Multispectral Lighting Simulation Approaches for Predicting Opsin-driven Metrics and their Application in a Neonatal Intensive Care Unit

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Abstract

Design decisions affect the intensity, spectra, and duration of light exposure in built environments, which in turn affects the health of occupants. Recent research shows that the neuropic light influences thermoregulation and metabolic rate. The aim of this paper is to i) discuss design decisions and their effect on photopic, melanopic, and neuropic light, and ii) to equip the multispectral lighting simulation tool (Lark v.3.0) with new features, including the computation of the neuropic light stimulus. Sample workflows are demonstrated through a neonatal intensive care unit (NICU) design. Results show the intensity of light strongly determines the magnitude of all light-induced responses, and electric light with specific spectral qualities can be used to supplement deficient spectral quantities. Design decisions for healthy lighting such as choice of glazing, electric light, and dynamic shading practices are discussed through multi-spectral lighting simulations and photobiological response analyses.

Highlights

- Spectral irradiance weighted with light-induced response curves to derive photobiological metrics
- Calculation of equivalent neuropic lux in addition to photopic and melanopic illuminances
- Evaluation of daylighting and programmable electric lighting in a neonatal intensive care unit

Introduction

There are increasing numbers of applications that require the computation of the lighting spectra along with intensity. Multispectral lighting simulations enable the computation of both the visual impacts (such as accurate prediction of color appearance, color temperature, and color rendering indices) and the non-visual impacts of light (prediction of circadian rhythm metrics).

There are a few existing tools that utilize multispectral simulations, such as Lark Spectral Lighting (Inanici et al., 2015), ALFA (Solemma, 2018), and OWL (Maskarenj et al., 2022). Lark is an open-source plugin in Rhino Grasshopper environment and the new release (v.3.0) includes an additional non-visual metric (neuropic illuminance and luminance), which is not available in other tools at this time. Neuropic light stimulus regulates temperature and metabolism (Zhang et al., 2020), and the photoreceptors for the neuropic response peak in the violet range of the visible spectrum. However, most glazing types filter the ultraviolet (UV) and violet portion of the spectra, and electric light sources are typically violet deficient. There is a need for continued development of tools to improve their accuracy and applicability in different settings.

Lark Spectral Lighting

As an open-source plugin in the Rhino Grasshopper environment, Lark has been developed by different research teams (Lark v.0 and v.1.0, Inanici et al, 2015, and Lark v.2.0 Gkaintatzi-Masouti et al., 2022). Lark is a Radiance-based simulation tool that differs from standard lighting simulations as follows:

- It is a simulation technique that utilizes *n* number of channels to approximate the spectral power distribution of light between 380nm and 780nm. Simulating each wavelength as a separate channel is not feasible, but increasing the number of channels beyond the conventional three-channel (RGB) format is necessary to accurately simulate the narrow-band spectral variability in light sources and materials along with different photobiological responses that span and peak at different wavelengths. In Lark, the spectrum is divided into 9 consecutive wavebands. Each set of 3 channels is simulated as a separate simulation and combined in a post-process. The number of wavebands can be increased with additional simulations.
- Sky, modeled as an equal-energy white light source in standard simulations, is colored in Lark based on global horizontal spectra or a Correlated Color Temperature (CCT).
- Apart from photopic quantities, Lark v.0-2.0 reports melanopic illuminance and luminances.

Lark has been compared against physical measurements and other software, with positive outcomes (Balakrishnan and Jakubiec, 2019; Jakubiec and Alight, 2021; Pierson et al., 2021, 2022; Inanici et al, 2022). However, continued development is needed to improve accuracy, and usability, and to align with new findings of the fast-paced circadian lighting research. The objective of this paper is to develop and demonstrate new features for Lark v.3.0. Although the tool remains a general-purpose multispectral simulation software, its capabilities are demonstrated through a NICU design and analysis.

Opsin-driven metrics and their implementation in the simulation tool

Opsins

Opsins are types of proteins that interact with light-sensitive chemicals to enable vision, circadian rhythms, and other light-induced reactions in living organisms (Oakley and Plachetzki, 2010). Photopsin (Opsin1) facilitates color vision through short-, middle-, and long-wavelength sensitive cones. Rhodopsin (Opsin2) facilitates scotopic (night-time) vision. Encephalopsin (Opsin 3), Melanopsin (Opsin 4), and Neuropsin (Opsin 5) are the photoreceptors that regulate circadian rhythms.

Recent research shows that certain neurons inside the brain detect violet light, and these neurons influence body functions, including temperature and metabolism (Zhang et al., 2020). Although it was known that lighting spectra impact human health via visual, circadian, neuroendocrine, and neurobehavioral responses (IES, 2008), the new discovery is significant as it is pointing to the impact of the violet region of the spectra on human health. Another study (Jiang et al., 2021) suggests that violet light could prevent myopia progression. Additionally, Zhang et al.'s research (2020) adds to the growing body of literature showing that photoreceptors are found not only in the retina but also expressed in the skin (Suh et al, 2020).

These preclinical and clinical findings have implications for how we design indoor luminous environments. As a continuous, full-spectrum source, daylight includes violet-rich light. However, daylight in indoor environments is filtered through glazing, and most glazing types filter the ultraviolet (UV) and violet portion of the spectra. Similarly, most electric light sources are violet deficient. It should be noted that UV rays can be harmful. They may cause skin burns as a result of short-term exposure; premature aging, skin cancer as a result of prolonged exposure, and retinal damage (CDC, 2022). However, as discussed above, there is increasing evidence that the violet portion of the spectra is beneficial. To explore how light affects human development and metabolism, the researchers at the Cincinnati Children's Hospital have implemented a programmable full-spectrum lighting system as part of their new NICU (CCH Research Horizons, 2021). The geometry of the setting in this paper is modeled based on the Cincinnati Children's Hospital Medical Center's private, single-patient NICU, completed in 2022.

Computation of opsins

Researchers and lighting designers simulate photopic light to study the visual environment. The photopic response curve peaks at 555 nm. Multispectral lighting simulation tools compute melanopic light that peaks at 490 nm to study its impact on sleep-wake cycles and alertness.

Although the action spectrum for encephalopsin is not well understood, research provides an action curve for neuropsin (Kojima et al., 2011). Neuropsin is active between 303 and 460 nm, peaking at 380. As a new feature, Lark v.3.0 computes neuropsin, but the spectral range is limited between 380 and 780 nm in computations to exclude the harmful effects of light below 380 nm.

Lark v.3.0 also differs from the previous versions in its segmentation of its nine channels. The updated segmentation offers a better use of the output of each channel based on photopic, melanopic, and neuropic efficiency functions. The RGB channels in Radiance are further divided into 3 channels. While the blue channel is divided into equal three parts, the green, and the red channels have variable lengths to better represent the slope of the melanopic and photopic curves (Figure 1). The intervals and the corresponding coefficients for 3 and 9 channels are computed and provided in Table 1.

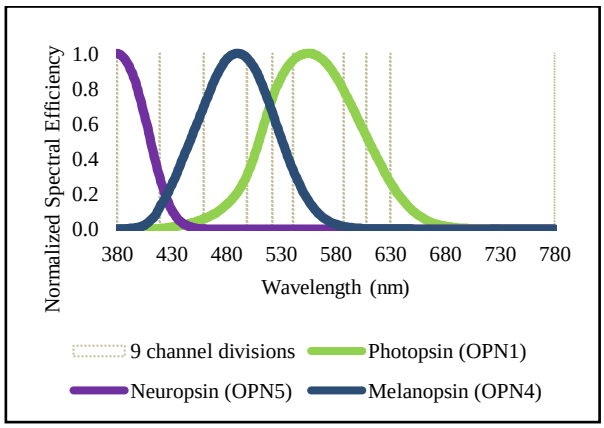


Figure 1: Normalized spectral efficiency curves for photopsin, melanopsin, and neuropsin and the 9-channel divisions.

Table 1: Photopic, melanopic, and neuropic coefficients for 3 and 9 channel divisions. The coefficients are calculated between 380 and 780 nm.

	Wavelength (nm)	Photopic (Pcoef)	Melanopic (Mcoef)	Neuropic (Ncoef)
3 channels				
R	587-780	0.265	0.0021	0
G	499-587	0.67	0.3911	0
B	380-499	0.065	0.6068	1
9 channels				
R3	630-780	0.0496	0.0001	0.0000
R2	608-630	0.0811	0.0003	0.0000
R1	587-608	0.1302	0.0017	0.0000
G3	558-587	0.2598	0.0190	0.0000
G2	529-558	0.2504	0.1033	0.0000
G1	499-529	0.1641	0.2688	0.0000
B3	459-499	0.0556	0.4165	0.0001
B2	419-459	0.0091	0.1784	0.0948
B1	380-419	0.0003	0.0119	0.9051

The illuminance metrics are defined as Photopic Lux, Equivalent Melanopic Lux (EML), and Equivalent Neuropic Lux (ENL). Each channel is multiplied by the corresponding coefficients given in Table 1 and the summation is multiplied by 179 to denote the "equivalent" value. Photopic luminous efficiency is defined by scaling the curve V(λ) by 683 lm/W. The numerical integration of the area under the curve leads to 179. Therefore, the melanopic and neuropic curves are scaled to use the same integration value (Equations 1-3).

$$Photopic\ Illuminance = 179 * \sum_{i=1}^{n} (Ch_i * PCoef_i) \quad (1)$$

Ch stands for computed radiometric quantity per channel (*n* is three for RGB channels, and nine for R3-B1). *PCoef*, *MCoef*, and *NCoef* stand for the corresponding coefficients given in Table 1.

$$Melanopic\ Illuminance = 179 * \sum_{i=1}^{n}(Ch_i * MCoef_i) \quad (2)$$

$$Neuropic\ Illuminance = 179 * \sum_{i=1}^{n}(Ch_i * NCoef_i) \quad (3)$$

The luminance metrics are quantified in cd/m^2, EM.cd/m^2, and EN.cd/m^2 for the photopic, melanopic, and neuropic luminances, respectively.

Opsin evaluation criteria

The photopic illuminance is evaluated based on useful illuminance levels between 300 lux and 3000 lux (Mardaljevic et al, 2012). Below 300 lux is underlit and above 3000 lux is overlit (i.e. prone to glare).

The melanopic criterion is determined as a minimum of 275 EML before or by noon at the latest and for at least four hours at eye level (IWBI, 2022). This threshold is utilized in this study regardless of the source of light (daylight or electric lighting). The four-hour duration is applied as the upper threshold of the analysis legend (1100 EML). Unlike the photopic response, the upper melanopic threshold does not denote discomfort, it saturates the melanopic response. The assumption is that entrainment with a four-hour duration at 275 EML can be achieved in an hour with 1100 EML. Due to the absence of criteria, the criteria for melanopsin is adopted to neuropsin with the same range between 275 and 1100 ENL.

NICU Lighting Design

Lighting in modern NICUs has changed dramatically since the 1950's including periods with cycled lighting characterized by brightness in the day followed by darkness at night (cycled), all bright, and all dim. (Rivekees, 2004). Rivekees showed cycled lighting reinforces circadian information with implications for neonatal care and illness. Bates et al. (2020) have shown that mothers entrain circadian rhythms of the fetus during pregnancy with health risks if this link is broken. Current healthcare lighting standards acknowledge the health benefits of daytime light to identify Hyperbilirubinemia (a.k.a neonatal jaundice), treat it (460-490 nm), and support emergent circadian rhythms. Recommendations include access to at least one daylight source coupled with electric lighting that supports day-night cycles with no direct view of sources. Additional research is needed around light intensity and timing (White, 2020; ANSI/IES, 2022).

There is increasing attention to the spectrum of lighting as it relates to color and visual acceptance by occupants. More importantly, spectral fidelity impacts the visual assessment of the patient by caregivers. This requires a color rendering index >80, full-spectrum color index >= 55, and gamut area between 65 – 100 (White). The NICU at Kentucky Children's Hospital features cycled, tunable lighting that changes intensity and spectrum between day (5000K) and evenings (3000K) (Wilkerson, et al., 2022). The NICU at Cincinnati Children's Hospital features custom, programmable luminaires with six separate channels to improve spectral fidelity including violet peaking at 405 nm for circadian cycles for fetal development. There is a need for improved predictive analysis of the visual and non-visual light efficacy from the combined effect of electric and daylight sources in spectrally accurate interiors.

Simulation setting and parameters

Geometry

The setting is a single, private NICU patient room (9.6m x 5.6m x 3.5m) with an East facing window (7.2m^2). The room has a patient bed (isolette), which positions the horizontal work plane at a height of 1.2 m (Figure 2). The simulation grid covers the patient and family area. The grid is a horizontal plane as the simulations are performed based on the patient's eye location and gaze direction while lying in the isolette. Other simulations are performed from the caregiver's point of view but excluded from this paper for brevity.

Figure 2: Plan and sectional perspective of the NICU

Materials

The spectral properties of the opaque materials are shown in Figure 3. Lark v.3.0 processes the spectra data into 3 or 9 channels based on the intervals specified in Table 1 and outputs one or three Radiance material files based on the number of channels. The spectra are derived from measured reflectance and RGB values, or approximated from similar materials in the spectral materials database (Jakubiec, 2022). The interior finishes were selected to create a warm and playful environment to support healing: neutral floors, wood look casework, and accent color (blue) for the wall were used while head wall featured neutral colors.

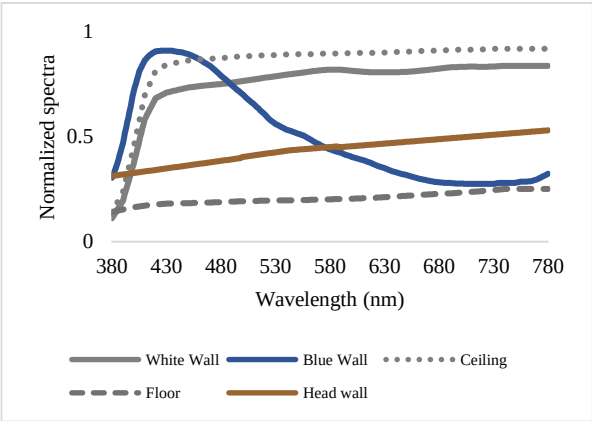


Figure 3: Spectral properties of opaque materials: photopic reflectances are 80% for white wall, 50% for blue wall, 44% for head wall, 90% for ceiling, and 20% for floor

Four different types of glazing have been simulated. These are representative of glazing selections from actual hospital projects, but their spectra are scaled to achieve uniform transmittance (Figure 4). This was deliberate to isolate the effect of the spectra than transmittance. Glazing differences can be driven by project specifications for energy, safety, UV protection, acoustics, and aesthetics. Glazing 1 and 4 have significantly different selectivity in the violet range than glazing 2 and 3.

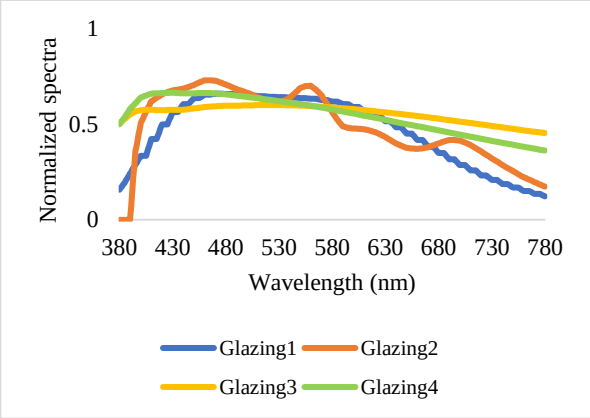


Figure 4: Spectral properties of glazing: each glazing has a photopic transmittance of 58%.

Daylight

The sky is modeled using Perez all-weather sky model with direct normal (measured with normal incidence pryheliometer), and diffuse horizontal (measured with Eppley 8-48 pyranometer) irradiance (NOAA, 2022). Both measurements are in the 280-3000 nm range. Global horizontal sky spectra are being measured (Ocean Insight Flame VIS-NIR Spectrometer) by the research team at a campus building since 2021. The calibrated spectral data is in 1 nm intervals between 380 and 780 nm. Standard Perez sky is modeled based on the direct and diffuse irradiance and colored based on global horizontal spectra in Lark workflow. Three point-in-time conditions are selected from yearlong measurements to represent the sunny and cloudy days during the morning time. Of the three point-in-time conditions, two clear day conditions are selected to represent medium and high CCTs (approximately 6000 and 9000K). Two dates within June have similar high irradiances but different CCTs at or around 10:00 am (Figure 5). For the simulation, direct and diffuse irradiance has been matched, and the date is fixed to June 21 at 10:00 am. Therefore, the differences are attributed to the effect of sky spectra. June and December data have similar CCTs (6000K) but different irradiances (June, with direct normal and diffuse horizontal irradiance of 863 and 167 W/m^2, December with 11 and 167 W/m^2).

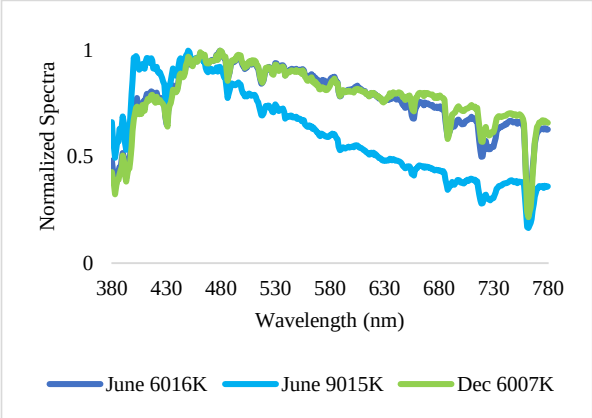


Figure 5: Sky spectra

Electric Lighting

The programmable spectral lighting approximates full-spectrum daylight changing over a 12-hour day based on emerging recommendations that support: i) Opsin 1 for high visual acuity and color quality to support cyanosis observation; ii) Opsin 4 for circadian entrainment; and iii) Opsin 5 to address myopia and metabolic growth of NICU patients.

The design includes two overhead recessed linear luminaires with an asymmetric distribution centered over the isolette that can be used for ambient or exam lighting. A diffused lens reduces glare. An indirect wall luminaire is centered behind the isolette to provide indirect light and follows the same program as overhead (the location of luminaires is shown in Figure 2). Electric light sources are modeled using the standard candlepower distribution curves (ies file format) with spectral data applied to the three luminaires used in the simulations.

Four types of spectral power distributions are investigated as follows: i) a fixed-spectra with a CCT of 3500K, ii) a market-ready technology with variable spectra. The spectra utilized in the simulation produce a CCT of 3500K. The spectra have a spike at 490 nm during the daytime to support melanopic stimulus, iii) a custom luminaire equipped with a set of violet-rich spectra optimized for melanopsin and neuropsin aimed to simulate twilight and daylight. The spectra used for the simulation produce 3500K, which achieves a high melanopic ratio with a spike at 482 nm and a high neuropic ratio with a spike at 400 nm. iv) Evening setting that produces a CCT of 2700K. Lights are assumed to be off at night with light leaks from the adjacent nursing station minimized with a curtain.

Simulation parameters

All simulations are performed in 9 channels. Radiance parameters are -ab 6, -ad 1024, -as 500, -ar 100, -aa 0.1, -lw 0.0001.

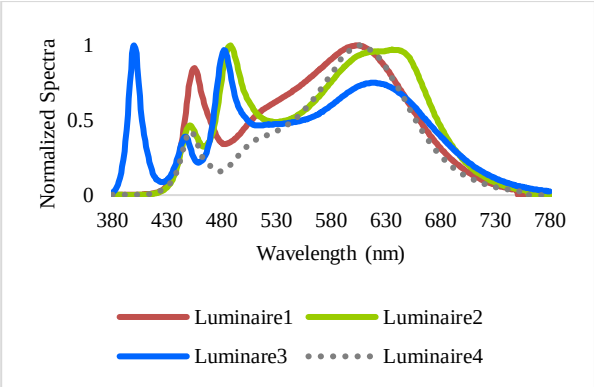


Figure 6: Electric lighting spectra: i) Luminaire1 is a fixed spectrum luminaire with a CCT of 3500K, ii) Luminaire2 is programmable with a CCT of 3500K and spikes at 490nm to support melanopic stimulus; iii) Luminaire3 is a custom luminaire with a CCT of 3500K and spikes at 482 and 405 to support melanopic and neuropic stimulus, iv) Luminaire 4 operates at night-time with CCT of 2700K.

Results: Healthy Lighting Prescriptions

The results are discussed through a series of vignettes.

Impact of sky spectra and intensity on photopic, melanopic, and neuropic illuminances

The spectra and intensity play a role in the distribution of photopic, melanopic, and neuropic illuminances. The comparison of June and December skies is given in Figure 7. As expected, the summer simulations with similar irradiances but different (high and medium) CCTs produce similar photopic light distribution across the room. For the melanopic light, 6000K spectra produced a 3% higher area of the room that satisfies the criteria than 9000K. This result goes against the assumption that higher CCT yields higher melanopic illuminance and shows the importance of the sky spectral distribution in resultant melanopic illuminance. As shown in Figure 5, the 6000K sky spectra have higher peaks in the 490nm region (where melanopic spectral efficacy peaks) than the 9000K sky spectra, resulting in higher melanopic illuminance. On the other hand, 9000K sky spectra spikes in the 400nm region, contributing to higher CCT and resulting in a 15% increase in the area of the room that satisfies the neuropic criteria. The photopic, melanopic, and neuropic illuminances are above the lower target value in the isolette area (i.e. satisfy the criteria). However, it should be noted that visual discomfort is observed in the window area. This will be further studied in the next vignette. Results from the winter sky with medium CCT showed limited penetration into the room due to lower intensity. The photopic, melanopic, and neuropic illuminances do not reach to the desired levels in the isolette area in December under overcast sky conditions.

Impact of glazing on photopic, melanopic and neuropic illuminances

Four glazing types are simulated for the June sky with a CCT of 9000K and the December sky with 6000K. Although each glazing has a photopic transmittance of 58%, their spectral selectivity is different, especially in the violet, blue, and red ranges (Figure 4). As a result, their performance is the same in the photopic quantities but varied in melanopic and neuropic metrics. Figure 8 is a cross-section of the room from the window to the rear wall that passes through the isolette (approximately 5m from the window). In general, the melanopic responses are higher than photopic responses, which are in return higher than neuropic responses. The photopic, melanopic, and neuropic responses are within the given criteria at the isolette for June without a shading fabric. However, the visual discomfort in the window area is likely to prompt the use of the shade fabric, which will reduce the light levels throughout the room. Glazing3 is also simulated with shade fabric (total transmission of 4%). With the shade fabric, the photopic, melanopic, and neuropic responses all fall below their respective criteria in the isolette area. Another important observation is that although the glazing spectra impact neuropic values significantly at the immediate window area, this impact becomes relatively insignificant as the measurement point moves beyond a few meters from the glazing.

Impact of electric lighting on photopic, melanopic, and neuropic illuminances

As the use of shade fabric to control visual discomfort is needed, and since the photopic, melanopic, and neuropic illuminances fall below their respective target values, it is necessary to supplement with electric lighting. Three daytime luminaires used in hospital projects were used to supplement daylighting. These luminaires are at 3500K, as there is wider acceptance to 3500K than higher CCTs in a hospital setting. However, the three luminaires have different peaks, luminaire2 is optimized for melanopic response, and luminaire3 is optimized both for melanopic and neuropic response. The first row of images in Figure 9 shows the light output and distribution from these three luminaires. The photopic responses are similar. The melanopic responses are in close proximity, but luminaire3 provides a higher stimulus. The most notable difference is with neuropic lux where luminaire3 provides the highest levels of neuropic stimulus. Luminaire3 is added to the June scene with the shade fabric and the December scene without the shade fabric. Both scenes were below target values in photopic, melanopic, and neuropic illuminances. With the addition of the luminaire3, all scenes provide adequate light levels. Since the NICU photopic light levels are typically accepted at around 600 lux, and IES recommendations for patient exam rooms are 1000 lux, it can be assumed that the electric lighting can be used at or close to full capacity during the exams, and can be dimmed to illuminate the isolette area at 600 lux. Shades can also be automated to take maximum benefit of daylight and reduce electric energy use. The luminare3 can entrain the melanopic and neuropic response within an hour at full capacity, or the dimmed electric light as described above would be adequate to entrain the circadian responses within 4 hours or less.

Photopic, melanopic, and neuropic luminances

Although it is more common to utilize illuminances in circadian studies, luminance maps are useful to visualize the contribution of various surfaces and design decisions on circadian metrics. Figure 10 illustrates the scene and the falsecolor images for photopic, equivalent melanopic, and equivalent neuropic cd/m^2. The neuropic stimulation of indoor surfaces is less than photopic and melanopic stimuli. As seen in Figure 3, the reflectance of indoor surfaces was less in the violet region compared to the other parts of the spectra.

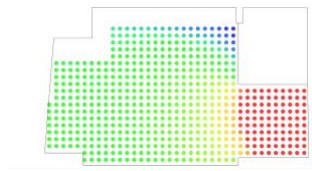
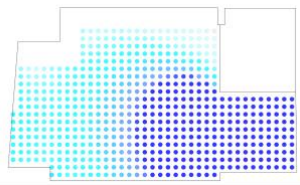
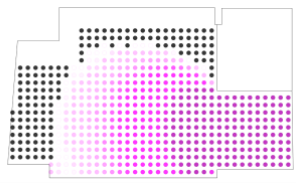
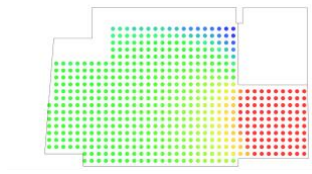
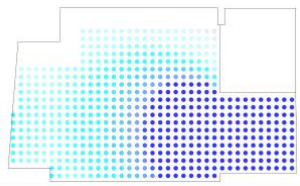
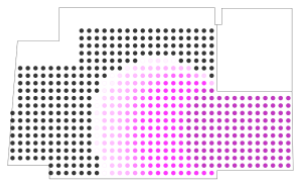
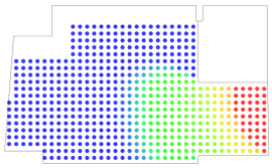
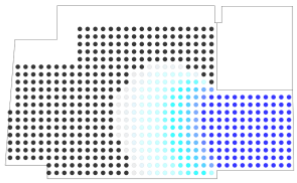
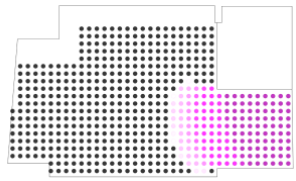
	Photopic Illuminance	Melanopic Illuminance	Neuropic Illuminance
June 21, 10:00 9000K DirN: 863 DifH:167 W/m^2			
	84% between criteria	62% between criteria	50% between criteria
June 21, 10:00 6000K DirN: 826 DifH:167 W/m^2			
	84% between criteria	65% between criteria	35% between criteria
Dec 21, 10:00 6000K DirN: 11 DifH:167 W/m^2			
	38% between criteria	28% between criteria	15% between criteria
Legend	 250 - 3000 lux	 275 - 1100 lux. < 275 lux	 275 - 1100 lux < 275 lux

Figure 7: Photopic, melanopic, and neuropic illuminances under different sky conditions

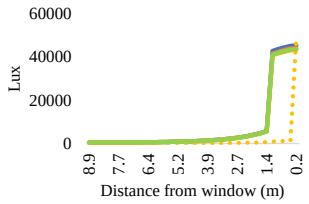
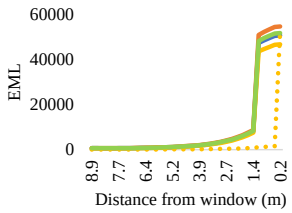
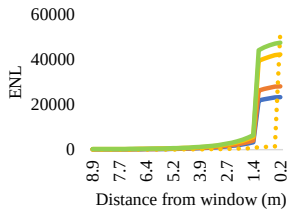
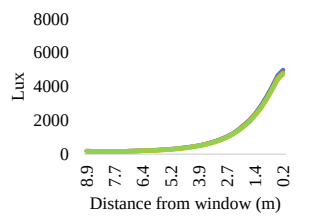
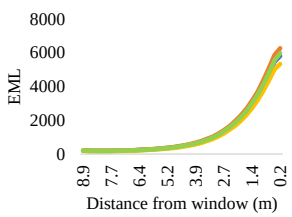
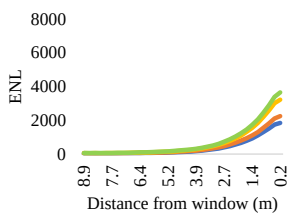
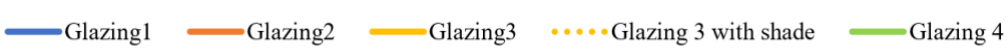
	Photopic Illuminance	Melanopic Illuminance	Neuropic Illuminance
June 21, 10:00 9000K DirN: 863 DifH:167 W/m^2			
Dec 21, 10:00 6000K DirN: 11 DifH:167 W/m^2			
Legend			

Figure 8: Photopic, melanopic, and neuropic illuminances with four glazing types and shade fabric. The photopic responses of the four glazing are uniform, as they have the same photopic transmittance. The melanopic and the neuropic responses vary, especially in the window area.

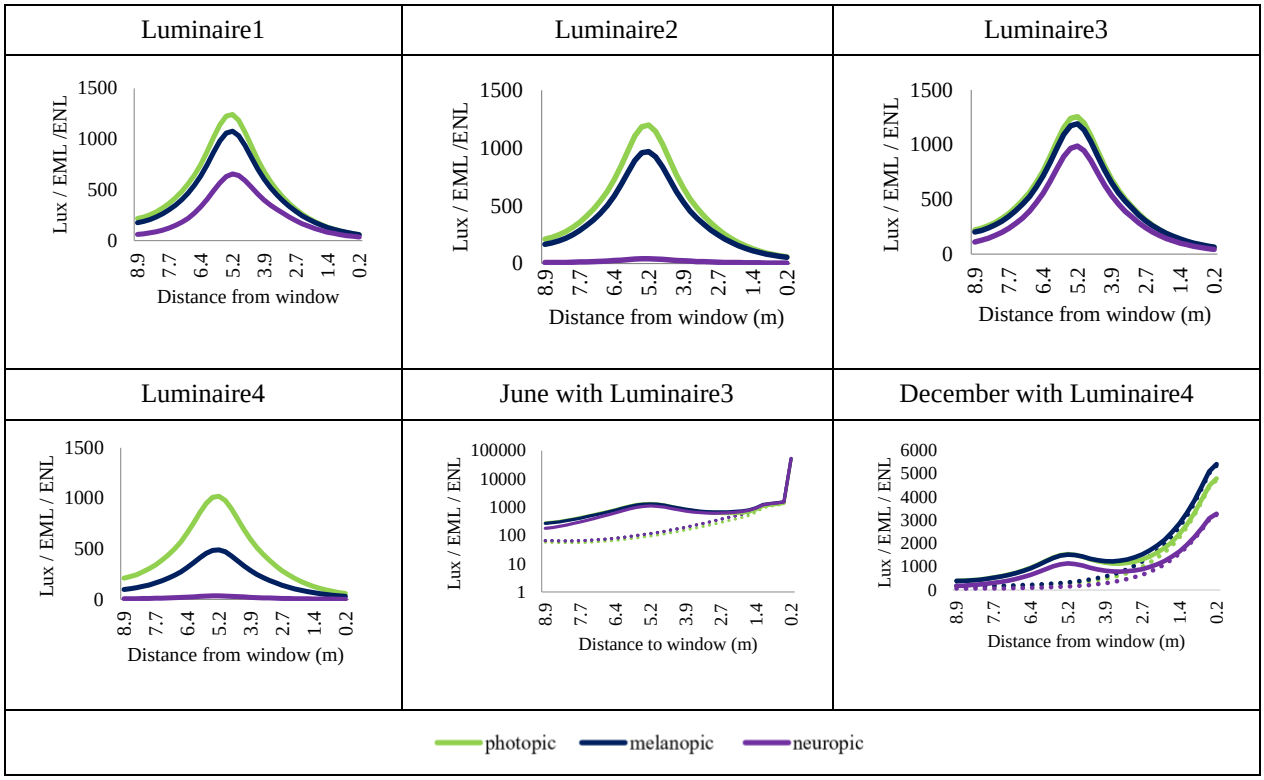


Figure 9: Photopic, melanopic, and neuropic illuminances with four luminaires; the first four graphs (top row and the left graph in the second row) show lighting generated from the studied luminaires. In the June and December graphs (bottom middle and right graph), the third luminaire is operated with daylighting. The dotted lines are without electric lighting, and the straight lines show the luminaire without dimming. Note that the vertical axis in June graph is in logarithmic scale.

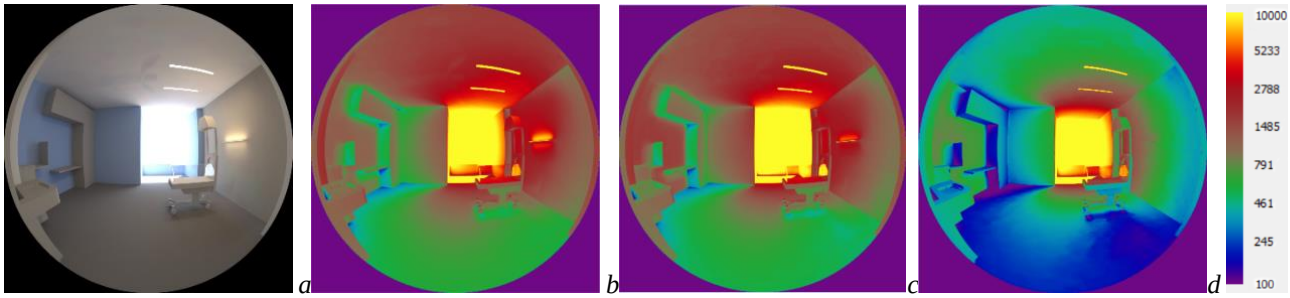


Figure 10: a.) Tone-mapped visualization of the NICU in June, b) falsecolor image for photopic luminances, c.) falsecolor image for melanopic luminances, d.) falsecolor image for neuropic luminances.

Conclusion

This paper has shown the development of new features for circadian lighting. Lark v.3.0 is provided as a free, open-source tool that can be continued to be developed as new knowledge emerges from photobiological sciences. The computed spectral irradiance from 9 channels is weighted with neuropic response to quantify neuropic illuminances and luminances in built environments. As the emerging research shows its importance in metabolic rate, thermoregulation, and ocular health, it is important to understand how design choices impact its levels indoors.

Another new feature revises the intervals of 9 channel divisions to better represent the slope of photopic, melanopic, and neuropic response curves.

The workflows are demonstrated in a NICU setting. NICU was chosen as a demonstration application as new research shows the impact of light cycles on neonatal health. The results show that the intensity of light strongly determines the magnitude of all light-induced responses. The impact of the spectra on daylighting is more predictable, as human biology has evolved under daylight. Yet, glare control strategies hamper the ability to deliver higher light levels indoors. The glazing spectra also impact the spectra of daylight indoors, but the results show that its effect on all opsins is limited to the immediate vicinity of the window area. Further research is warranted to conclude whether the spectral selectivity of the glazing could be improved for better photobiology. Electric light sources with spikes on targeted wavelengths (blue and violet-rich spectra) can efficiently supplement the melanopic and neuropic responses. Targeted spectra can also present an energy-conscious alternative as target levels for all opsins can be achieved with dimming. It

should also be cautioned against using 3 channel simulation to assess neuropic responses as it will over simplify the effect of light regardless of violet or blue spectra. To study the overall effect of changing spectral qualities of both daylight and electric light, different conditions can be simulated in time series. However, further clinical research is required to finalize the criteria for intensity and timing.

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