CRI	90 CRI	80 CRI	90 CRI
2700K	-	-	0.918	0.784
3000K	0.946	0.778	0.944	0.815
3500K	1.000	0.850	0.977	0.856
4000K	1.053	0.919	0.998	0.883
4500K	1.062	0.934	1.016	0.916
5000K	1.062	0.934	1.03	0.924
6500K	-	-	1.045	0.949

Controlling VividTune Tunable White

VividTune luminaires make tunable white more accessible by using simple and familiar controls. From wall dimmers to wireless controls, VividTune tunable white luminaires are compatible with industry standard 0-10V dimming controls. A single 0-10V dimming input is used to control intensity (brightness) while a second 0-10V dimming input is used to adjust CCT. For suggested control configurations, go to www.eaton.com/lighting for tunable white application guides.

Example of Lumen Adjustment Calculation

J2-WL-40L93050 ...
at 90 CRI tuned to 4000K

Lumen Adjustment Factor = 0.919

Light Output Per Foot=
990 lm/ft x 0.919 = 910 lm/ft

$$\text{Efficacy} = \frac{910\ \text{lm}}{9.2\text{W}} = 99\ \text{lm/W}$$

Appendix B. Occupant Response Survey

Circadian Lighting Survey UNMC

How's the Lighting?

This form has been created to help gather employee feedback about perceived changes to the lighting conditions in your workspace. Please consider taking a brief moment to reflect on your observation of the lighting system's operation today. Thank you.

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.
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.
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.
.
.
.

Today's Date:

Did you…

Enjoy the lighting system's operation today? ☐ Yes | ☐ No

Observe any changes throughout the day? ☐ Yes | ☐ No

Think that the light promoted your focus and performance? ☐ Yes | ☐ No

Did you think that the changes were:

☐ 1 ☐ 2 ☐ 3

Too Scarce Too Frequent

Did you feel that the room was:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Too Dark Too Bright

Other Comments:

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