

# Daylighting beyond Instrumentality and Dynamic Metrics

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**ABSTRACT:** The relationship between sustainable architecture and daylighting design has suffered from a limited approach where architects reduce daylighting to an instrumental quality and objective metrics related to daylighting quantities - devoid of its relationship to aesthetics, daylighting quality, and subjective impacts on space perception and indoor environmental quality. In design practice, architects and engineers place most emphasis on the visible transmittance of glazing and the quantity of daylight rather than spectral properties and the wavelengths that affect physiological response to light. This trend prioritizes daylight's dynamic metrics as the basis for green building rating systems' credits criteria. Seldom are other qualities of daylight, such as the biological effective wavelengths from different spectral power distributions or the impacts of daylighting on occupant's mood and behavior considered.

Non-visual benefits of daylight that affect well-being include: regulating the circadian biological clock, hormones (melatonin, cortisol, etc.), body temperature, heart rate, mood, stress, and depression. These are impacted by different characteristics of daylight such as luminance, spectral power distribution, color rendering index, correlated color temperature, duration of exposure, directionality, dynamics, and timing. Though architects often overlook the energy in the non-visible portions of the light spectrum, it must be considered in the overall appraisal of daylighting systems.

In this paper, we examine a meta-analysis of previous assessments on the relationship between occupant's health and well-being in relation to metrics, certification systems, and the attributes that guide their interactions. We explore the importance and influence of interdisciplinary research in addressing issues of daylighting design for sustainable architecture, which affect people on an individual, community, and global scale. The paper concludes with frameworks relating health effective light to appropriate metrics which will guide future daylighting design processes for sustainable architecture.

**KEYWORDS:** Daylight, Health, Rating Systems, Metrics, Circadian System

## INTRODUCTION

As a stand-alone term, daylighting is difficult to define. This may as well be the reason behind its appeal and justify stakeholders' desire and fascination with a concept which cannot be easily constrained. Attempts have been made in defining daylighting in relation to sustainable design. Results of an online survey on the role of daylighting in sustainable design indicate some of many different viewpoints and approaches to this topic which have a significant body of work published in the field (Reinhart and Galasiu 2006).

- *Architectural definition:* the interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment
- *Lighting Energy Savings definition:* the replacement of indoor electric illumination needs by daylight, resulting in reduced annual energy consumption for lighting
- *Building Energy Consumption definition:* the use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting)
- *Load Management definition:* dynamic control of fenestration and lighting to manage and control building peak electric demand and load shape
- *Cost definition:* the use of daylighting strategies to minimize operating costs and maximize output, sales, or productivity

Light inspires us and can enliven space; it adds a higher level meaning to the experience and identity of a space (Ozorhon and Uraz 2014). However, there are common misconceptions that daylight has only an

architectural and aesthetical value, and all other daylight functions can be replaced by electrical lighting solutions. Hence, with technological advancements, occupants tend to resort to electric lighting for its instrumental benefits as it offers a controlled electric lighting system with uniform illumination to meet visual task needs. It is constant and predictable, whereas daylight is dynamic and can be unpredictable (Haans 2014).

Emphasis within the field gravitates depending on current trends. The energy crisis of the 1970s shifted the practice back to the integration of daylight in building design - towards a focus on sustainability as a response to the energy-related concerns of the time. Design solutions proposed included increasing glazing on façades to incorporate daylighting that could minimize the demand for electric lighting. This resulted in the development of metrics which focused on task-based illumination levels as well as limited visual discomfort metrics based on illumination levels as a proxy to problematic glare in daylit spaces (Reinhart, Mardaljevic, and Rogers 2006).

These metrics reduce daylighting to an instrumental and objective qualities with emphasis on performance measures and standards - devoid of its relationship to aesthetics and subjective impacts on space perception and indoor well-being. In this paper, we make an argument about these aspects of the daylit environment that are ignored through current standards and ratings systems. We more specifically look at the impact of daylight's biological effective wavelengths on occupant health and well-being, and the role architecture can play in achieving a balance to daylighting design that combines both objective and subjective measures in the design of well-daylit spaces.

## 1.0 EVALUATING DAYLIGHT

### 1.1. Instrumental and Dynamic Daylight Metrics

The following luminous quantities outlined are some of many that have been extensively used in the literature for the assessment of daylight and the luminous environment (Mardaljevic, Heschong, and Lee 2009, Reinhart, Mardaljevic, and Rogers 2006).

- *Daylight Factor*: the ratio of internal illuminance to unobstructed horizontal illuminance under standard CIE overcast sky conditions, expressed as a percentage.
- *Daylight Autonomy*: the percentage of the year when a minimum illuminance threshold is met by daylight alone. It uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that an occupant can work by daylight alone.
- *Useful Daylight Illuminances*: determines when daylight levels are 'useful' for the occupant, that is, neither too dark (<100 lux) nor too bright (>2000 lux).
- *Annual Light Exposure*: defined as the cumulative amount of visible light incident on a point of interest over the course of a year, measured in lux hours per year.
- *Realized Savings Ratio*: the ratio of predicted to realized energy savings.
- *CIE Glare Index*: an index used for luminaire sources of glare, it requires both direct and diffuse illuminances - above 28 is intolerable, below 13 is barely perceptible.
- *Daylight Glare Index*: an index that considers glare from the sky viewed through a window - above 31 is intolerable, below 18 is barely perceptible.
- *Daylight Glare Probability*: glare sources are detected by contrast ratios - above 0.45 is intolerable, below 0.3 is barely perceptible.
- *Visual Comfort Probability*: the percentage of people predicted to feel comfortable with the luminous environment.

These commonly used metrics clearly reflect the academic research, lighting design, and manufacturing communities' priorities in relation to defining daylighting. This is seen in their abundant use of illuminance measurements, which are relatively simple to measure, for meeting visual task needs and energy savings. Though determining the impacts of illuminance levels in the luminous environment is essential, what about the other dimensions of daylight? Do these illuminance-based metrics unjustly overshadow the other components of daylight?

### 1.2. Daylight in its Third Dimension

To retort to the postulations by those who do not appreciate lighting's many facets, a wide body of research has investigated the non-instrumental benefits of light. Daylight embodies information about the weather, the time of day, and satisfies other deeply rooted psychological and biological needs. As opposed to electric lighting, there are both visual and non-visual health benefits received from daylight that cannot be replicated (Jennifer A. Veitch 2000). These are impacted by different characteristics of daylight such as luminance spectral power distributions (SPD), color rendering indices (CRI), and correlated color temperature (CCT),

duration of exposure, directionality, dynamics, and timing (van Bommel 2006). Though there is a dominance of the eye and vision, and suppression of other senses and biological functions, the non-visual aspects of light and health are critical (Pallasmaa 2012). These non-visual benefits of daylight that affect well-being include: regulating the circadian biological clock, hormones, body temperature, heart rate, mood, stress, and depression (Lucas et al. 2014).

The biological effects of light on humans are usually translated from SPD and measured in 'equivalent melanopic lux', a proposed alternate flux density metric that is weighted to the intrinsically photosensitive retinal ganglion cells (ipRGCs) luminous efficiency function, which peaks at 480 nanometers and is based on the action spectrum of melanopsin - instead of the cones' photopic luminous efficiency function  $V(\lambda)$ , which peaks at 555 nanometers and is based on the response of foveal, long and middle-wavelength sensitive cones, which is the case with traditional lux. This translation is used to understand how much the spectrum of a light source stimulates ipRGCs and affects the circadian system. However, using this metric by quantifying light in terms of melanopic lux has been deemed to be inaccurate (Mariana Figueiro 2017). This is because photometric units have not been established for the circadian luminous efficiency function, the impact on the suprachiasmatic nucleus by different levels of melanopic lux is still unknown, and the fact that basing the metric on melanopsin alone disregards other combined neural channel responses.

Though designers often overlook the energy in the non-visible portions of the light spectrum, it must be considered in the overall appraisal of daylighting design. Daylight contains 4.6% ultraviolet radiation, 46.4% visible light and 49% infrared radiation. Vitamin D is best produced by exposure to UVB with wavelengths of 290-300 nm. The glass industry has emphasized its concern for human health. Thus, it has stressed the importance of photoprotection against UV detrimental effects including cancer, sunburn, skin aging, damaging the immune system and eyes (Holick and Jenkins 2003). This, however, is somewhat contradictory because they are disregarding health effective radiation as humans require UVB for the synthesis of vitamin D. This is especially important since statistics indicate that people spend more than 90% of their time indoors (Frontczak 2011).

## 2.0 METRIC APPROPRIATENESS

Upon reviewing the dynamic daylight metrics that are predominantly in use, it is important to investigate the appropriateness of their use in the current context of designing the luminous environment to enhance occupant health and well-being. Some of the leading green building assessment tools include: Leadership in Energy and Environmental Design (LEED™), Building Research Establishment (BRE) Environmental Assessment Method (BREEAM, United Kingdom), Green Building Council of Australia Green Star (GBCA, Australia), Deutsche Gesellschaft für Nachhaltiges Bauen e.V (DGNB, Germany), Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan), and Korea Green Building Certification (KGBC) as examples. These rating and certification systems provide frameworks for assessing a building's performance, though they are also generally used as design guides by professionals. This brings into question how effectively these comparable green building rating systems can help a design team to implement critical components of human health benefits associated with indoor environmental quality, and how reliable are the metrics they use?

### 2.1. LEED

The Indoor Environmental Quality section of LEED v4 BD+C (Council 2018) covers the light and well-being aspects of the luminous environment which are within the scope of this paper.

The *interior lighting* credits aim "to promote occupants' productivity, comfort, and well-being by providing high-quality lighting" by means of specifying individual lighting controls, using light sources with a CRI of at least 80 and minimizing 'direct only' overhead lighting to 25% or less of total connected lighting for all regularly occupied spaces, or use light sources that have a rated life of at least 24,000 hours for 75% of total connected lighting load. The *daylight* credits aim "to connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space." These are achieved by the project teams' demonstration through computer-aided simulation and illuminance calculations that designs achieve appropriate sunlight exposure. Teams are also encouraged to provide manual or automatic glare-control devices for all regularly occupied spaces. The *quality views* credits aim "to give building occupants a connection to the natural outdoor environment by providing quality views." The requirements for these credits is to achieve a direct line of sight to the outdoors via vision glazing of 75% of all regularly occupied floor area. 75% of all regularly occupied floor area must have at least two of the four kinds of views: (1) Multiple lines of sight to vision glazing in different directions at least 90 degrees apart. (2) Views that include at least two of the following: (a) flora, fauna, or sky; (b) movement; and (c) objects at least 25 feet from the exterior of the glazing. (3) Unobstructed views located within a distance of three times the head height of the vision glazing. (4) Views into the interior atria may be used to meet up to 30% of the required area.

Upon reviewing this section, it is noted that the LEED standards reference reinforcing circadian rhythms only once in the daylight credits, but they provide no guidance as to how this is expected to be achieved. The illumination-based metrics are not addressing health effective light; emphasis is still clearly placed on photopic vision and its visual architectural applications.

## 2.2. WELL

The Green Business Certification Inc not only administers the LEED certification program, but also a lesser-known WELL Building Standard (Institute 2017) which was launched in October 2014 by The International WELL Building Institute. This standard aims to implement, validate and measure features that support and advance human health and wellness through seven categories: air, water, nourishment, light, fitness, comfort, mind and innovation. It references existing standards, practice guidelines set by governmental and professional organizations and integrates scientific and medical research and literature on environmental health, behavioral factors, health outcomes and demographic risk factors that affect health with leading practices in building design and management. This standard is commendable as it not only assesses the design and operations of buildings much like the predominant rating systems, but it, more importantly, looks at how they impact and influence human behaviors related to health and well-being.

The light category in the WELL standard aims to "minimize disruption to the body's circadian system, enhance productivity, support good sleep quality and provide appropriate visual acuity." The credits cover aspects of visual lighting design, circadian lighting design, electric light glare control, low-glare workstation design, color quality, surface design, automated shading and dimming controls, right to light, daylight modeling, daylighting fenestration, light at night, and circadian emulation. The standard details circadian lighting design in terms of melanopic intensity for work areas, living environments, breakrooms and learning areas. Here, we notice the use of melanopic lux as a metric to establish the standard's benchmarks.

For *work areas*, they should meet at least one of two requirements: (1) At 75% or more of workstations, at least 200 equivalent melanopic lux is present. (2) For all workstations, electric lights provide maintained illuminance on the vertical plane of 150 equivalent melanopic lux or greater. In *living environments* such as bedrooms, bathrooms, and rooms with windows, one or more fixtures should provide 200 or more equivalent melanopic lux. Lights in workplace *breakrooms* are required to maintain an average of at least 250 equivalent melanopic lux. They may be dimmed in the presence of daylight but should be able to independently achieve these levels. *Learning environments* need to meet at least one of two requirements: (1) At least 125 equivalent melanopic lux is present at 75% or more of desks, for at least 4 hours per day for every day of the year. (2) Ambient lights provide maintained illuminance on the vertical plane of equivalent melanopic lux greater than or equal to the lux recommendations in the Vertical (Ev) Targets of the American National Standards Institute and Illuminating Engineering Society IES-ANSI RP-3-13.

The circadian emulation category aims to "provide light which has intensity and spectrum similar to that of the daily changes of sunlight." It details how light systems should follow users' set "bed time" and "wake time" by gradually increasing light levels and providing a maintained average of at least 50 to 250 equivalent melanopic lux as prescribed. Though it has already been established that the equivalent melanopic lux metric is not a reliable measure, it is noteworthy that the WELL standard has taken a step further and addressed health effective light in a more rigorous manner.

## 2.3. The National Fenestration Rating Council

Window and glazing choices should be considered holistically. The Lawrence Berkeley National Laboratory has developed many widely available computer programs and repositories including WINDOW, THERM, COMFEN, RESFEN, Optics, IGDB, CGDB, Radiance, and AERCalc. These have been mostly used by the glass industry manufacturers for calculating total window performance indices (U-values, solar heat gain coefficients, shading coefficients, and visible transmittances). These are useful for assessing glazing in terms of thermal comfort, heat gains and losses, condensation control, acoustic control, energy requirements and visual requirements (privacy, glare, view), daylighting, shading and sun control, ultraviolet control and color effects.

Similarly, The National Fenestration Rating Council provides an NFRC label to certify whole product performance. Its fenestration energy rating system rates the performance of window and skylight products in terms of U-factor, Solar Heat Gain Coefficient (SHGC), Visible Light Transmittance (VT), and optionally Air Leakage (AL) and Condensation Resistance (CR). Building energy codes, tax credits and utility incentives, ENERGY STAR and other major standards for window energy efficiency base their criteria on these ratings.

There is a lot of hidden value in this data but most designers often do not look past these figures to see how they can be translated and reflected in their designs. Glazing is usually prescribed in accordance with performance and aesthetics. However, there should be more awareness of how these design decisions not only affect occupants' perception of the space due to the filtered and transmitted light properties through the glazing; but also, how this modifies biologically effective wavelengths. This modification may or may not be perceived by occupants. Regardless, designers should get ahead and anticipate outcomes and

repercussions from glazing property variables. Thus, designers would benefit if NFRC labels included biological impact criteria.

Studies should attempt to elaborate on the glass industry's research on the transmittance of light through different glazing types to look at the effects of glazing on the transmission of the electromagnetic spectrum within a space's interior. More specifically, on how the light that is being transmitted affects occupant health, wellbeing, and perception of the space. Occupants' preferences of internal space and lighting conditions due to different glazing properties should be taken into consideration to assess how the subjective aspect of lighting preferences conditions correlates with the objective results of biologically effective spectral light transmittance. This would give helpful insight into the overall effectiveness of design interventions, the relative impact of independent variables, the strength of the relationship between variables, and how this could affect the design practice.

### **3.0. TOWARDS A UNIFIED FRAMEWORK**

It is becoming increasingly apparent that there is a conflict within the research, design and manufacturing communities in defining the metrics and standards for daylighting design. This is due to the development of inconsistent light quantities and units by various disciplines though they are all ultimately driven to describe a similar phenomenon dealing only with the objective qualities of daylighting. There is a need for a common, integrated metrics that would help transfer this knowledge and effectively evaluate and report the potential non-visual responses of daylight. The following section of the paper brings forward two approaches that have worked towards integrating frameworks through interdisciplinary research.

#### **3.1. Circadian Stimulus**

The Lighting Research Center at Rensselaer Polytechnic Institute has proposed a metric, known as “the circadian stimulus” for applying circadian light in the built environment (Mariana Figueiro 2017). It uses irradiance weighted by the spectral sensitivity of every retinal phototransduction mechanism that stimulates the biological clock, as measured by nocturnal melatonin suppression. The metric is derived from a transformation of circadian light into relative units, from 0 to the response saturation of 0.7, and is directly proportional to nocturnal melatonin suppression after one hour of light exposure (0 to 70%). The recommended levels aim for a circadian stimulus greater than 0.3 during the day and less than 0.1 in the evening.

This circadian stimulus metric was developed from several lines of biophysical and retinal neurophysiology interdisciplinary research. It has been validated in several controlled experiments and has been used successfully in a number of real-world applications including nuclear submarines, senior facilities for persons with Alzheimer's disease and offices. A circadian stimulus calculator is also made available online for lighting professionals to enable them to convert the photopic illuminance at the eye provided by any light source and level, into the effectiveness of that light for stimulating the human circadian system (Rea and Figueiro 2016, Rea et al. 2010). Though the science behind the circadian stimulus metric may be difficult in understanding for designers who have not specialized in lighting, it should not be a reason to adopt the simpler, alternate approaches that either disregard health effective light or are knowingly inaccurate, unreliable and without validation.

#### **3.2. Relative Spectral Effectiveness**

The Interdisciplinary Laboratory of Performance-Integrated Design at the École Polytechnique Fédérale de Lausanne has developed a new visualization tool, the “SpeKtro” dashboard - available online at [spekro.epfl.ch](http://spekro.epfl.ch), where it is possible to upload and analyze the SPD of any light source. It is based on two unit-less quantities: the energy-related and the vision-related relative spectral effectiveness (RSE) factors (Ámundadóttir, Lockley, and Andersen 2015). The energy-related RSE enables the evaluation of a SPD for a light source in terms of its comparative ‘energy’ relationship to an equal-energy spectrum for any system of photoreception. Similarly, the vision-related relative RSE factor enables the evaluation of a SPD for a light source in terms of its comparative ‘brightness’ relationship to an equal-energy spectrum.

The relative SPDs are shown for the visible part of the electromagnetic spectrum, between 390 nm and 700 nm. These spectral weighting functions show the relative spectral sensitivity of the five human photoreceptors and the photopic luminous efficiency. The interactive dashboard outputs light quantity dose-response curves that display the biological impact of melatonin phase shifts, melatonin suppression percentages and KSS rating of subjective alertness.

This unifying effort builds on existing literature and aims to help communicate information on non-visual spectral effectiveness in a universal way (Ámundadóttir, Lockley, and Andersen 2016). The dashboard can be adopted as an option to investigate the biological impacts of light sources. As it is fairly new tool, it could benefit from its use in many studies for exposure and validation.

#### 4.0. STRAUB HALL PILOT STUDY

To further investigate the impacts of daylighting beyond its instrumental quality, a pilot study was conducted as a proof of concept for a larger study. This domain of work aims to elaborate on the glass industry's research by investigating the effects of window design decisions (location, orientation, type) on the transmission of the electromagnetic spectrum within a space's interior and how the light transmitted affects occupant perception of the space, health and wellbeing.

##### 4.1. Background, Methods and Procedures

A pilot study was conducted on the 26<sup>th</sup> of January in Straub Hall at the University of Oregon campus in Eugene during the morning (8-10am) hours of the day. The aim of this study is to investigate the extent of change in spectral power distributions (SPD), color rendering indices (CRI), and correlated color temperature (CCT) in relation to distance from a clear window in the hallway and how this correlates to the decrease in illuminance levels. This is because using instrumental, dynamic metrics that simply measure illuminance levels neglect components of daylight that are responsible for human response to visual interest, psychological and biological impacts which are affected by SPD, CRI, and CCT.

With the use of an Asensetek Lighting Passport Pro spectrometer, SPD, CRI, CCT, and illuminance levels measurements were taken. This data was collected at different distances from the window, at 5ft marks. It was then converted in circadian stimulus using the circadian stimulus calculator developed by The Lighting Research Center.

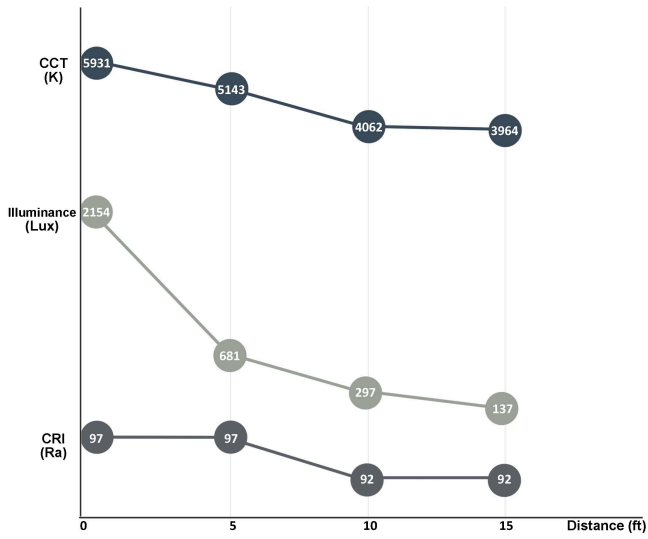
##### 4.2. Findings and Future Implications

The results indicate that differences in SPD, CRI, and CCT are subtler than the perceivable changes in illuminance levels (Table 1, Fig 1-3). However, these marginal differences still needed to be translated into biological impact for circadian entrainment in order to make this data transferable and fully comprehend the necessity of taking it into consideration for the sake of non-instrumental benefits of daylight.

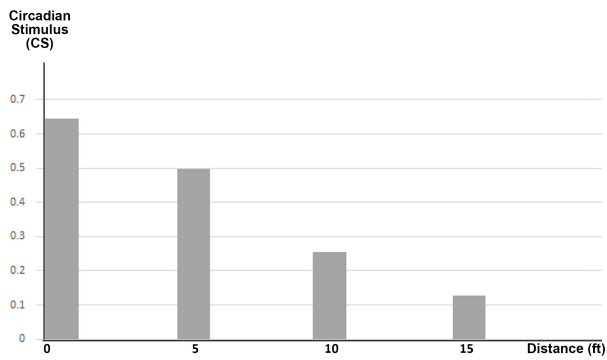
When the SPD was converted to biological impact using the circadian stimulus calculator, the findings proved to identify false assumptions that illuminance levels and circadian entrainment necessarily go hand in hand. The readings at 10ft indicate that illuminance levels marginally reach 300 lux which is recommended for such a space. However, at that same 10ft mark, the 0.256 circadian stimulus fails to meet the recommended 0.3 benchmark as seen in Fig 2. This indicates that relying on illuminance-based metrics for health effective light might be insufficient in quantifying its applicability and impacts on occupant's well-being. This also gives insights into added considerations of changes in SPD as occupants step away from the window and rely on electric lighting. This influence could be used to maintain or increase illuminance levels, but it may still fail to meet the benchmarks for health effective light.

**Table 1:** Straub Hall Hallway Daylight Analysis. Source: (Author 2018)

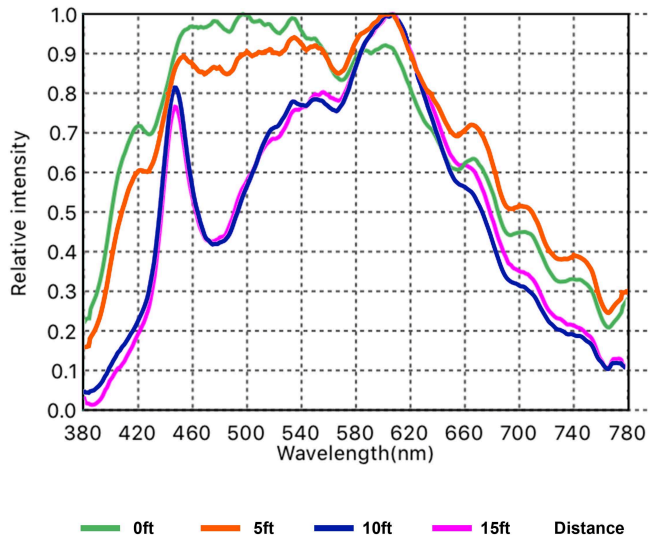
Distance (ft)	Illuminance (Lux)	CCT(K)	CRI (Ra)	Circadian Stimulus (CS)
0	2154	5931	97	0.6442802
5	681	5143	97	0.498229045
10	297	4062	92	0.255852422
15	137	3964	92	0.127484796



**Figure 1:** Straub Hall Hallway Illuminance, CCT, CRI. Source: (Author 2018)



**Figure 2:** Straub Hall Hallway Circadian Stimulus. Source: (Author 2018)



**Figure 3:** Straub Hall Hallway Spectral Power Distribution Analysis - Normalized. Source: (Author 2018)

## CONCLUSION

In this paper, we have aimed to shed light on the shortcomings of the design community in regards to designing some aspects of the daylight environment. This is in the hope that this knowledge entices professionals to prepare and respond to the rising expectations of designing the luminous environment - not only to meet visual needs and related concerns such as reduction of glare but also to support human health and well-being. In order to integrate circadian lighting strategies, designers need to understand the behavior of occupants in the space, the sources of light and glazing types that transmit daylight so that the guidelines ensure the design intent is met. This can only be achieved if they have familiarized themselves with the appropriate metrics for health effective light. If lighting professionals do not have a proper grasp of how to measure light as an enabler for health and well-being, then their designs cannot be effectively delivered. Further studies need to acknowledge this limitation and develop applicable metrics for the proper quantification of instrumental and health impacts of daylighting in approachable terms for lighting designers and architects.

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