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Review of spectral lighting simulation tools for non-image-forming effects of light

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Abstract. Light via our eyes influences visual performance, visual comfort and visual experience, but also affects several health related, non-image-forming (NIF) responses. New metrics have been developed to quantify the NIF effects of light. In order to incorporate these in lighting design practice, simulation tools are required that are able to process information about the spectral distribution of light sources and materials. However, most of the tools currently used for daylight and electric light simulations simplify the spectrum into RGB (Red, Green, Blue) colour values. This paper presents an overview of the currently used programs for simulating the NIF effects of light in building design and discusses the possibility of using existing spectral rendering software as an alternative. A review of literature shows that mostly Radiance or Radiance-based programs have been used so far, but new user-friendly tools could employ existing spectral rendering tools. As the NIF effects of light gain greater importance in lighting design, new simulation workflows are needed. This paper aims to support the development of future workflows by presenting the current state-of-the-art.

1. Introduction

An increasing amount of research during the last years indicates that light does not only stimulate the human visual system, but it also triggers several non-image-forming (NIF) responses that are related to health and well-being [1]. These responses depend on the light's spectrum, intensity, spatial distribution and temporal factors, such as timing, duration and previous light history [2]. Since people spend the majority of their time in buildings [3], daylighting and electric lighting design of indoor spaces largely defines the light patterns to which they are exposed [4]. To account for the NIF effects of light within buildings, new lighting design workflows and tools are needed.

The ocular photoreceptors that drive the NIF responses (called intrinsically photosensitive retinal ganglion cells or ipRGCs) have a peak spectral sensitivity at the short wavelength bluish light, which differs from the sensitivity of the visual system, but there is evidence that other photoreceptors also contribute to these responses [5]. Due to the different spectral sensitivities, the photometric quantities such as luminance and illuminance are no longer suitable to fully describe light. To address this issue, the International Commission of Illumination (CIE) has adopted five α-opic metrics which are weighted with the sensitivities of the currently known photoreceptors in the eye (S-, M-, L- cones, rods and ipRGCs) [6]. The implication of this for lighting design is that it is now important to describe and calculate light radiometrically.

In lighting design process, computer simulation is a valuable tool for evaluating design alternatives. Conventionally, the simulation software used in lighting design simplifies the visible spectrum into a three-dimensional RGB (Red, Green, Blue) color space, where the RGB values are converted to luminances. Yet, the incorporation of NIF effects of light in lighting design practice requires simulation tools that can process information about the spectral distribution of light sources and materials. When the light source has a non-continuous spectrum (such as fluorescent light sources and LEDs) or when materials are not neutral, spectral simulations become essential for a reliable result. Two tools that solve this problem are Lark (https://faculty.washington.edu/inanici/Lark/Lark_home_page.html) and ALFA (https://www.solemma.com/alfa), but in the field of computer graphics several other programs exist that calculate light spectrally, meaning that they solve light transport equations for each wavelength. This paper presents (1) a literature review on the currently used software for NIF light simulations in buildings focusing on spectral definitions of light sources and materials and (2) an overview of existing spectral rendering software that could potentially be useful for NIF light simulations.

2. Existing simulation tools for NIF effects of light

A literature review was conducted to investigate the state-of-the-art in computer simulation tools for NIF effects of light. This is part of a larger (yet unpublished) literature review which investigates the existing simulation workflows applicable for investigating NIF effects of light in daylighting and electric lighting design practice. Here, the focus is on software and spectral information, whereas the broader review investigates the frameworks and methods used for NIF light simulations.

2.1. Methodology of literature review

The literature review was conducted using four groups of keywords: (1) “light” or “daylight, (2) “non-image-forming” or “non-visual”, “circadian”, “health”, (3) “simulation” and (4) “building design” or “lighting design”, “architectural design”, “built environment”, “design support”, “design process”, “design parameters” in the search engines Web of Science, Scopus and Science Direct, which resulted in 15 relevant publications. These 15 publications were forward traced by identifying the articles that cited them after they have been published in Scopus, Web of Science and Google Scholar. Eventually, 31 journal articles and conference papers were included in the literature review [7]-[37]. The analysis of the publications identified the simulation software that was used and whether light sources (daylight or electric light) and materials were spectrally defined or not.

2.2. Results of literature review

Out of the 31 papers, 20 studied only daylight, 5 studied only electric light and 6 both daylight and electric light. Radiance (https://www.radiance-online.org/) and Radiance-based programs, specifically Daysim (https://github.com/MITSustainableDesignLab/Daysim), Lightsolve (http://lightsolve.epfl.ch/), Honeybee (https://www.ladybug.tools/honeybee.html), DIVA (https://www.solemma.com/diva), Lark and ALFA, were used in 28 papers. It is noteworthy that all the publications that performed daylight simulations used a Radiance-based tool. For electric lighting simulations, in addition to Radiance-based tools, Relux (https://reluxnet.relux.com/en/), Dialux evo (https://www.dialux.com/en-GB/) and an in-house spectral simulation tool (called Colour Quality Assessment Tool or CQAT [17]) were used.

Four recent publications performed spectral Radiance simulations using an n-step (or n-channel) algorithm described by Inanici et al. [14] in order to calculate NIF light metrics. This was implemented in the tool Lark, a plugin for the visual programming environment Grasshopper for Rhinoceros 3D. The n-step algorithm refines the spectral resolution of Radiance, which typically performs standard RGB simulations [38]. It divides the visible spectrum in n wavebands, where increasing the n increases the spectral resolution. Since Radiance is by default a 3-channel renderer, in order to implement, for example, a 9-step algorithm, three individual simulations need to be combined (each accounting for a different part of the visible spectrum). Lark simulates in a 9-channel resolution (but 3-channel simulation is also possible) and allows the user to insert spectral reflectance and transmittance values of materials and a spectral power distribution of the sky, while assuming a neutral (white) sun. Lark was developed for daylight simulations, but it could be modified for electric lighting simulations since its code is open source.

Amongst the most recent publications, the tool ALFA is gaining popularity (used in 7 studies). ALFA also uses Radiance as its core engine in a modified workflow that allows it to perform multi-spectral simulations in an 81-channel resolution. Spectrally resolved materials can be selected from a database or defined by the user. ALFA computes a spectral sun and sky using atmospheric profiles but does not allow user defined spectral daylight data. In contrast with Lark, ALFA is a licensed software.

The simulation approach of the studies can be categorized into four groups: (1) multi-spectral simulation, in which spectrum of light source and of materials is considered, (2) RGB simulation, in which the RGB color triplets of light source and materials are used, (3) simulations of photometric quantities that are post-processed based on the spectral power distribution (SPD) of the light source, and (4) simulations of photometric quantities that are post-processed based on the SPD of the light source and the spectral properties of materials. The studies in the first group (12 studies) used ALFA, Lark, CQAT or a separate implementation of the n-step algorithm to simulate daylight or electric light. The studies in the second group (4 studies) used a standard 3-channel Radiance simulation to compute irradiance in three wavebands which are multiplied with three coefficients calculated based on a circadian action function. The third group of studies (13 studies) assumed that materials are neutral (white or grey) and therefore inter-reflections do not affect the color of the light. With this assumption, a NIF quantity can be calculated from a photometric quantity multiplied by a coefficient derived from the SPD of the light source. The approach of the fourth group (2 studies) is similar to the third one, with the difference that the SPD of the light sources is multiplied by the spectral reflectance of the materials, taking either a dominant material (e.g. colored desk) or assuming that different materials occupy a percentage of the field of view. Finally, there is one study that cannot be categorized in any of the above groups. That study only uses photometric quantities (vertical illuminance) and does not account for spectrum in any way. Overall, the majority of the studies in this review took into consideration the SPD of the light source (25 studies) and 17 of the studies consider the color of materials, either directly or by post-processing. Table 1 presents an overview of all the studies included in the review.

Table 1: Summary of reviewed papers. The materials are "neutral" (if they are white or grey), "colored-RGB" (if their color is defined by three RGB channels) or "colored-spectral" (if their color is defined by nine or more channels). The light sources are "spectrally defined" (if their SPD is used directly or as post-processing) or "non-spectrally defined" (if their SPD is not used).

* Radiance-based tool, ☀ = daylight, ♀ = electric light

Study	Software	Source	Spectral properties			Group
			Materials	*Daylight*	*Electric light*	
[7]	Daysim (3 channels)* Relux (3 channels)	☀ ♀	Neutral	Spectrally defined	Spectrally defined	(3)
[8]	Radiance (3 channels)	☀♀	Colored-RGB	Spectrally defined	Spectrally defined	(2)
[9]	Daysim (3 channels)*	☀	Neutral	Spectrally defined	-	(3)
[10]	Daysim (3 channels)*	☀	Neutral	Spectrally defined	-	(3)
[11]	Lightsolve (3 channels) *	☀	Neutral	Not mentioned	-	(3)
[12]	Radiance (3 channels)	☀	Neutral	Spectrally defined	-	(3)
[13]	Lightsolve (3 channels) *	☀	Neutral	Not mentioned	-	(3)
[14]	Radiance (9 channels)	☀	Colored-spectral	Spectrally defined	-	(1)
[15]	Radiance (3 channels)	☀	Colored-RGB	Not mentioned	-	(2)
[16]	Honeybee (3 channels) *	☀	Neutral	Spectrally defined	-	(3)
[17]	CQAT (unknown channels)	♀	Colored-spectral	-	Spectrally defined	(1)
[18]	Radiance (9 channels)	☀	Colored-spectral	Spectrally defined	-	(1)
[19]	Daysim (3 channels) *	☀♀	Neutral	Non-spectrally defined	Non-spectrally defined	-
[20]	CQAT (unknown channels)	♀	Colored-spectral	-	Spectrally defined	(1)
[21]	Daysim (3 channels) * Radiance (3 channels) Lark (3 channels) *	☀ ♀ ☀♀	Colored-RGB	Spectrally defined	Spectrally defined	(2), (3)
[22]	DIVA (3 channels) *	☀	Neutral	Spectrally defined	-	(3)
[23]	Radiance (3 channels)	♀	Neutral	-	Spectrally defined	(3)
[24]	Lark (9 channels) *	☀	Colored-spectral	Not mentioned	-	(1)

[25]	Daysim (3 channels) *	☀ ♀	Colored-spectral	Spectrally defined	Spectrally defined	(4)
[26]	ALFA (81 channels) *	☀ ♀	Colored-spectral	Spectrally defined	Spectrally defined	(1)
[27]	ALFA (81 channels) * Lark (9 channels) * Radiance (3 channels)	☀ ☀ ☀	Colored-spectral	Spectrally defined	-	(1)
[28]	DIVA (3 channels) *	☀	Neutral	Not mentioned	-	(3)
[29]	ALFA (81 channels) *	♀	Colored-spectral	-	Spectrally defined	(1)
[30]	ALFA (81 channels) *	☀	Colored-spectral	Spectrally defined	-	(1)
[31]	Honeybee (3 channels) *	☀	Neutral	Spectrally defined	-	(3)
[32]	Radiance (3 channels)	☀	Not mentioned	Spectrally defined	-	(2)
[33]	ALFA (81 channels) *	☀	Colored-spectral	Spectrally defined	-	(1)
[34]	ALFA (81 channels) *	☀	Colored-spectral	Spectrally defined	-	(1)
[35]	ALFA (81 channels) *	☀	Colored-spectral	Spectrally defined	-	(1)
[36]	Dialux evo (3 channels)	♀	Neutral	-	Spectrally defined	(3)
[37]	Daysim (3 channels) *	☀	Colored-spectral	Spectrally defined	-	(4)

3. Spectral rendering tools

The findings of the literature review showed that spectral workflows of RGB rendering tools (specifically Radiance) have started to emerge and are increasingly being used to simulate NIF effects of light in building design. However, useful applications can also be found among photorealistic visualization tools that model light spectrally. In architectural design practice, using rendering tools to visualize design ideas is a common method and therefore expanding the capabilities of this type of tools could result to the smoother integration of NIF simulation workflows in design practice.

3.1. Methodology of spectral rendering tools review

A review of solar design tools and methods by Jakica [39] was used as the source of spectral rendering tools presented in this paper. Jakica presented an overview of almost 200 solar design tools used across different disciplines (e.g. design of photovoltaics, daylighting, visualization, multiphysics) and analysed several of their features. From that overview, the spectral rendering tools of the disciples "daylighting/lighting/solar" and "visualisation" were selected, as they might have the potential to be used for spectral NIF simulations. Tools that could no longer be found online were excluded. The features of the 15 selected tools included here are based on self-testing or on the review of Jakica [39].

3.2. Results of spectral rendering tools review

A summary of the 15 spectral rendering tools is presented in Table 2. This includes four free and open source programs (Mitsuba, LuxCoreRender, Appleseed and Pbrt) and 11 commercial programs (Ocean, VRED, Maxwell Render, OctaneRenderer, Felix Render, Thea Render, Maverick Render, moskitoRender, Indigo RT, Indigo Renderer and FluidRay). Using an open source program offers the advantage that the code can possibly be modified to calculate NIF metrics. It should be mentioned that none of the software presented here has been developed with the purpose of estimating NIF light effects, but mainly for computing realistic images. However, it could be beneficial to consider if they can be used beyond their original scope.

Rendering tools typically produce images as an output, but Ocean and Mitsuba can also provide spectral irradiance or radiance as a result. From spectral irradiance/radiance, α-opic weighted quantities can be calculated. Moreover, Ocean offers the possibility to insert user-defined action functions (e.g. the sensitivities of the five photoreceptors) directly in the software. Rendered images could also be used to calculate NIF metrics (in a workflow similar to the one presented by Geisler-Moroder and Dur [8]) although with the disadvantage that the spectral result is again collapsed to RGB arguably losing much of the spectral information.

Natural light from sun and sky is modelled in the software with analytical models of luminance distribution or from High Dynamic Range Images (HDRI) of the sky. Mitsuba allows for the integration of spectral and spatial sky models, where color is defined for each patch of the skydome (as was implemented by Kider et al. [40]), but typically color is assigned uniformly for all sky patches. Twelve of the programs in Table 2 can additionally model electric light by using luminaire files (such as .ies files) to which either a preset or a user defined SPD can be assigned.

Table 2. Spectral visualization software.

Software	License	Daylight	Electric light (.ies files)	Output as image	Output as spectrum	Link
Ocean	Paid	Yes	Yes	Yes	Yes	http://www.eclat-digital.com/
Mitsuba	Free	Yes	No	Yes	Yes	https://www.mitsuba-renderer.org/
Maxwell Render	Paid	Yes	Yes	Yes	No	https://maxwellrender.com/
OctaneRenderer	Paid	Yes	Yes	Yes	No	https://home.otoy.com/render/octane-render/
Felix Render	Paid	Yes	Yes	Yes	No	https://www.felixrender.com/home
LuxCoreRender	Free	Yes	Yes	Yes	No	https://luxcorerender.org/
Thea Renderer	Paid	Yes	Yes	Yes	No	https://www.thearender.com/
Maverick Render	Paid	Yes	Yes	Yes	No	https://maverickrender.com/#1
moskitoRender	Paid	Yes	Yes	Yes	No	https://www.cebas.com/?pid=news_article&nid=525
Indigo RT	Paid	Yes	No	Yes	No	https://www.indigorenderer.com/indigo_rt
Indigo Renderer	Paid	Yes	Yes	Yes	No	https://www.indigorenderer.com/indigo3
Appleseed	Free	Yes	Yes	Yes	No	https://appleseedhq.net/
FluidRay	Paid	Yes	Yes	Yes	No	https://www.fluidray.com/
Pbrt	Free	Yes	No	Yes	No	https://github.com/mmp/pbrt-v2
VRED	Paid	Yes	Yes	Yes	Unknown	https://www.autodesk.com/products/vred/overview

4. Discussion and conclusion

This paper presented two aspects: (1) an analysis of simulation tools that are used for estimating NIF effects of light in the built environment through a systematic review of literature and (2) an overview of spectral rendering software that could potentially be used for the same purpose. Since the spectrum of light that reaches the eye of an observer is an important factor for NIF responses, it needs to be integrated in simulation workflows. Most studies use Radiance or Radiance-based tools, but new user-friendly tools could employ existing spectral rendering software. In this paper, 15 spectral rendering programs were reviewed, out of which Ocean and Mitsuba could be suitable for NIF simulations since they provide spectral information as a result. Mitsuba has the benefit of being open source, which adds flexibility.

However, there are significant obstacles to the use of spectral rendering programs. Most importantly, it is unclear how accurately these programs can compute quantitative results. The aim of photorealistic visualization software is not to precisely calculate light, but to produce realistic images. Therefore, in order to make use of these tools in lighting design, rigorous validation studies will be needed. Daylighting simulations with Radiance have been extensively validated against measurements (e.g. [41]–[43]) and are continuously improved by users. An important asset of Radiance is the open source structure with users that are dedicated to improve and preserve validity, which is lacking from other software. Another important obstacle, especially for commercial software, is that it is unclear which processes and algorithms are being used to generate a result. For example, the software often adjusts the result of a simulation based on parameters such as exposure time, aperture and white balance (equivalent to the parameters of a real camera) which affect the outcomes.

Overall, since the research on the NIF effects of light is relatively new, the development of suitable simulation tools is still at an early stage but it is likely that new tools will emerge. Spectrum of light is one of the parameters that needs to be included, together with temporal and spatial characteristics.

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