SPECTRAL DAYLIGHTING SIMULATIONS: COMPUTING CIRCADIAN LIGHT

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ABSTRACT

Recent studies have demonstrated that the spectral content of light at typical interior daylight levels affects human circadian rhythms. Lighting simulation tools are developed, used, and validated mainly for computing the visual aspects of lighting. This paper demonstrates utilization of a multi-spectral simulation method that can be employed to design and analyse circadian lighting in built environments. The methodology is context-based, allowing the researchers and designers to consider local skies, exterior context, glazing optics, surface materials, interior design, and viewer location.

INTRODUCTION

In lighting simulations, computation of light at each wavelength throughout the visible spectrum is prohibitively time consuming. Lighting is commonly simulated through tristimulus color space such that spectral information for lights and materials are defined and computed with the RGB data. RGB combinations are metamers for the spectral power distributions of light in the physical world. In principle, it is appropriate to use the tristimulus color space; humans are trichromat, i.e. they perceive color through three channels in the visual pathway. However, in the physical world, the interaction between the lights and materials occurs in full spectrum. There are certain discrepancies associated with the simulation of light and materials with the RGB values in comparison to the full spectral data. The discrepancies may hinder the accurate computation of color dependent lighting metrics, especially the ones that are not dependent on the CIE photopic spectral sensitivity curves (V(λ)), such as the circadian light.

Circadian Rhythm

A growing body of research has shown that human ocular system functions in a dual manner both to facilitate vision and to reset the internal circadian body clock to synchronize it with the 24 hour daily cycle (or with the local time). A technical memorandum has been prepared by the Illuminating Engineering Society to provide information on non-visual impacts of architectural lighting that include circadian, neuroendocrine, and neurobehavioral responses in occupants (Figueiro et al, 2008). Many aspects of human responses (such as sleep/wake cycles, alertness, core body temperature fluctations, and production of melatonin and cortisol) are dominated by 24 hour rhythms. Internal body clock in human beings are close to (but not equal to) 24 hour cycle, and it requires environmental cues (i.e. light:dark cycle) to synchronize with the local time (Lockley, 2009). Circadian entrainment is influenced by the timing, intensity, duration and wavelength of light along with the preceding record of exposure. The following points are important for understanding circadian rhythms (Figueiro et al, 2008; Lockley, 2009):

- Research demonstrates that spectra and intensity of light affects the daily internal clock. The time of light exposure can either advance or delay the internal clock.
- The human circadian system is most sensitive to light at 460 nm (blue region of the visible spectrum), whereas the visual system is most sensitive to 555 nm (green region).
- Various research studies demonstrate that circadian response (e.g. nocturnal melatonin suppression) approaches maximum levels after 0.5 hr to 1.5 hr exposure periods of white light at 300 lux (Cajochen et al, 2000). Longer duration (6.5 hr) saturate the circadian response at 200 lux at the cornea (Zeitzer et al., 2000). Research also suggests that 100 lx at the cornea can initiate a 50% response, whereas 600-1000 lx can saturate the system (Zeitzer et al., 2000). The above numbers are photopic-lux values generated from a particular light spectra. Therefore, their circadian-lux equivalences are different and needs to be computed in order to be used as an analysis criteria. Further discussions are available in “Results and Evaluation” section.

Multi-spectral Lighting Simulations

Ruppertsberg and Bloj (2006, 2008) shown that Radiance Lighting Simulation and Visualization System’s (Ward, 1994) color simulation accuracy can be improved through an N-step method, where the spectrum is divided into N consecutive wavebands and a simulation is carried in N channels rather than the standard three channels (RGB). This paper adopted this technique, where the light spectrum is divided into 9 channels; i.e. the material and light values are defined in 9 channels and the light transport computations are performed in 9 intervals that span the entire lighting spectrum for each scene. These multiple channels are then post-processed by V(λ) to derive per-pixel photopic luminance (or illuminance) values and by circadian spectral sensitivity curve C(λ) to derive per-pixel circadian luminance (or illuminance) values.

Spectral Response Functions

Although light is part of the electromagnetic spectrum (extending from 380 to 780 nm), the radiometric measures cannot be used to measure light because the effects of radiation on the human visual and non-visual systems vary distinctly with the wavelength. It is believed that multiple photoreceptors (intrinsically photosensitive retinal ganglion cells (ipRGCs), 3 types of cones (Short-, Medium-, and Long wavelength), and rods) play a role in visual and non visual pathways. In photometry, spectral power distribution of light is weighted by the spectral luminous efficiency functions of the human eye V(λ). In circadian metrics, spectral power distribution of light is weighted by a spectral circadian efficiency function. There is not a standard circadian curve, yet. Most commonly used curves are Gall (2004), Rea et al. (2005), and Lucas et al. (2014).

Previous studies

Impact of lighting on non-visual responses is an open and fast changing research area in which most of the published scientific knowledge stem from controlled laboratory environments and clinical experiments (Figueiro et al, 2008). However, there is a clear need to quantify the impact of light stimuli on circadian rhythms in built environments. Few studies propose and utilize lighting simulations to predict circadian light levels. These studies are grouped as follows:

- While some of the studies estimated circadian values from three channel simulations (Pechacek et al., 2008; Mardaljevic et al, 2013; Andersen et al, 2012; Amandadottir et al, 2013), others utilized multi-channel techniques (Krzysztof, 2006; Geisler-Moroder and Dur, 2010; Belia and Seracani, 2014). These studies reference Gall's (2004) circadian response curve.
- The simulation techniques vary in terms of simulation periods: Point in time simulations (Krzysztof, 2006; Geisler-Moroder and Dur, 2010) and annual simulations (Pechacek et al., 2008; Mardaljevic et al, 2013; Andersen et al, 2012; Amandadottir et al, 2013) were performed.
- Some of the studies reported radiometric units (W/m^2), circadian equivalent lux (W-C(λ)), whereas others reported lighting units (lux and/or cd/m^2).
- These studies are mainly limited with neutral colors both in the material definitions and sky models.

Objective

The methodology in this paper differs from the previous studies in the following ways:

- The workflow combines the 9-step multi-spectral channel computation. The circadian model adopted in this paper calculates circadian values with both Rea et al. (2005) circadian spectral sensitivity curve and Lucas et al. (2014) melanopsin spectral sensitivity curve. Due to the page limit of the paper, results are provided with the circadian values derived from Rea et al.
- Daylighting is modelled with a variety of sky types that have color variations beyond neutral white light. This study includes CIE sky models along with mathematical models derived from measured data. Both sky luminance distributions and daylight spectra are modelled.
- Variation of color in architectural surfaces allow studying the impact of interaction of light sources and materials on circadian response.
- Calculations of Circadian-units along with photopic-units demonstrate the two distinct approaches that needs to be employed to study the non-visual and visual responses to a given environment.
- Circadian literally means "about a day". The temporal nature of circadian rhythms necessitate a time series approach to simulation. By simulating daily time series over selected days throughout the year, it is possible to study the circadian variations at an hourly dose resolution.

The objective of this paper is to utilize a multi-spectral lighting simulations workflow that facilitates computation of color dependent lighting metrics. Although the examples demonstrated herein are limited to circadian light computations, the workflow supports the simulation of other spectral response metrics.

THE SIMULATION METHODOLOGY

The Setting

The simulation setting is a north facing conference room in an office building in Seattle (47.6°N Latitude and 122.3°W Longitude). Dimensions of the space and material properties were measured on site. The color and reflectance of the materials of the opaque materials for the base case are determined using a GretagMacbeth ColorChecker© Color Rendition Chart and the Radiance *macbethcal* program. The spectral properties for the glazing system was obtained through the International Glazing Database 14-5 (LBNL, 2015). The spectral properties of materials for subsequent runs (Macbeth colors #3, 7, and 15) utilize data given in wavelengths from 380 to 780 nm in 2 nm intervals.

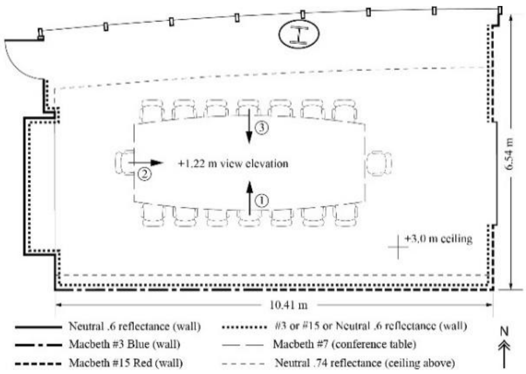

Figure 1 Research setting: View points used in simulations are illustrated as View 1 (facing North window), 2 (facing East wall), and 3 (facing South wall) along with material designations

The Simulation Methodology

The image generation process refers to a particular set of color bins (channels), defined by their wavelength intervals. Material and daylighting definitions are provided in 9 channels, and light transport is computed using a set of three Radiance simulations set to obtain 9 channel multi spectral simulations. The material and daylighting data are derived from the average from spectral values for each channel. Post processing of imagery involves conversion of the per-pixel color bins to photopic or circadian-luminance (or illuminance) values through a summation operation, which takes an N element vector representing the color bins in a given pixel and multiplies with an N element vector representing the corresponding spectral response. The spectral responses are derived by integrating the photopic or circadian curves in a given interval. The post processing operations are performed using an in-house Matlab function and Radiance commands for the 9-step simulation.

Photopic luminance values in Radiance are calculated as follows for a standard three-channel (RGB) imagery (Equation 1):

$$L = 179 * (0.2651 * R + 0.670 * G + 0.065 * B) \qquad (1)$$

The wavelength intervals for a standard three-channel (RGB) imagery in Radiance are calculated as 380-498 (B), 498-586 (G), and 586-780 nm (R) based on their respective coefficients in Equation 1. These intervals are further divided into 3 channels to achieve 9 channel bins (Figure 2). These divisions create equal bins in red and blue regions. The bin intervals in green region are slightly offset so that the divisions incorporate the color opponency in Rea et al. curve, where subadditivity is displayed in the wavelength intervals beyond 550 nm. The bin intervals are quite deliberate: They not only support the color opponency theory, but they allow assembling 3 channel Radiance simulations from 9 channel simulations. Moreover, dividing the original RGB intervals to roughly equal bins in each channel allow future workflows that can support the simulation of other spectral response metrics.

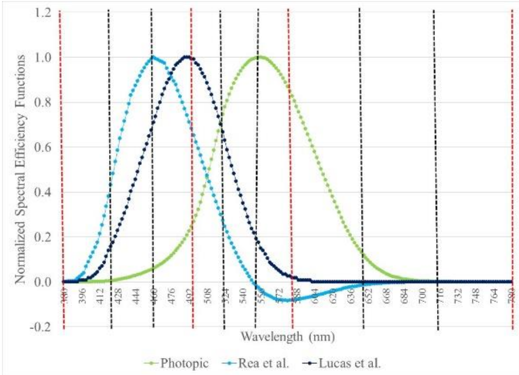

Fig 2 Normalized efficiency functions for CIE photopic curve, Rea et al. and Lucas et al. circadian curves: The vertical red lines demonstrate the RGB intervals in Radiance, grey lines demonstrate the further divisions for 9 channel simulations

179 is the luminous efficacy coefficient of the equal energy light that is used in calculating luminance and illuminance in Radiance (Ward and Shakespeare, 1997), and it is driven from the V(λ). The visual response peaks at a wavelength of 555 nm (V(λ) and the luminous efficiency is defined by scaling the normalized V(λ) curve by 683 lm/W. The numerical integration of the area under the curve leads to 179. Since this coefficient is derived from the V(λ) curve, it cannot be directly applied to C(λ). The conventional utilization of 683 lm/W dictates that the luminous efficacy is determined at 555 as 683 lm/W, however given that the human response curves can be at negative in this wavelength, it is suggested to scale the C(λ) peak at 460 nm to 683 lm/W (Rea, 2015). The resulting luminous efficacy coefficient is calculated as 130 for the Rea et al. curve (148 for the Lucas et al. curve). Therefore, the results in this paper are given in photopic-lux or photopic-cd/m^2 (photopic-Nits) for the visual responses, and circadian-lux or circadian-cd/m^2 (circadian-Nits) for the non-visual responses.

Table 1
Coefficients for Photopic and Circadian Response Functions

	Wavelength	Photopic	Rea et al.	Lucas et al.
B1	380-422	0.0004	0.0669	0.0166
B2	422-460	0.0095	0.394	0.1819
B3	460-498	0.0522	0.4264	0.3973
G1	498-524	0.1288	0.1464	0.2468
G2	524-550	0.2231	0.0362	0.1204
G3	550-586	0.3174	-0.0294	0.0351
R1	586-650	0.2521	-0.038	0.0018
R2	650-714	0.0162	-0.0026	0
R3	714-780	0.0002	0	0

$$Photopic\ L = 179(p1*B1+p2*B2+p3*B3+p4*G1+p5*G2+p6*G3+p7*R1+p8*R2+p9*R3) \qquad (2)$$

$$Circadian\ L = 130(c1*B1+c2*B2+c3*B3+c4*G1+c5*G2+c6*G3+c7*R1+c8*R2+c9*R3) \qquad (3)$$

Equations 2 and 3 illustrate the photopic and circadian luminance (and illuminance) calculations from 9-step multispectral simulations. The coefficients for the photopic and circadian (Rea et al. and Lucas et al) response functions are given in Table 1.

Daylight Spectra

The daylight spectral data are generated in 2nm intervals from the measurements of Correlated Color Temperature (CCT) using the Excel Daylight Series Calculator (Munsell Color Science Laboratory, 2002). The calculation method is based on the definitions of CIE standard illluminants (Wyszecki and Stiles, 2000).

The first set of simulations is performed for 9 am in December 21st, March 21st, and June 21st with a view point facing the East wall (view 2 in Fig. 1). Either a standard CIE sky or an all-weather Perez sky can be utilized in Radiance to generate the sky luminance distributions. However, it is important to note that in their default mode, all of these models assume a white sky throughout the sky dome, regardless of the intensity, location, or the season. For the purposes of the study, the overall color of the sky is altered using the relevant spectral information. Sky luminance distributions are determined with the *gensky* command in Radiance, with specified horizontal diffuse irradiance (-B option) and horizontal direct irradiance (-R option) values. *gensky* is preferred as it allows altering the color of the sky along with the luminance distribution patterns.

December 21st under cloudy sky conditions is selected as the lowest daylight availability. Overcast skies typically produce CCT of 7000 K; daylight with sunlight present is typically measured around 5000 K; and blue skies in summer can range between 10,000 to 25,000 K (Lechner, 2014). The variability between the sky types and the corresponding CCT are based on probable spectral distributions of various sky types: the association of cloudy sky in December to 7000 K, intermediate sky in March to 5000 K, and clear sky in June to 25000 K was done to study the effects of probable sky luminance distribution spectra combinations (Table 2). These sky combinations are indicative of the lighting variability throughout the year under naturally occurring sky types.

Table 2
Global Horizontal Illuminance and CCT values used for the sky models for 9 am

	E	**CCT**
Dec 21st, Overcast sky	2717 lux	7,000 K
Mar 21st, Intermediate sky	13090 lux	5,000 K
June 21st, Clear sky	68440 lux	25,000 K

The horizontal diffuse irradiance (-B option in gensky) is originally associated with a white sky, but the RGB values in the sky dome can be altered from a default white sky (RGB values of 1,1,1) to any color. The color of the sky is defined from the spectral data of a specific CCT; i.e. 9 bins are formed by averaging the spectral data in given intervals. Horizontal direct irradiance (-R option) utilizes the default Radiance model; i.e sun is assumed to be an equal energy white source. Figure 3 illustrates the default white sky model in Radiance along with the colored sky models. Note that both the horizontal illuminance values and the sky luminance values are the same for a default Radiance (white) sky model and the colored sky models; the difference is an overall change of sky color based on the specified CCT. This approach assumes uniform color throughout the skydome. Future research is planned to develop sky models that support color variation based on orientation in the sky dome.

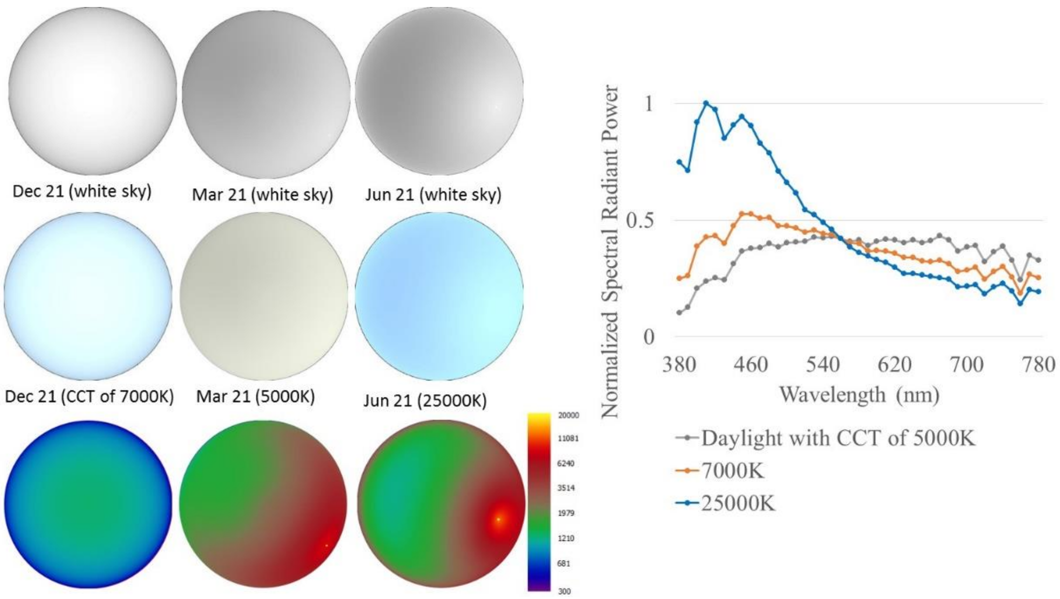

Figure 3 Simulation of overcast sky in December 21, intermediate sky in March, and clear sky in June at 9 am: the original white Radiance skies and the colored skies with respective CCTs yield the same sky luminance

Daily time series simulations are performed from field measurements. These simulations demonstrate that the simulation technique utilized here is not restricted to hypothetical sky models. Field measurements can be utilized to model any sky luminance distribution and the spectra as derived from measured global illuminance values and the measured CCT. The data shown here are collected on April 4, from 8 a.m. to 7 p.m. under partly cloudy sky conditions. Horizontal global illuminance and CCT measurements are recorded (Table 3) using a hand-held chroma meter (Minolta CL-200A). Reindl (1990) method is used via *gen_reindl* command (Reinhart, 2001) to estimate the diffuse horizontal and direct horizontal components. The luminance sky distributions are generated using the intermediate sky option via the *gensky* command in Radiance, with specified horizontal diffuse and horizontal direct irradiance values. CCT measurements are used to determine the spectra of the sky with the Daylight Series Calculator Munsell (Color Science Laboratory, 2002). These time-series studies have been generated for views facing three axial orientations of the conference space (view 1 (N facing window), view 2 (E wall), and view 3 (S wall).

Table 3
Measured global horizontal illuminance and CCT data for daily time series simulations

Apr 4	E(LX)	CCT		E(LX)	CCT
8:00	7094	7245	14:00	83650	5401
9:00	34310	5446	15:00	18820	6873
10:00	50750	5676	16:00	16490	7250
11:00	68030	5545	17:00	43590	5121
12:00	78040	5502	18:00	19030	5169
13:00	75470	5509	19:00	2238	8902

RESULTS AND EVALUATION

As mentioned in the introduction, the levels required for phase shifting is not well established. There are two main issues: 1) the data stems from highly controlled laboratory experiments and their application in real world cases needs further research; and 2) various studies report photopic-lux values generated from a variety of light sources. This is a problematic and incomplete information, as the circadian-lux equivalences can only be computed if the spectral properties of both the light sources and the surface materials were reported. Andersen et al (2012) report that Philips color840 4100K fluorescent tubes were used for the Cajochen et al. (2000) study, and the maximum nocturnal melatonin suppression was achieved around 300 Photopic-lux (Pechacek et al, 2008). Given the lack of material data and assuming neutral surface properties, spectral power distributions of the light source was singularly considered to calculate the equivalent of 300 photopic-lux in circadian-lux units, and it is 80. This number is used as the criteria in this paper as a criteria for instigating 100% circadian response (Figure 4).

Photopic and circadian values are illustrated for varying sky luminance distributions and sky spectra for the solstices and equinox in Figure 5. The hemispherical fisheye images are generated to simulate the viewpoint of a person sitting at the conference table (camera or eye height 1.22 m). The illuminance value at the camera and/or at the eye is derived by integrating the luminances from the hemispherical fisheye imagery and multiplying with π.

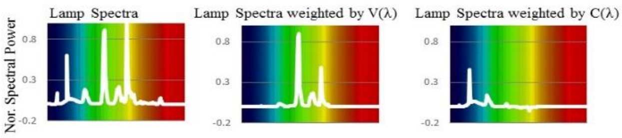

Figure 4 a) The spectral distribution of Philips color840 4100K fluorescent tube, b and c) lamp spectra weighted by photopic and circadian curves

In the studied scene, the right wall is partitioned into two, where one half is assigned a circadian-rich color (blue, Macbeth color #3) and the other half is assigned a circadian-deficient color (red, Macbeth Color #15). The results clearly demonstrate the effect of the color choice in Figure 5, where the blue partition always yields higher circadian values in comparison to the red partition.

For the December 21 and March 21 simulations, circadian-illuminances are lower than the photopic-illuminances. The circadian values are too low to facilitate maximum shift in December and March at 9 am for this viewpoint, but it is sufficient for June as it is above 80 circadian-lux. This is not only due to the higher daylight levels of the clear sky in June, but also due to the blue rich spectra of the sky modelled at 25,000 CCT (Figure 5).

Fig. 6 demonstrates the impact of view direction in a daylit room. Three viewpoints of occupants are simulated for March 21st 9 am. The person facing the window receives more photopic and circadian light in comparison to the person sitting parallel to the window. The circadian level for the person facing the window is above criteria to instigate maximum circadian shift. The people facing the East and South walls do not reach to the maximum shift levels.

Illuminance studies have also been carried out as the entire wall surfaces for this conference room varied from blue to red for March 21st at 9:00 am. Blue and red surface materials (Macbeth color patches #3 and #15) have diffuse photopic reflectance values of 18% and 19%, respectively. Therefore, photopic-illuminance values demonstrate that the simulation with the red and blue wall colors yield to similar values; however circadian-lux values are different favouring the blue color (Table 4). The results are particularly striking with June 21st with 25000K CCT. The interactions of the blue-color rich daylighting with blue-colored room surfaces provide much higher circadian-lux values compared to the red-colored one.

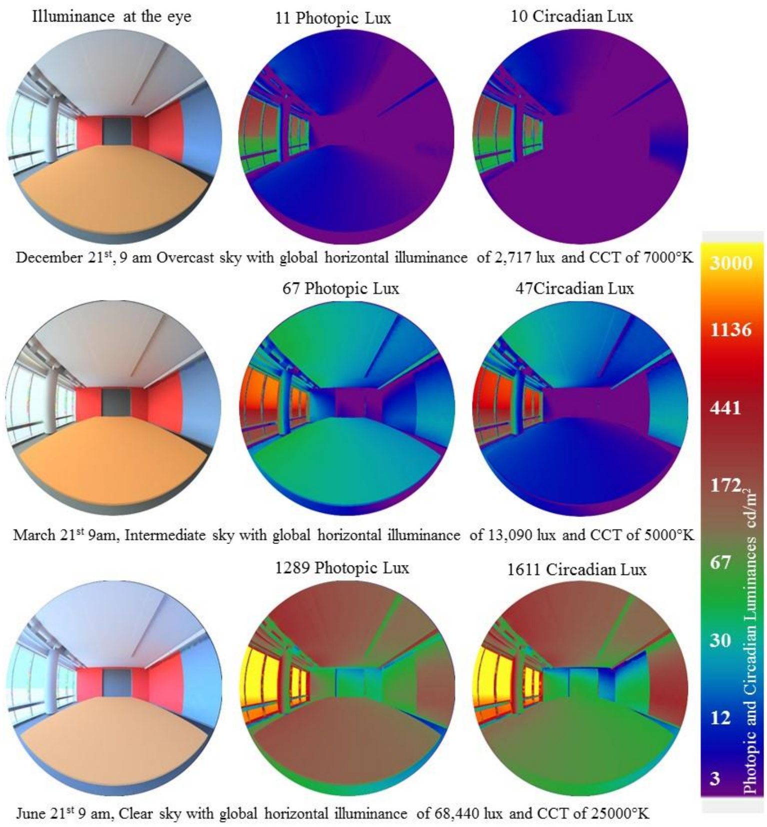

Figure 5 Photopic- and circadian-luminance distributions and illuminance values at the scene for 9 am at selected dates (view looking towards East)

Table 4 Effect of surface colors on the photopic- and circadian-Lux values for different view angles

	 blue vs red walls 						
		View1 (N)		View2 (E)		View3 (S)	
	Lux	Red	Blue	Red	Blue	Red	Blue
Dec	V(λ)	68	68	34	34	11	12
	C(λ)	59	61	27	30	5	7
Mar	V(λ)	339	340	206	208	51	53
	C(λ)	227	232	130	140	15	26
Jun	V(λ)	2560	2558	1236	1273	290	320
	C(λ)	3205	3212	1455	1574	164	309

The results from day-long simulations of April 4 reveal that with the given spectra (Table 3), the circadian-lux values are less than phototpic lux-values; but at 9:00 am, all of the view positions receive circadian-lux levels above 80 circadian-lux. These values should be high enough to impact the circadian system (Fig. 7)

Image formation is believed not to be a component of the circadian system, and ipRGCs are uniformly spread throughout the retina (Rea et al, 2005). As a result, many circadian studies concentrate on irradiance or illuminance, not on luminance. This research incorporates both Circadian-Luminance and Circadian-Illuminance calculations. Generating Circadian-Luminance maps in hemispherical fisheye projections serve three purposes: 1) This process creates graphic representations that can readily convey the effect of material color choice on the circadian resource to design professionals. It is also useful to visualize the impact of photopic and circadian responses at a pixel level. In a research area that is new and growing, better visualization techniques are imperative for the dissemination of knowledge. 2) Derivation of Circadian-Illuminance values at the camera (eye level) from hemispherical fisheye lens images is a straightforward task, it does not require new simulations. 3) There are emerging data that suggest that light coming from the upper visual field or nasal portion of retina is more effective in impacting the circadian rhythm than the same amount reaching from the horizon or the temporal portion (Figueiro et al., 2008). Therefore, simulation of spatial circadian-luminance maps can be useful to study complex built environments.

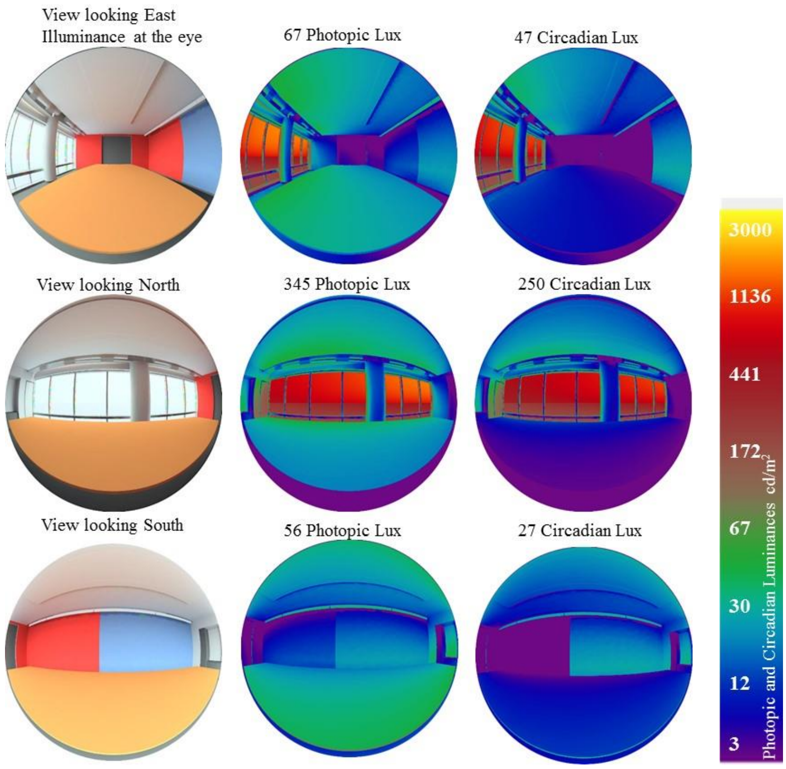

Figure 6 Photopic- and circadian-luminance distributions and illuminance values for March 21st 9 am

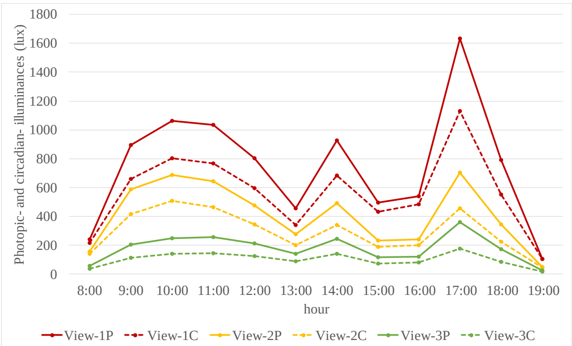

Fig. 7 Daily simulations of photopic- and circadian-illuminances from measured sky data for April 4th under partly cloudy conditions

CONCLUSION

Multi-spectral simulations account for the complex interactions of wavelengths between skies, glazing, color in space, and a point of view. This paper demonstrates that spectral skies can be customized to a site and time; spectral properties of glazings and other material properties can be utilized to achieve better accuracy in lighting simulations. It has also been shown that multi channel outputs can be post-processed for color-based response curves such as photopic- and circadian light values.

Computed per-pixel photopic and circadian luminance maps provide evidence against the current common practices in lighting industry, where color based lighting metrics are rarely used to make design decisions or to establish lighting system installations. Color scheme of a space is determined by the color properties of the light source as well as the color properties of the surface finishes. It is important to realize that the properties of the light emitted by these sources are predominantly modified by spectral transmission and reflection properties of the surrounding architectural surfaces. 3-channel (RGB) spectral simulation is integral to point in time daylighting workflows in Radiance. If a designer or researcher is rendering a view to understand the photopic luminance or glare source, it is a natural step to output the circadian luminance and illuminance from the same render. One obstacle that comes with any lighting simulation is the development of physically accurate material libararies. This task naturally increases with 9-channel simulation, and indicates a need for physically accurate spectral material libraries.

Temporal dosages of light based on hourly increments can be explored in depth for critical times of the year and day using both luminance and illuminance metrics. Calculating circadian illuminance at the eye allows one to estimate a human circadian response, whereas luminance falsecolors allow the designer to understand the circadian light spatially in a complex setting. Researchers using N-step simulation can predict circadian illuminance in research settings to record the luminous environments and develop guideliness. Architects and lighting designers using N-step simulation can begin to predict circadian illuminance in complex environments to inform design solutions that deliver high quality circadian light to the human eye.

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