Simulating Circadian Light: Multi-Dimensional Illuminance Analysis

Phillip H. Ewing¹, John Haymaker², Eve A. Edelstein¹,³,⁴
¹Human Experience Lab, Perkins+Will
²Research Labs, Perkins+Will
³Design + Health CoLab AIA Research Consortium
⁴Center for Healthy Environments NSAD (NewSchool of Architecture & Design)

Abstract
The effects of building design on human circadian rhythms have been linked to health, behavior, and performance outcomes. Limited options, however, are available for predicting circadian stimuli during the design process, other than via quantification of a single variable known as melanopic illuminance. Several additional circadian illuminance quantities (including rhodopic-, cyanopic-, chloropic-, and erythropic-lux) have not, to date, been utilized in simulating circadian exposure. We demonstrate how daylight, spatial, and material choices may alter the contribution of five currently-known photoreceptor channels to regulating circadian rhythms. This novel 3D rendering system will also support future circadian research and applied solutions.

Introduction
Visual and Non-Visual Responses to Light
There is a mounting body of evidence for lighting’s influence on “nearly every physiological, metabolic and behavioral system” (Lucas et al. 2014). Human exposure to light and dark patterns is associated with changes in endocrine function, growth, digestion, core body temperature, reaction times, fatigue, cognitive function and mood states. Research has demonstrated statistically-significant changes in heart rate variability (HRV), a reliable indicator of health risk as well as cognitive engagement, even in the presence of short-term exposure to electrical light (Edelstein et al. 2008). Light therapy has been applied to ameliorate conditions such as seasonal affective disorder (SAD), dementia, the effects of traumatic brain injury, and various sleep disorders; further, it has been used to counteract fatigue from jetlag, night shift work, and even space flight (Zatz [ed.] 2005).

For most of evolutionary history, solar light was the primary stimulus to indicate the time of day, and to entrain human ‘circadian rhythms’, the biological functions that cycle around the time of day. The advent of electrical lighting at the turn of the 20th century, however, has disrupted this relationship. This presents numerous challenges, as well as potential opportunities, for architectural designs that more effectively serve human wellbeing and performance. Indeed, the American Medical Association (AMA) adopted a policy statement in 2012 citing evidence that links circadian rhythm disruption to impacts on human health, including “cell cycle regulation, DNA damage response, and metabolism” (Stevens et al. 2013). Further, the AMA notes that there is accumulating “epidemiologic support for a link of circadian disruption from light at night to breast cancer” (p. 343).

Historically, the scientific community thought that the conventional visual photoreceptors of the human eye – the rod cells and three types of cone cells in the retina – were responsible for entraining these circadian rhythms. Relatively recently, however, Brainard et al. (2001) and Thapan et al. (2001) discovered a new category of photoreceptors: intrinsically photosensitive retinal ganglion cells (ipRGCs). These cells are primarily responsible for ‘non-visual’ processing of light integrated over time. These cells – and associated retinal bio-circuitry that include the rods, cones, and various connector cells – transmit neural signals to a part of the brain known as the suprachiasmatic nucleus (SCN), the body’s ‘master’ circadian clock. The SCN, in turn, innervates a complex network of neural and endocrine systems that send hormones coursing through the blood stream, and influence the brain, mind, body, and behavior. To date, however, most physiological models of human retinal function continue to quantify light in terms of the visual responses of the rods and cones alone. In particular, the commonly-used photopic spectral sensitivity function (also known as the ‘luminosity’ function in color science and related disciplines) describes the contributions of mostly long- and middle-wavelength cone cells to an aspect of visual function that hardly includes shorter wavelengths of light. This photopic function ($V(\lambda)$, or $y(\lambda)$) is derived from the CIE RGB model of color perception, and used as the color matching function for the Y channel in the tristimulus CIE XYZ color space model, first published by the Commission Internationale de L’Eclairage (CIE) in 1932. Although updates have been made, the original RGB and XYZ models are still widely used in colorimetric applications, and still remain the basis for the Système International (SI) photometric units.

Visual Lighting Simulation and Rendering Systems
As a result of this narrow focus, a majority of conventional lighting simulation software platforms compute the
appearance of light and materials in the form of red, green and blue (RGB) color channels. The behavior of light in the real world however, is a complex interplay of various wavelengths of light being emitted from, transmitted through, and reflected off various physical objects in the environment. Although it is computationally efficient to collapse the representation of light into three primary values – as opposed to performing raytracing calculations for every wavelength of light at every point in a given field of view – tristimulus-based simulations pose known discrepancies in relation to the accurate simulation or perception of light. Since it is possible for two materials with different spectral reflectances to correspond to the same RGB value under certain lighting conditions – a phenomena known as metamerism (Wyszecki and Stiles 2000)– RGB-based calculations can, and occasionally do, yield incorrect color or illuminance values for certain scenes. Further, the CIE RGB color model and the associated photopic spectral sensitivity function are known to distort the complex contribution of blue light to color and illuminance perception for the sake of developing a linear, additive model for photometric units (Rea and Figuerio 2010).

**Melanopic Lighting Simulation and Rendering Systems**

Further, the CIE RGB color space and associated models do not correspond precisely to our current knowledge of the non-visual, circadian impact of light. Over the past decade, however, much attention has been placed on analyzing the role of ipRGCs, which have the greatest photosensitivity to light with wavelengths in the range of 447-484 nm (roughly the ‘blue-cyan’ portion of the visible electromagnetic spectrum for a monochromatic light source; included in Figure 1) (Lucas et al. 2014). Since ipRGCs gain their photosensitivity from the presence of a photopigment known as melanopsin, various curves have been proposed in scientific literature for characterizing the spectral sensitivity of ipRGCs have often been referred to as ‘melanopic’ functions. In contrast, the CIE photopic spectral sensitivity function, which describes visual perception of brightness, has a peak at 555 nm (corresponding to ‘tennis ball yellow’ in appearance), and groups together the response of all of the associated retinal bio-circuitry into a single metric of photopic illuminance. A number of researchers have developed methods for simulating the melanopic component of circadian illuminance in the context of building design. Rea et al. (2012) incorporated biological research in their Circadian Stimulus (CS) calculator, which includes the effects of sub-additivity and color opponency processes in its version of a melanopic spectral sensitivity function, and facilitates the calculation of circadian efficiency for a given light source. Inanici et al. (2015) implemented a full-spectral rendering technique developed by Ruppersberg and Bloj (2006, 2008) as the basis from which the authors calculated melanopic illuminance for given 3D scenes. This technique is further developed in their Lark Spectral Lighting Tool for lighting simulation and rendering (Inanici and ZGF Architects 2015). Based upon this increasing body of research, melanopic illuminance analyses are now informing the building design profession. For example, the International WELL Building Standard (International WELL Building Institute 2016), recently provided a computational method to calculate equivalent melanopic lux (EML), and have recommended minimum EML exposure durations and illuminance guidelines for projects seeking WELL certification.

**Pentachromatic Lighting Simulation**

By focusing on melanopic illuminance alone, however, these systems do not consider the complex, nuanced contribution of other circadian functions. More recent findings demonstrate that multiple retinal and physiologic factors, including the rods, cones and ipRGCs, contribute to non-visual as well as visual mechanisms. Ho Mien et al. (2014) demonstrated that alternating red light – light with wavelengths beyond currently-proposed peak spectral sensitivity ranges for melanopsin – can mediate circadian phase resetting of physiologic rhythms in some individuals. Their results also show that sensitivity thresholds differ across non-visual light responses, suggesting that cones may contribute differentially to circadian phase resetting, melatonin suppression, and the pupillary light reflex during exposure to continuous light. Gooley et al. (2012) further demonstrate that rods, cones, and ipRGCs play different roles in mediating pupillary light responses during exposure to continuous light, and suggest that it might be possible to enhance non-visual light responses to low-irradiance exposures by using intermittent light to activate cone photoreceptors repeatedly in humans. Lucas et al. (2012) reviewed electrophysiological and behavioral data to provide a model in which each photoreceptor class plays a distinct role in encoding the light from the environment. As the intact retina is a composite of extrinsic (rod/cone) and intrinsic (ipRGC) mechanisms, the authors propose that all three photoreceptor classes, including the ipRGCs, contribute light information to the brain’s circadian clock.

![Probability-Normalized α-Opic Sensitivity Curves](image-url)

**Figure 1:** The five α-opic spectral sensitivity curves recommended by Lucas et al. (2014), along with the photopic function for reference. As further recommended by the authors, each curve has been ‘probability-normalized’ or scaled for equal area underneath each curve. The color of each curve (excluding the photopic function) roughly corresponds to the apparent color of the peak wavelength.
A seminal paper published by leading experts in circadian research noted that currently, “the most appropriate use of that capacity [referencing the ability to record or simulate the spectral power distribution of light sources] would be to calculate the effective irradiance experienced by each of the rod, cone and melanopsin photoreceptors capable of driving non-visual responses” (Lucas et al. 2014, p. 6). They devised a new light measurement strategy that takes into account these complex non-visual mechanisms, and categorized illuminance stimuli into five individual photoreceptor components: cyanopic (short-wavelength cones), chloropic (medium-wavelength cones), erythropic (long-wavelength cones), rhodopic (rods), and melanopic (ipRGCs) illuminance quantities. Each of these photoreceptor components (collectively referred to as ‘α-opic’ components) have different spectral sensitivity curves (see Figure 1). In addition, the authors provided a spreadsheet for calculating these illuminance quantities for a given light source of a specified spectral power distribution and photopic illuminance value.

**A Novel Pentachromic Lighting Simulation and Rendering System**

While the spreadsheet developed by Lucas et al. (2014) allows for calculation of multiple circadian illuminances given a single light source of known spectral power distribution, the building professions must also begin to consider how light reflection, absorption and transmission through building materials may alter lights’ spectral characteristics and impact circadian exposure calculations. In addition, designers must consider each occupant’s field of view and exposure to light as it interacts with the geometry and spatial arrangement of materials. The calculation methodology to be presented in this paper addresses these considerations; further, it is applicable to all building types, as the circadian impact on human function is relevant to any place that humans occupy (Edelstein et al. 2008).

In order to simulate circadian light in ways that incorporate the varying photoreceptor functions mentioned above, we developed a raytracing-based computational method to render the spectral reflectance and transmission of daylight entering and interacting with a 3D model, from a user’s singular point of view and location, at a particular date and time. These analyses are carried out across an arbitrary number of spectral channels or bins (nine, in the case of this paper), as opposed to conventional three-channel raytracing and simulations.

**Methodology**

**Setting**

Sprout Space,™ (Figure 2) a high-performance, modular, single-room classroom system, was used as a vehicle for exploring the impact of conceptual design and material choices on metrics describing circadian exposure. A digital model was developed at geographic coordinates and EPW weather conditions for Los Angeles, CA (34.0522°N, 118.2437°W). June 21, 9:00AM PDT was the chosen date and time for all analyses performed. The sky dome color correlated temperature (CCT) was set to 12,000K; this is consistent with typical blue sky CCT measurements occurring in the range of 9,000-25,000K (Lechner 2014). No artificial light sources were included in the model. The chosen viewpoint for the analyses is in the center of the classroom, standing height (chosen as 1.829 m above finished floor), looking straight north, with a view angle towards two windows facing northeast and northwest, respectively. A 0.6 m roof overhang extended around the entire building. Matte-finish Munsell color chip reflectance spectra, measured in 1 nm increments and compiled by Spectral Color Research Group at the University of Eastern Finland (n.d.), are used as proxy data for simulating opaque material choices. Spectral properties for glazing choices, measured in 5 nm increments, were retrieved from the International Glazing Database 14-5 (Lawrence Berkeley National Laboratory 2011). Material data included in the analysis are provided in Tables 1 and 2.

**Calculation Methodology**

We extend the calculation methods proposed by Inanici et al. (2015) to include coefficients for circadian illuminate in rhodopic-, cyanopic-, chloropic-, and erythropic-lux for nine-channel spectral lighting simulations to be performed using the Radiance Lighting Simulation and Rendering System (Ward 1994). In Radiance, three-channel (RGB) lighting calculations and how they relate to photopic lumiance or illuminance quantities can be described as shown in Equation 1:

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

where the coefficients for Radiance are defined as R (586-780 nm), G (498-586 nm), and B (380-498 nm) to correspond to each channels’ relative contribution to photopic lumiance. The luminous efficacy factor for equal-energy white light in Radiance is 179 (lm/W). Some readers may note that the peak spectral efficiency of the photopic luminosity function is 683.002 lm/W at 555 nm, approximately corresponding to ‘tennis ball yellow’ in apparent color. Lighting in Radiance, however, is considered spectrally-neutral and not ‘tennis ball yellow’, and the factor 179 corresponds to average luminous efficacy for all visible wavelengths of light (380-780 nm).

The nine spectral bin intervals proposed by Inanici et al. (2015) are also retained for the purposes of this analysis.
Table 1: Munsell color chip reflectance spectra to be included in α-opic illuminance analyses.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5R 9/2</td>
<td>Pale Red</td>
</tr>
<tr>
<td>5R 4/12</td>
<td>Medium Red</td>
</tr>
<tr>
<td>5YR 6/12</td>
<td>Medium Red-Yellow</td>
</tr>
<tr>
<td>5YR 2.5/1</td>
<td>Dark Red-Yellow</td>
</tr>
<tr>
<td>5Y 7/10</td>
<td>Medium Yellow</td>
</tr>
<tr>
<td>5GY 8/10</td>
<td>Medium Green-Yellow</td>
</tr>
<tr>
<td>5BG 5/8</td>
<td>Medium Blue-Green</td>
</tr>
<tr>
<td>5PB 6/10</td>
<td>Medium Purple-Blue</td>
</tr>
</tbody>
</table>

'Specification' denotes the official Munsell name for the material, whereas 'Description' denotes the name to be used in this paper.

Table 2: Munsell color chip reflectance spectra to be included in α-opic illuminance analyses.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilkington North America Optiwhite</td>
<td>Clear Glazing, TVis = 0.91</td>
</tr>
<tr>
<td>Hankuk Glass Industries Inc. HanGlas Hanlite Green 8mm</td>
<td>Green-Tinted Glazing, TVis = 0.68</td>
</tr>
<tr>
<td>Pilkington North America Graphite Blue</td>
<td>Blue-Tinted Glazing, TVis = 0.61</td>
</tr>
</tbody>
</table>

'Specification' denotes the IGDB manufacturer and product name for the selection, whereas 'Description' denotes the name to be used in this paper.

This allows for increased spectral resolution over typical three-band increments, in order to more accurately capture inflections in lighting and material spectral data, as well as each of the various α-opic spectral irradiance or functions. The 24 illuminance analyses and raytracings of the example model included in this paper can be completed within the course of an 8-hour working day. Finer spectral resolution may be achieved by designating more bins, at the cost of performing additional renderings and incurring additional analysis time.

Spectral photosensitivity functions \(N_{\alpha}(\lambda)\) (also referred to as ‘filters’ for shorter reference) for the five human photopigments included by Lucas et al. (2014) in the Irradiance Toolbox spreadsheet, normalized to unity in surface \(\int_{380}^{780} N_{\alpha}(\lambda) d\lambda = 1\), are integrated over each of the nine spectral bins as follows (Equation 2):

\[
c_{\alpha,n} = \frac{\lambda_{n,1} - \lambda_{n,0}}{\lambda_{n,1} - \lambda_{n,0}} \sum_{\alpha} \int_{\lambda_{n,0}}^{\lambda_{n,1}} N_{\alpha}(\lambda) d\lambda
\]  

(2)

where \(c_{\alpha,n}\) is the spectral band coefficient to be calculated, \(\lambda_{n,1}\) and \(\lambda_{n,0}\) are the corresponding boundaries in nm for the given spectral bin, and \(\int_{380}^{780} N_{\alpha}(\lambda) d\lambda = 1\). This yields the following coefficients shown in Table 3. For melanopic illuminance, we use the Lucas et al. (2014) spectral sensitivity function. As bin coefficients were summed from data interpolated (Catmull spline) to 1 nm resolution from the original 5 nm data in Lucas et al.’s (2014) supplementary Irradiance Toolbox spreadsheet, bin intervals were also start-offset by 1 nm from the values defined by Inanici et al. to avoid overlapping values at bin boundaries. It should be noted that Inanici et al.’s (2015) approach uses photopic and melanopic spectral sensitivity functions of equal peak amplitude (683 lm/W), whereas Lucas et al. (2014) and the methodology presented here begin with spectral photosensitivity functions of differing amplitude, but with equal areas under each curve (refer to Figure 1). Both methods aim to offer mathematical convenience in the sense that α-opic illuminance quantities have similar orders of magnitude, and can be more readily compared to each other in a given set of analysis results. It should not be construed, however, that the magnitude of each quantity implies any ‘functional’ weighting with respect to photoreceptors’ contribution to circadian responses, as further scientific research is needed to accurately describe the relative contribution of each photoreceptor to circadian responses, as well as under what scenarios.

Next, raytracing analyses for each of nine spectral bins are performed in Radiance. For materials, the reflectance or transmittance quantities for each run are derived by taking the average reflectance or transmittance over each spectral bin. These material spectral reflectance or transmittance quantities are then assigned, three at a time, to sub-analyses in order to perform illuminance calculations and renderings in Radiance.

To calculate α-opic illuminance (or per-pixel α-opic luminance for renderings) each spectral bin result \(p_{\text{bin}}\) in radiometric units (watts, W) is weighted by a corresponding \(c_{\alpha,n}\), summed, and scaled by the 179 lm/W Radiance luminous efficacy constant (Equation 3):

\[
L_{\alpha} = 179 \sum_{i=1}^{n} \frac{c_{\alpha,n} p_{\text{bin}}}{n} \tag{3}
\]

In the specific case of the analyses performed in this paper, this calculation may be simplified to a notation similar to the equations given in Inanici et al. (2015), as shown in Equation 4:

\[
L_{\alpha} = 179(c_{\alpha,1} p_{1} + c_{\alpha,2} p_{2} + c_{\alpha,3} p_{3} + c_{\alpha,4} p_{4} + c_{\alpha,5} p_{5} + c_{\alpha,6} p_{6} + c_{\alpha,7} p_{7} + c_{\alpha,8} p_{8} + c_{\alpha,9} p_{9}) \tag{4}
\]

An important note is that here, the Radiance luminous efficacy constant 179 lm/W is held constant for all of the α-opic illuminance calculations, and is not scaled as in Inanici et al. (2015). This is to conform with the recommendation by Lucas et al. (2014) in their Irradiance Toolbox spreadsheet documentation that the various α-opic illuminance values are always equal to photopic illuminance (and each other) for a theoretical equal-energy radiator. Inanici et al. (2014) recommend a melanopic luminous efficacy constant of 148 lm/W for the Lucas et al. (2014) melanopsin photosensitivity curve and 130 lm/W for the Rea (2005) version. Melanopic illuminance results
Table 3: Nine spectral analysis bins and corresponding weighting coefficients for calculating α-opic illuminances.

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>Wavelength</th>
<th>Erythropic</th>
<th>Chloropic</th>
<th>Rhodopic</th>
<th>Melanopic</th>
<th>Cyanopic</th>
<th>Photopic</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>380-422</td>
<td>0.005353</td>
<td>0.006532</td>
<td>0.012830</td>
<td>0.017681</td>
<td>0.141026</td>
<td>0.000421</td>
</tr>
<tr>
<td>B2</td>
<td>423-460</td>
<td>0.027821</td>
<td>0.050377</td>
<td>0.124047</td>
<td>0.184631</td>
<td>0.618178</td>
<td>0.009797</td>
</tr>
<tr>
<td>B3</td>
<td>461-498</td>
<td>0.083861</td>
<td>0.157113</td>
<td>0.290932</td>
<td>0.398948</td>
<td>0.230136</td>
<td>0.053295</td>
</tr>
<tr>
<td>G1</td>
<td>499-524</td>
<td>0.119148</td>
<td>0.181933</td>
<td>0.246991</td>
<td>0.247485</td>
<td>0.009820</td>
<td>0.131072</td>
</tr>
<tr>
<td>G2</td>
<td>525-550</td>
<td>0.169969</td>
<td>0.216596</td>
<td>0.199600</td>
<td>0.118204</td>
<td>0.000748</td>
<td>0.224349</td>
</tr>
<tr>
<td>G3</td>
<td>551-586</td>
<td>0.279473</td>
<td>0.260651</td>
<td>0.111940</td>
<td>0.033460</td>
<td>0.000074</td>
<td>0.316548</td>
</tr>
<tr>
<td>R1</td>
<td>587-650</td>
<td>0.292456</td>
<td>0.124616</td>
<td>0.013745</td>
<td>0.002134</td>
<td>3.91E-06</td>
<td>0.248866</td>
</tr>
<tr>
<td>R2</td>
<td>651-714</td>
<td>0.021719</td>
<td>0.002299</td>
<td>0.000087</td>
<td>0.000134</td>
<td>3.91E-06</td>
<td>0.248866</td>
</tr>
<tr>
<td>R3</td>
<td>715-780</td>
<td>0.000249</td>
<td>0.000022</td>
<td>1.02E-06</td>
<td>1.73E-07</td>
<td>0.000201</td>
<td>0.000201</td>
</tr>
</tbody>
</table>

Results and Evaluation

Design Decision-Making

Although the precise impact of different and combined dosages of the various circadian illuminance levels are not yet well-defined in the scientific literature, it is possible to compare the impact of design choices to each other based on their impact on the various components of circadian illuminance. This paper limits its scope of decision-making to visualization and analysis of design choices on maximizing or minimizing each α-opic illuminance value.

Results

In Figure 3, the false-color scale (y-axis) shows the difference from the photopic visible spectrum, with the greatest difference in yellow (12,000 cd/m²) and no difference in purple (0.00 cd/m²). In the baseline condition with the yellow-green wall (Figure 3a-3f), the greatest absolute difference from photopic luminance is observed with the cyanopic filter (3d), and a moderate difference is seen with the rhodopic (3b) and then melanopic (3c) filters. The least difference is observed with the erythropic (3f) and then chloropic filters (3e). In the test condition with a purple-blue wall (Figure 3g-3l), the false-color scale also shows the greatest difference from the photopic filter (3g) with the
cyanoopic filter (3j). However, the compared to the baseline room condition in the row above, there is greater change in the melanopic (3i) than in the chloropic (3h) filter. The least change is observed in the erythropic (3l) rather than in the chloropic filter (3k).

We observe almost no difference for $\alpha$-opic quantities on the ceiling in the baseline scenario. Aside from the dark color of the ceiling limiting reflected light in general, another observation would be that if any differences in $\alpha$-opic luminances were to occur due to reflected light from the yellow-green walls, we might expect the yellow-green-sensitive chloropic filter to most strongly illustrate such differences (3e). Since the photopic filter is already heavily weighted towards the chloropic filter, little difference occurs in this scenario. In contrast, when the purple-blue wall is introduced (Figure 3g-3l), we see some absolute difference in the ceiling luminances in the rhodopic (3h), melanopic (3i) and cyanopic (3j) filters, which are all in the blue range of the spectrum.

The $\alpha$-opic illuminance values in Figure 4 show changes for each decision variable of wall, ceiling, floor or glazing materials. Across all of the trials, we notice that cyanopic illuminances are typically the highest among the various $\alpha$-opic illuminance quantities. This makes sense, given the short-wavelength (‘blue’) light from the clear blue sky is the dominant light source in the scene. It is also noticeable that the photopic illuminance quantities for each run are often more similar to the chloropic and erythropic illuminance quantities than to other $\alpha$-opic illuminance quantities. This is consistent with Rea and Figuerio’s (2010) discussion of how photopic spectral sensitivity weightings (defined by the luminosity function $V(\lambda)$) are primarily derived from the photosensitivities of medium-wavelength cones (chloropic-lux) and long-wavelength cones (erythropic-lux). Further, in our wall analysis trials (Figure 4a), the ‘spike’ in photopic illuminance for a medium yellow wall material is mirrored in the chloropic and erythropic illuminance quantities, but not the rhodopic, melanopic or cyanopic illuminance quantities.

The ceiling material trial (Figure 4b), $\alpha$-opic illuminance values typically increased for all changes from the baseline analysis run. Given the dark material chosen for the ceiling (a dark-red Munsell color sample), it makes sense that lighter materials would generally reflect more light and increase illuminance almost across all $\alpha$-opic quantities. The peak values for each $\alpha$-opic illuminance quantity, however, correspond with the peak reflected wavelength of each material. For chloropic illuminance, which reflects the spectral photosensitivity of medium-wavelength or ‘green’ cone cells, medium blue-green ceiling material results in the highest chloropic-lux value.

Conversely, $\alpha$-opic illuminance quantities typically decreased for almost every alternative floor material choice (Figure 4c), compared to the baseline analysis run. Since the baseline floor material reflectivity was relatively high to start, it makes sense that the series of darker material alternatives generally absorbed more light and decreased $\alpha$-opic illuminances.

In the glazing material trial (Figure 4g), clear glass ($T_{vis} = 0.91$), unsurprisingly, yields the greatest $\alpha$-opic illuminance values. The green-tinted glass ($T_{vis} = 0.68$) yielded greater $\alpha$-opic illuminance values than the blue-tinted glass.
Figure 5: Parallel coordinates plot of different material inputs and illuminance levels.

Legend: Each y axis denotes a particular design parameter or feature; input parameters for each run are denoted in the left half, and results are denoted on the right half. The black line denotes the baseline configuration; the purple line denotes the impact of changing the walls to a purple-blue material; the light orange line denotes the impact of increasing ceiling specularity ($S = 0.2$) while holding all other variables constant; the dark orange line denotes the same, for an intermediate specularity ($S = 0.1$); the green line denotes the impact of green-tinted glazing ($T_{vis} = 0.68$); the blue line denotes the impact of blue-tinted glazing ($T_{vis} = 0.61$).

(Tr = 0.61), which yielded the lowest $\alpha$-opic illuminance values among all of the 24 analysis runs. This result may demonstrate the effect of reduced visual transmittance for the green- and blue-tinted glazing selections on visual transmittance compared to the clear glazing. Continued exploration of the design decision space would be a way of further evaluating this finding.

The parallel coordinate plot in Figure 5 explores the interaction of multiple architectural variables on the $\alpha$-opic illuminance values for the Sprout Space design alternatives. This method allows visualization of interactions that can be a useful design tool to evaluate a series of decisions. The physical input variables are plotted on the left side of the graph, and the resultant $\alpha$-opic illuminance values are plotted on the right. The black line represents the initial baseline run using Munsell colors of yellow-green walls, a dark red ceiling, a pale red floor, and clear glazing.

Relative to this baseline, increasing the ‘shininess’ or specularity $S$ of the dark red ceiling surfaces (up to $S = 0.2$) was associated with the largest values across photopic, rhodopic, melanopic, chloropic and erythropic illuminance quantities (Figure 5, light orange line), as well as a relatively high value for cyanopic illuminance. The intermediate setting for ceiling specularity ($S = 0.1$), however, shows a decrease in the various $\alpha$-opic illuminances compared to the ‘shiniest’ ceiling (Figure 5, dark orange line).

However, a change to purple-blue walls (Figure 5, purple line), even with the lowest specularity settings for ceiling, walls and floor ($S = 0.0$), yields a clear cyanopic peak (with ceiling, floor, and glazing colors maintained at the baseline design configuration).

In comparison to clear glazing used in the baseline condition, the introduction of a green-tinted glazing with a lower transmittance ($T_{vis} = 0.68$), demonstrates a drop in all $\alpha$-opic illuminance values (Figure 5, green line). Here, we again see that the blue glazing material (Figure 5, blue line) tested had the lowest transmittance ($T_{vis} = 0.61$), and yielded the lowest $\alpha$-opic illuminance values.

A more systematic exploration of the design space and continued evaluation of such interactions are needed to validate these findings, and to understand more precisely how changes to material properties, geometries and proximities may impact $\alpha$-opic illuminance quantities.

**Conclusion**

Current physiologic research demonstrates that a pentachromatic visual system influences human circadian responses, and yet few simulation and rendering techniques have attempted to calculate more than a single melanopic function. The methods reported in this paper demonstrate the computation and rendering of light in terms of five retinal irradiance functions, which may then be applied to architectural design scenarios and design decision processes. In addition, the system described shows the disparate impact that material choices may have on the interactions between the various $\alpha$-opic spectral irradiance functions, simulated in both visual and false-color renderings.

With this tool, we can use visual pattern and color recognition to rapidly assess where maximal circadian exposure would occur. With this tool, the differential impact of each
filter can be computed, simulated and predicted in isolation and in combination with changes to material parameters. The literature to date shows us that these different opic filter impact human outcomes. By using this tool in combination with on-site, real-world and empirical studies, we can advance our understanding of the relative impact of each retinal irradiance function in human terms.

Although it is not yet possible to predict the relative impact of each retinal irradiance function, the value of continued research is clear. Clinical studies confirm the deleterious effects of both over and under exposure to light on the brain, mind, body and behavior. Yet, lighting trends and preferences often result in exposure to unnatural wavelengths and intensities, and the pervasive use of computer monitors, smart screens, and street lighting systems add further risk to human health.

However, the development of programmable LED lighting systems may provide the dynamic control necessary for each individual to tune their lighting exposure to their visual acuity, circadian status, and non-visual sensitivities. The output of such lighting systems would take into account the effects of circadian exposure that vary as a function of time, duration, and wavelength of light.

With the advancement of research that defines the specific influences of different wavelengths, rendered simulations may assist in guiding architectural programming, planning and design. The design of the material properties, spatial geometries, and architectural fenestration will offer a more nuanced means to optimize light for human visual and circadian health.

References


