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VALIDATION OF SPECTRAL SIMULATION TOOLS FOR THE PREDICTION OF INDOOR ELECTRIC LIGHT EXPOSURE

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Abstract

As the interest in design applications related to responses to light beyond vision is growing, two simulation tools, *ALFA* and *Lark*, have been developed to incorporate spectral characteristics of light in the evaluation of indoor lighting conditions. The spectral characteristics of light are of particular relevance when studying ipRGC-influenced responses. This paper aims to assess the reliability of these tools in predicting indoor spectral irradiance specifically from electric lighting. Spectral irradiance was measured under three indoor electric lighting scenarios and compared against spectral irradiance simulated in *ALFA* and *Lark*. While the outcomes of the study tend to show that *ALFA* is both more accurate and faster, rather large errors were found for spectral irradiance (-28.6% to 33.4%). In comparison to a prior study focusing on daylighting, these results seem to indicate that spectral simulations of electrically lit scenes are generally less accurate than those of daylight scenes with these tools.

Keywords: Spectral Simulation, ALFA, Lark, Electric Light, Validation

1 Introduction

A new area of research, that of the ipRGC-influenced responses to light (also known as non-visual effects of light), has emerged in the field of lighting with the discovery of the ipRGCs (intrinsically photosensitive retinal ganglion cells), a new class of photoreceptors in the eye (Brainard et al., 2001). In the presence of light, the ipRGCs express a photopigment, the melanopsin, which mediates several behavioural and physiological responses in humans, such as the synchronization of the circadian clock to the light/dark cycle, the sleep propensity, or the inhibition of pineal melatonin secretion (Schlangen and Price, 2021). Consequently, our ocular light exposure affects our health, well-being, and productivity through these responses (Xiao et al., 2021). As we typically spend around 90% of our time indoors (Klepeis et al., 2001), there is a need to make sure our built environment is suitable to fulfil occupants' psychological and physiological needs. For that purpose, simulation tools are needed that are able to predict the impact of building design and electric lighting decisions on the occupants' light exposure.

Our ipRGC-influenced responses to light depend on various aspects of light exposure, among which its intensity and timing, as well as its spectral content (Amundadottir, 2016). The non-visual system is more sensitive to short-wavelength light given the spectral sensitivity of ipRGCs, although knowledge concerning the extent to which rods and cones also play a role in driving non-visual responses to light is still growing (Gooley et al., 2010). Unlike the visual responses for which light is described solely based on the photopic action spectrum and its related photometric units, there is no single action spectrum applicable to ipRGC-influenced responses. To provide guidance for the description of light in the context of ipRGC-influenced responses, the CIE therefore recommends the use of a framework based on five α -opic spectral sensitivity functions (CIE, 2018). The application of this framework requires to evaluate light radiometrically, and not photometrically. Such change in the evaluation of light implies that most current light simulation platforms are not appropriate for the study of ipRGC-influenced responses, as they are usually based on a 3-dimensional colour space and on photometric quantities (Ayoub, 2020; Ochoa et al., 2012).

Two spectral simulation tools, *ALFA* (Solemma LLC and Alertness CRC, 2018) and *Lark* (Inanici and ZGF Architects LLP, 2015), have been developed to alleviate this problem and support the

study of indoor spaces in relation to the ipRGC-influenced responses to light. Both tools rely on the physically accurate *Radiance* rendering engine, but *Lark* offers a 9-channel spectral resolution while *ALFA* allows for an 81-channel resolution. The respective characteristics of both tools can be compared in Table 1, which also specifies the need to have access to the spectral power density (SPD) of the light sources.

As the interest in design applications related to the ipRGC-influenced responses to light is growing and studies already use the outcomes of *ALFA* and *Lark* to inform design decisions (Altenberg Vaz and Inanici, 2020; Potočnik and Košir, 2021), there is an urgent need to confirm the reliability of these tools. In a previous study, we aimed at validating these two spectral simulation tools for the prediction of indoor daylight exposure (Pierson et al., 2021). It was shown that under daylight, the *Lark* 9-channel simulations were the most accurate in predicting spectral irradiance indoors (most errors within the $\pm 20\%$ range), despite being the most time-consuming. In this study, we aim at validating *ALFA* and *Lark* when it comes to the accurate prediction of indoor electric light exposure in terms of spectral irradiance. When combined, these two studies –based on either daylight or on electrically lit conditions – aim to provide a comprehensive assessment of the performance of *ALFA* and *Lark* in simulating spectral irradiance indoors.

Table 1 – Comparison of features between *ALFA* and *Lark* simulation tools

Feature	<i>ALFA</i>	<i>Lark</i>
Number of channels	81	9
Geometry	<i>Rhinoceros 3D</i> model	<i>Rhinoceros 3D</i> model
Materials	spectrally defined (material library or material property inputs)	spectrally defined (material property inputs)
Simulated sky	spectrally defined (atmospheric profiles from sky type inputs)	spectrally defined (global sky SPD and irradiance inputs)
Simulated sun	spectrally defined	non-spectrally defined (white light)
Simulated electric light	spectrally defined (luminaire SPD and IES photometric file inputs)	spectrally defined in a custom version of <i>Lark</i> (luminaire SPD and IES photometric file inputs)
Availability	licensed	open source

2 Methods

The methodology applied in the present study consists of comparing spectral irradiance measured under electric light conditions against the corresponding spectral irradiance simulated in *ALFA* and *Lark* at three desk positions in an office-like user-test facility.

2.1 Measurements

Two types of measurements were required for this study; the measurements of the indoor electric light exposure and those required to run the corresponding spectral simulations.

The measurements of the indoor electric light exposure were conducted in an office-like user-test facility (Figure 1) located in Eindhoven, the Netherlands. Opaque blinds on the façade prevented daylight from entering the room. Three distinct electric lighting scenarios were created using two types of ceiling luminaires:

- the “Fluorescent” scenario, with two luminaires *Philips TBS600 1xTL5 49W HFP* (~3000K)
- the “Warm LED” scenario, with two luminaires *Philips PowerBalance recessed tunable RC464B PSD W60L60 1 xLED80S TWH* (~2700K)
- the “Cool LED” scenario, with two luminaires *Philips PowerBalance recessed tunable RC464B PSD W60L60 1 xLED80S TWH* (~6300K)

These electric light sources were selected based on their somewhat common use for indoor lighting combined with their non-flat SPD – unlike the white daylight spectrum – which is likely to make their simulation more dependent on channel resolution. As illustrated in Figure 1, the experimental setup consisted of three desks with computer screens placed in the user-test

facility in such a way that one position had only indirect light (Desk 1), one had mostly direct light (Desk 2), and one had a combination of direct and indirect light exposure (Desk 3). Since simulation errors might be caused by miscalculation of either the direct or the reflected light component, this layout could be helpful in identifying potential causes of errors. Spectral irradiance was measured at eye level in seated position (1.2 m above the floor) in front of the three desks facing the computer screens with three *Ocean Insight* USB4000 spectrometers. The spectrometers were all calibrated with a radiometric calibrated light source. Additionally, a *Hagner* SD2 luxmeter was located next to each spectrometer to measure vertical illuminance. At each desk, both devices logged measurements continuously for one hour for each of the three lighting scenarios. The measurement interval was one minute for the spectrometer and ten seconds for the luxmeter. Collected illuminance values were used to check the validity of the simulation model and scale the measured spectral irradiance if needed. Two desks were also equipped with a *Bee-Eye* luminance camera with a 180-degree fisheye lens (Kruisselbrink et al., 2017). The luminance maps collected by these devices were used as a check to ensure that the measurements were not interrupted and for the validation of the simulation model as in Figure 2.

Figure 1 – Experimental setup of the lighting scenarios (fluorescent on the left and LED on the right) in the office-like user-test facility; the light sources are represented in yellow.

Measurements were also needed as inputs to run the spectral simulations corresponding to the three lighting scenarios. To create the experimental setup in *Rhinoceros 3D*, the room dimensions, desk and equipment placement, and luminaire positions were measured. The spectral reflectance of the materials was also measured with a *Konica Minolta* CM-2600d spectrophotometer. At last, the SPD of each light source was measured directly below it with a *Konica Minolta* CS-500A spectrometer. These SPDs are needed to spectrally simulate the light sources, as explained below.

2.2 Simulations

The spectral irradiance at each desk was simulated for the three scenarios with both *Lark* and *ALFA*. Although electric lighting was constant in each scenario, the simulations were run for every six minutes over one hour to match the measurements. In total, the dataset contains 90 data points (10 time steps * 3 desk positions * 3 scenarios) of measured and simulated spectral irradiance.

2.2.1 Validation of the simulation model

Before running the spectral simulations in *Lark* and *ALFA*, a basic *Radiance* RGB simulation was run for each time step to validate the simulation models of the experimental setup. The

simulations were run on a *Windows 10* computer with *Rhinoceros 3D* v.6 SR29, *Radiance* v.5.4, *Grasshopper* v.1.0.0007, *Honeybee* v.0.0.65, and *Ladybug* version 0.0.68. The *Radiance* parameters used for the simulations are provided in Table 2.

To simulate an electric light source in *Radiance*, the IES photometric file of the luminaire and a Light Loss Factor (LLF) are needed. The former was obtained from the manufacturer of the luminaires directly. The second was evaluated based on the context, as the LLF represents the difference between the actual light output of the luminaire in the field and the light output that would occur if the lamp operated at its initial rated lumens in laboratory conditions without any system variation or depreciation (Rea, 2000). The LLF is the product of several independent effects, some of which are recoverable and others nonrecoverable. Nowadays, the LLF is typically evaluated based on two main effects: the luminaire dirt depreciation (LDD) and the lamp lumen depreciation (LLD) (IESANZ, 2013). In this study, the LDD was assessed at 0.85 for the fluorescent light sources and 1 for the LED light sources (Rea, 2000), and the LLD was assessed at 0.94 for the fluorescent light sources and 1.1 for the LED light sources (Royer, 2014). This means that an LLF of 0.8 was used for the simulation of the fluorescent light sources and of 1.1 for the LED light sources. It should be noted that *Radiance* does not allow for an LLF higher than 1 to be used. Therefore, the LLF of the LED light sources was applied during the postprocessing phase to the simulation outputs.

Table 2: *Radiance* parameters used for the simulations.

Parameters	<i>Radiance</i>	<i>Lark</i>	<i>ALFA</i>
Ambient bounces (-ab)	6	6	6
Ambient divisions (-ad)	1000000	1000000	/
Ambient accuracy (-aa)	0	0	/
Ambient super-samples (-as)	0	0	/
Limit reflections (-lr)	0	0	/
Limit weight (-lw)	0.00001	0.00001	0.01

After running the *Radiance* RGB simulations for the ten time steps, three desk positions, and three scenarios, the relative error (RE) between the measured and simulated vertical illuminances, expressed through Equation (1), was computed. These relative errors (RE) are plotted in Figure 2.

$$RE [\%] = \frac{E_{v,RGB \text{ sim}} - E_{v,meas}}{E_{v,meas}} * 100 \quad (1)$$

where

$E_{v,RGB \text{ sim}}$ is the *Radiance* RGB-simulated vertical irradiance;
 $E_{v,meas}$ is the measured vertical irradiance.

In the literature, it has been shown that, for daylight simulations, the distribution of relative illuminance errors between *Radiance* RGB simulations and measurements is fairly symmetric at the 0% line, and the main body of the distribution is contained within the $\pm 17.5\%$ range (Mardaljevic, 1999). Regarding electric lighting simulations, to our knowledge, only one study compared the outputs of *Radiance* RGB simulations with actual measurements in a real office environment for different types of luminaire (Houser et al., 1999). Although an LLF of 0.8 was applied in that study, the results showed that the simulated mean luminance of the scene was 9 to 51% larger (depending on the type of luminaire and scene) than the measured mean luminance. In contrast to this last result, there seems to be no significant bias error between the *Radiance* RGB simulations and the measurements in our study as the errors in vertical illuminance fluctuate around 0% (Figure 2). The relative illuminance errors (for the ten time steps, at each desk, and under each scenario) are all within the $\pm 17.5\%$ range observed for daylight simulations. Additionally, a comparison of the simulated and measured luminance maps at Desk 2 is provided in Figure 2. It should be noted that the measuring equipment at each desk was set up in such a way that the spectrometer was centred on the screen; as a result, the *Bee-Eye* camera, located next to the spectrometer, was not centred. This explains the slight difference between the measured and simulated field of view in the images. Overall, the results of these *Radiance* RGB simulations basically demonstrate that the models for all three scenarios are valid, and the spectral simulations can be run in *ALFA* and *Lark*.

2.2.2 Spectral simulations in *Lark* and *ALFA*

In *Lark*, a 9-channel spectral simulation is achieved by running three *Radiance* simulations and combining their outputs, as explained in (Pierson et al., 2021). Since the current version of *Lark* does not include a component for electric lighting simulations, *Lark* developers shared with us a custom *Grasshopper* sheet based on existing *Lark* components to run such simulations. The method adopted by *Lark* developers consists in:

- dividing the SPD of the simulated electric light source into nine consecutive wavebands (three triplets),
- scaling these nine values in such a way that when they are multiplied by their corresponding photopic coefficients (derived from the photopic spectral luminous efficiency function) and summed up, their sum is equal to 1, and
- replacing the three colour coordinates in the IES file by the scaled triplet corresponding to each of the three standard *Radiance* RGB simulations operated by *Lark*.

The ten simulation time steps were automated for each scenario in *Lark*. Since *Lark* runs on the *Grasshopper* plugin, the automation for *Lark* was implemented through the component *Fly*. These simulations were run on a *Windows 10* computer, with *Rhinoceros 3D* v.6 SR29, *Radiance* v.5.4, *Grasshopper* v.1.0.0007, *Honeybee* v.0.0.65, *Ladybug* version 0.0.68, and *Lark* version 0.0.1. The *Radiance* parameters used for the simulation in *Lark* are detailed in Table 2. In *Lark*, the required inputs besides the model are the materials' spectral reflectance and the characteristics of the electric light sources, i.e., the IES photometric file, the LLF, and the SPD of the luminaire. The LLF used for the *Lark* simulations are the same as the ones used for the *Radiance* RGB simulations, i.e., 0.8 for the fluorescent light and 1.1 for the LED light. As detailed in (Pierson et al., 2021), the average spectral irradiance over each of the nine consecutive wavebands in *Lark* (Inanici et al., 2015) was derived from the RGB values resulting from each simulation run.

Figure 2 – RE between measured and *Radiance*-simulated vertical illuminance for each electric lighting scenario and each desk (some jitter has been added for legibility) (left); comparison of the measured and simulated luminance maps at Desk 2 for each scenario (right).

Since *ALFA* does not yet allow to automate time-stepped simulations, the ten simulation runs were started manually for each electric lighting scenario. The simulations were run on a *Windows 10* computer, with *Rhinoceros 3D* v.6 SR29, and *ALFA* v.0.5.6.99. *ALFA* was set up to make 75 passes and the parameters were set as in Table 2. In *ALFA*, the electric light source is characterized by its IES photometric file and SPD. The software does not yet allow to account for an LLF; hence the *ALFA* simulation outputs were postprocessed to apply the same LLF as the one used in *Lark*. Moreover, it is not possible to apply a custom SPD to a luminaire in *ALFA*;

the SPD must be chosen from a library of 29 typical SPDs. The SPDs that most closely matched the measured ones were chosen. A comparison of these SPDs is available in Figure 3.

2.3 Analyses

Similarly to the analyses applied in our previous study on indoor daylight exposure (Pierson et al., 2021), the measured and simulated spectral irradiance were compared through the normalized root mean square error (NRMSE) and the median relative bias error (MRBE). The former indicates how far the simulated spectrum fluctuates around the measured one –the variance error, while the later expresses whether the simulated spectrum tends to be larger or smaller than the measured one –the bias error. Since there are 30 data points for each electric lighting scenario (3 desks * 10 time steps), the mean of the MRBE and the NRMSE were computed over these data points and are presented in the graphs below (Figures 4-7). Contrary to the previous study on daylight validation, the mean was chosen over the median since there are only three main error values for each scenario corresponding to the three desks (the error values tend to stay constant over the ten time steps).

Figure 3 – Comparison between measured SPD of the three types of electric lighting and most closely matching SPD in the ALFA library; the grey shades represent the SPD multiplied by the melanopic and photopic spectral sensitivity functions.

3 Results and Discussion

It was decided to run most analyses separately for the three lighting scenarios as they produce different results in terms of accuracy of the spectral simulation tools. The first analysis that was applied aimed at comparing the accuracy of a standard *Lark* 9-channel and a standard *ALFA* simulation. The mean MRBE and NRMSE for each electric lighting scenario is displayed for both tools in Figure 4.

Figure 4 – Mean MRBE and NRMSE comparison between ALFA, Lark 9-channel, and Lark 3-channel simulations for each electric lighting scenario.

As expected, *ALFA* produces less deviation from the measurements (lower NRMSE) and a reasonable bias error compared to *Lark*, due to the higher spectral resolution. From the MRBE graph in Figure 4, we can observe a large positive error bias for the *Lark* 9-channel simulations

of the fluorescent scenario. If we look directly at the comparison of a measured and simulated spectrum in that scenario (Figure 5 - left), it can be observed that since *Lark* averages the spectrum over 9 channels, most of the points of the actual fluorescent spectrum – those in between the peaks having very small irradiance values – are simulated at a higher value due to the peaks increasing the average. *ALFA* follows the peaks and troughs of the spectrum much more closely since it averages over 81 smaller wavebands. This large MRBE issue for the *Lark* 9-channel simulations is not present for the LED scenarios since the LED spectra are more continuous and do not have troughs with very low irradiance values (Figure 5 - right).

As it appears that the channel resolution is one of the main factors affecting the performance of the spectral simulation tools for electric lighting, it was decided to perform *Lark* 3-channel simulations as well and add them to the comparison. In that way, the channel resolution factor is isolated as this is the only difference between *Lark* 9-channel and *Lark* 3-channel simulations. A comparison between *ALFA*, *Lark* 9-channel, and *Lark* 3-channel simulations is also provided in Figure 4. This additional comparison confirms that the higher the channel resolution is, the more accurate the simulation results will be.

Figure 5 – Measured and simulated spectral irradiance at Desk 2 under the fluorescent scenario (left) and the cool LED scenario (right).

Another aspect that seemed worth investigating is the impact that neglecting the actual SPD of the electric light source can have on the simulation results. When you run a *Radiance* RGB simulation of an electrically lit scene, only the IES photometric file of each luminaire is required, and by default this one does not include any colour information. On the opposite, besides the IES photometric file of each luminaire, *Lark* 3-channel also considers the SPD of the luminaires by averaging it over its three channels (similarly to what is described above for *Lark* 9-channel simulations). Therefore, a comparison of *Lark* 3-channel and standard *Radiance* simulations (with the default IES photometric file) was made, as shown in Figure 6. As expected, accounting for the SPD of the electric light source in *Lark* 3-channel produces more accurate results than neglecting it in *Radiance*. However, it should be noted that the material definition is slightly different between the two simulation processes, hence the difference cannot be fully attributed to the SPD consideration. Additionally, the deviation from the measured spectra in both cases is high with a positive bias since both simulation processes have a 3-channel resolution.

Similarly to what was done in the daylight validation study, accounting for the SPD of the light source and increasing the channel resolution could also be achieved by postprocessing the results of a standard *Radiance* simulation. Indeed, the *Radiance*-simulated vertical illuminance under a specific electric light source can be used to scale the SPD of this specific light source afterwards. This *Radiance*-based simulation process was compared to *ALFA*, the most accurate spectral simulation tool up to here, for the three electric lighting scenarios in Figure 7.

For the specific (and somehow unrealistic) scenarios studied here, the *Radiance* simulation with an SPD scaling postprocess seems more accurate and less biased than *ALFA*. However, we should keep in mind that this simulation process would only be reasonable to use when there is only one type of light source (or that the mixed light sources SPD is known) and for indoor environments with relatively neutral colours. Otherwise, the SPD of the light at the observer's eyes that need to be used in the postprocess cannot be anticipated since it will depend on the interactions between the light sources, as well as on the materials.

Figure 6 – Mean MRBE and NRMSE comparison between *Lark* 3-channel and *Radiance* RGB simulations for each electric lighting scenario.

Figure 7 – Mean MRBE and NRMSE comparison between *ALFA* and *Radiance* (postprocessed to scale the output with the appropriate SPD) simulations for each electric lighting scenario.

Another aspect of simulations that hangs in the balance besides simulation error is simulation time. The five spectral simulation processes analysed above for their accuracy in predicting spectral irradiance under indoor electric lighting were also compared for their respective simulation time, together with another version of *ALFA* relying on a lower number of passes (supposed to be faster but less accurate). In Figure 8, the time for one simulation run conducted on the same computer for these six simulation processes is plotted against the accuracy of these simulation processes described by their mean, minimum, and maximum NRMSE. It can be observed that, in the case of electric lighting only, the best performing simulation process, *ALFA*, is also the quickest one. Additionally, it appears that increasing the number of passes in *ALFA* extends the simulation time for no visible improvement in NRMSE. A basic *Radiance* RGB simulation of which the output is used to scale the initial SPD also provides good accuracy for a reasonable simulation time. However, this simulation type can only be applied to a restricted number of scenes (as is the case for all 3-channel simulation processes represented by empty symbols in Figure 8), as explained above.

From these analyses, *ALFA* seems the most appropriate spectral simulation tool when it comes to indoor electric lighting simulations. As can be observed in Figure 9, the MRBE of *ALFA* in this study ranges from -28.6% to 33.4%. This range of error in spectral irradiance for *ALFA* is larger than the observed range of error in vertical illuminance for *Radiance* (Figure 2) and also seems worse than the distribution of error in spectral irradiance for *Lark* 9-channel under

daylight conditions (where most errors were within the $\pm 20\%$ range) (Pierson et al., 2021). Although it may seem, from this range of errors, that spectral simulation tools are unreliable to simulate electric lighting indoors, this assumption should be balanced with the fact that:

- the electric light sources studied here were chosen for their non-flat spectrum that was assumed to be the most complicated to simulate. Luminaires with more continuous spectrum might yield more reliable simulation results.
- the purpose of the spectral simulation will determine whether this range of errors can be accepted or not. In a follow-up study, we plan to investigate whether such errors in simulated spectral irradiance yield acceptable results when it comes to indicators of ipRGC-influenced responses to light.

Figure 8 – Mean NRMSE versus simulation time; the symbol represents the simulation tool (ALFA, Lark, or Radiance) and an empty symbol is used for 3-channel simulation processes.

Figure 9 – MRBE between the measured and ALFA-simulated spectral irradiance for each electric lighting scenario and each desk.

At last, no apparent trend can be noticed between the three desk positions in Figure 9. This could imply that the tool performs similarly for direct and indirect lighting scenes. In view of the small number of studied scenarios however, no definite conclusion should be drawn on this yet.

4 Conclusion

In this study, two spectral simulation tools were tested for their accuracy in predicting building occupants' electric light exposure in terms of spectral irradiance. The light exposure at three

desk positions under three electric lighting scenarios were measured and simulated for the analyses. Unlike the outcome of a previous daylight validation study (Pierson et al., 2021), the most accurate and quickest spectral simulation tool for indoor electric lighting simulations appears to be *ALFA*. More specifically, it seems that for electric lighting, the higher the channel resolution of the simulation tool is, the most accurate its results are. However, despite being the most accurate, the range of relative errors in spectral irradiance for *ALFA* in this study goes from -28.6% to 33.4%. By comparison to the distribution of relative errors of the best spectral simulation tool in the daylight validation study, this somehow larger range of errors seems to indicate that spectrally simulating electrically lit scenes is less accurate than daylight scenes. Based on the results from both studies, it can be hypothesized that the more continuous the light source SPD is (i.e., the fewer peaks it contains), the better it can be spectrally simulated with existing tools.

More generally, it remains questionable whether such range of errors should be accepted or not. In a future study, we plan to address this question for spectral simulations intended for the study of building occupants' ipRGC-influenced responses to light. More specifically, the goal will be to determine the extent to which such simulation errors may affect the outputs of non-visual response models. Besides translating these simulation error values into values probably easier to interpret, this study will also open the discussion about the significance of a difference in light exposure when it comes to ipRGC-influenced responses. Until we have a better understanding of ipRGC-influenced responses to light, we will not be able to evaluate whether a difference in exposure matters, and thereby will not have the means to determine relevant error thresholds for spectral simulation tools when it comes to the study of ipRGC-influenced responses to light.

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