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A conceptual simulation workflow to guide design decisions regarding the effects of daylight on occupants’ alertness

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Abstract. Recent developments in the lighting research field have demonstrated the importance of a proper exposure to light to mediate several of our behavioral and physiological responses. However, we spend nowadays around 90% of our time indoors with an often quite limited access to bright daylight. To be able to anticipate how much the built environment actually influences our light exposure, and how much it may ultimately impact our health, well-being, and productivity, new computational tools are needed. In this paper, we present a first attempt at a simulation workflow that integrates a spectral simulation tool with a light-driven prediction model of alertness. The goal is to optimize the effects of light on building occupants, by informing the decision makers about the impact of different design choices. The workflow is applied to a case study to provide an example of what learnings can be expected from it.

1. Introduction

1.1. Background
The discovery of a new type of photoreceptor in the eye, the intrinsically photosensitive Retinal Ganglion Cell (ipRGC) [1], and its connection to the Suprachiasmatic Nucleus (SCN), opened up a new field of research. Via this pathway, light induces several behavioral and physiological responses in humans, such as regulation of the sleep-wake cycle and circadian phase shifting, or melatonin suppression and control of alertness [2]. These new insights demonstrate the importance of a proper exposure to light for our health, well-being, and productivity.

The so-called non-visual responses to light depend on various aspects of the ocular light exposure, among which its intensity and timing, as well as its spectral content. Unlike the visual responses for which light metrics are derived from the photopic action spectrum, there is currently no consensus for a single action spectrum for non-visual responses. Our limited understanding of the spectral sensitivity of the non-visual system, however, implies that light needs to be evaluated radiometrically in order to predict non-visual responses. Therefore, new computational tools based on a radiometric description of light are needed to anticipate how much the built environment influences our light exposure, and ultimately impact our health, well-being, and productivity. For instance, a computational tool to study the effects of daylight on occupants’ alertness requires the following steps; first, the prediction of the occupant’s daylight exposure, then, the prediction of the alerting effects related to the exposure.
1.2. Prediction of indoor daylight exposure
Since the action spectrum of the non-visual responses is not yet established, the indoor daylight exposure of occupants must be defined radiometrically. For this reason, most current light simulation platforms are not appropriate for the study of non-visual effects. Rather than using a three-dimensional color space and photometric units, spectral simulation tools need to be used instead.

A recent study [3] aimed at comparing two spectral simulation tools for building design applications, ALFA [4] and Lark [5]. Both tools rely on the physically accurate Radiance rendering engine but offer different “spectral” resolutions (9 channels for Lark against 81 channels for ALFA). In the study, the two tools were assessed for their reliability and accuracy in predicting spectral irradiance in daylit indoor spaces. Due to a yet unresolved reproducibility issue in ALFA, Lark provided the most accurate results under daylight conditions, with no bias and an error distribution similar to what can be expected from a standard Radiance RGB simulation, i.e., most errors within the ±20% range.

1.3. Prediction of alerting effects of daylight
Alertness is affected by multiple physiological and environmental factors including ocular light exposure. Alertness has become the focus of many investigations lately due to its implication on safety and productivity issues in occupational settings [6, 7], and for its role in discussions about health and well-being in the built environment. As our understanding about the mechanisms behind psychophysiological light-induced responses is developing, computational models have emerged to anticipate these aforesaid responses. Light-driven prediction models of alertness now exist and can be a useful tool for tailored light interventions in occupational settings or for informed design decisions in the built environment. However, these models lack validation outside controlled laboratory environments and for daylight exposure.

A recent study [8] aimed at comparing three prediction models of alertness [9, 10, 11] for daytime indoor daylit conditions. These three physiology-based, light-driven models were assessed for their reliability and accuracy in predicting daylight-induced alertness variations in participants in near-realistic conditions. Although none of the three models could predict with an error of less than 10% specific values of alertness, the non-visual direct response (nvRo) model [9] performed best, displaying a moderate positive correlation between the measured and predicted data of alertness.

In this paper, we present a first attempt at a simulation workflow to predict the effects of certain design decisions in terms of occupants’ light exposure, and ultimately, on their alertness. This work builds upon the results of two previous studies [3, 8] by combining the best performing tool and model into a workflow to inform the design process. To check the adequacy of this workflow, it is applied to a simple case study –a classroom– for which two different sets of material finishes are tested and compared (i.e., base case vs. blue variant) for their predicted impact on occupants’ alertness.

2. Methods

2.1. Simulation workflow
This paper presents a conceptual workflow that integrates a spectral simulation tool with a prediction model of alertness to inform the design process. A schematic view of the workflow is given in Figure 1.

![Fig. 1: Schematic view of the simulation workflow used in this study to inform the design process by predicting the effects of indoor daylight exposure on occupants’ alertness.](image-url)
Further explanations on how to apply this simulation workflow to a case study under daylight conditions are provided below, together with the example of a classroom.

2.1.1. Simulation of spectral irradiance. To simulate the daylight exposure of a building occupant over a certain period in terms of spectral irradiance with Lark, the inputs required are:

- the sky models over that period (defined by the location and time information, the global sky Spectral Power Distribution (SPD), the global horizontal irradiance (GHI) or the direct normal (DNI) and diffuse horizontal irradiance (DHI), and the dew point temperature),
- the indoor space model,
- the virtual sensor (representing the position and view direction of the occupant), and
- the simulation parameters.

In the context of a design process, what will be of primary importance in influencing occupants’ light exposure is the indoor space model. By varying the materials and glazing spectral characteristics, or by modifying the building geometry, the occupants’ light exposure will be modified, which can impact their alertness.

When being fed with these inputs, Lark first divides the spectrum of the sky into nine consecutive wavebands, then runs a standard Radiance RGB simulation for each triplet of consecutive wavebands. Through some postprocessing [3], the outputs of the three RGB simulations done in Lark can be transformed into the spectral irradiance to which the occupants would be exposed to. The simulations can be automated in Lark in such a way that the tool loops through all the sky models in the simulated period, hence producing a time series of simulated spectral irradiance.

2.1.2. Prediction of alertness. The nvR₀ model takes as input a time series of effective irradiance. To derive effective irradiance from spectral irradiance, there are two options [9]: either applying the ipRGC-cone shift model, which accounts for the dynamics of the spectral sensitivity of the non-visual response system, or applying the ipRGC static model, which uses the spectral sensitivity of the ipRGCs only.

Although further knowledge is needed on the variation in spectral sensitivity of the non-visual system, the ipRGC-cone shift model seems to be appropriate only for light exposures occurring after adaptation to dim light [12]. Since in the context of a design process, the light exposure history of the building occupants is unknown, it was decided to derive effective irradiance in this workflow by applying the ipRGC static model to spectral irradiance.

The model then transforms the time series of effective irradiance into a time series of relative responses (r₀), through the action of four main components that reflect the intensity-response curve of melatonin suppression and the temporal processing between the light input and the output response. These r₀ values, predicted for an average person having no memory regarding prior light exposure and an already entrained behavior, can be interpreted as the direct driving force of the light exposure on the non-visual system. They can then be integrated over time to generate a cumulative response (R₀), which represents the capacity of the light exposure to have an effect on occupants’ alertness: the larger the cumulative response, the more the simulated space has the potential to boost occupants’ alertness.

2.2. Case study

To check the adequacy of the simulation workflow, it was applied to the case study of a classroom. The classroom (2.8 H x 10 W x 14 L), an actual classroom for which a Rhinoceros 3D model was available (Fig. 2), is located near Lausanne (46°31’15”N,
Table 1: Radiance simulation parameters.

| Parameter            | Value      |
|----------------------|------------|
| Ambient bounces (-ab) | 6          |
| Ambient divisions (-ad) | 1000000   |
| Ambient accuracy (-aa) | 0         |
| Ambient super-samples (-as) | 0      |
| Limit reflections (-lr) | 0         |
| Limit weight (-lw)    | 0.00001    |

6°33’58”E) and has windows facing south. No context (surrounding buildings or trees) was accounted for in the simulations, but a neutral ground with a spectrally uniform albedo of 0.2 was added [13]. Two time series of spectral irradiance were simulated at eye-level for 20 potential seated positions in the classroom, as shown in Figure 2. The simulated time series each extended from 9a.m. until 5p.m. with a time step of 6 minutes, over two different days around the equinox: a fully clear sky day (24th of September) and a fully overcast sky day (22nd of March). The sky models for these two days were defined in Lark based on the SPD of the CIE Standard Illuminant D65, as well as the DNI, DHI, and dew point temperature extracted from Meteonorm v.8.0.3. The simulations were run on a Windows 10 computer, with Rhinoceros 3D v.6.29, Grasshopper v.1.0.0007, Honeybee v.0.65, Ladybug v.0.69, Lark v.0.0.1 with the sky component being modified to use gendaylit program instead of gensky [3], and Radiance v.5.4. The parameters used for the simulation in Lark are detailed in Table 1.

As a base case, the simulations were performed with similar materials as in the reality, i.e.: white painted ceiling (ρv=0.82), white plaster walls (ρv=0.59), gray carpet floor (ρv=0.04), green board (ρv=0.02), gray concrete parapet (ρv=0.40), gray tables (ρv=0.44), black window frames (ρv=0.06), and double-glazing with a neutral tint (τv=0.66). The spectral characteristics of the materials were downloaded from an online database based on real material measurements [14]. In order to show the difference in outputs that can be expected from the workflow when varying architectural features, the simulations were run a second time for a variant case of the classroom. Both the intensity and the spectral content of occupants’ light exposure could be altered by modifying some architectural features and can impact their alertness. To take full advantage of the spectral simulation in the workflow, it was decided to modify the spectral characteristics of some of the materials towards a more blueish scene, but to keep the vertical illuminance (Ev) as similar as possible to the base case. The walls and floor materials were therefore modified to blue painted walls (ρv = 0.27) and a blue carpet floor (ρv=0.06). A 180° view of the base case and the blue variant are available in Figure 3. As it was impossible to maintain a similar Ev for all desk positions at the same time, the analysis focuses on the specific desk position highlighted in Figure 2. The glazing visual transmittance was increased (τv=0.71) without altering its neutral tint for Ev at that desk position to match the base case (Fig. 4).

3. Results and Discussion

The case study presented here provides a rather limited study of the architectural features having the potential to affect occupants’ alertness. This paper indeed aims to present how the workflow can be used, and how its results should be interpreted.
3.1. Comparison of simulated spectral irradiance

The occupants’ light exposure in both classroom scenarios can be analyzed according to the CIE metrology system for ipRGC-influenced responses to light [15]. As we want to compare these light exposures in their capacity to influence the occupants’ alertness, it is relevant to derive the melanopic Equivalent Daylight Illuminance (EDI). Moreover, some recommendations have recently been issued in terms of melanopic EDI for healthy daytime, evening, and night-time indoor light exposure [16].

In Figure 5, the melanopic EDI at the studied desk is larger for the blue variant than for the base case throughout the day and for both sky types, while $E_v$ is similar or even lower (Fig.4). This means that both scenarios would provide the same amount of light for visual tasks at the studied desk, but the blue variant would provide a light exposure that is more efficient in inducing non-visual responses such as promoting alertness. Additionally, in this case, only the blue variant under clear sky conditions reaches the minimal recommendation for healthy light exposure for most of the day. Under an overcast sky, none of the scenarios reaches the minimal recommendation, and supplemental electric lighting should be provided, although the requirements for this electric lighting will be slightly lower for the blue variant.

3.2. Comparison of predicted alertness

The two classroom scenarios can also be compared directly in terms of their alertness potential through the cumulative response, $R_D$, which represents the capacity of the light exposure to have an effect on occupants’ alertness. In Figure 6, it can be observed as expected that $R_D$ is larger for the blue variant than for the base case at the studied desk position under both sky conditions. This demonstrates, on the one hand, the sensitivity of the model (and of behavioral responses) to react to lighting conditions with different spectral content. On the other hand, this shows the potential of the workflow for evaluating variations in the luminous environment via daylighting strategies for psychophysiological regulation. Although more research is needed to accurately interpret the $R_D$ scale, a recent study [8] showed that a difference of around 0.14 in $R_D$ after six hours of indoor daylight exposure was related to statistically significant differences in self-reports of alertness (measured with the Stanford Sleepiness Scale [17]), of well-being (measured with the Global Vigor scale [18]), and of objective reaction times (measured with a Psychomotor Vigilance Task (PVT) test [19]). In this case study, a difference in $R_D$ of 0.19 under clear sky conditions and of 0.32 under overcast sky

![Fig. 5: Comparison of the simulated melanopic EDI for the studied desk position between the base case and blue variant under clear (solid) and overcast sky conditions (dashed lines); the dotted line shows the recommended threshold for daytime exposure.](image1)

![Fig. 6: Comparison of the simulated cumulative response for the studied desk position between the base case and blue variant under clear (solid) and overcast sky conditions (dashed lines); the dotted line shows the recommended threshold for daytime exposure.](image2)
conditions after six hours of indoor daylight exposure was observed between the two scenarios. Following the same rationale, a potential effect on correlates of alertness could also be expected between the two classroom scenarios presented here.

4. Conclusion
In this paper, we present a simulation workflow integrating a spectral simulation tool and a light-driven prediction model of alertness. The goal is to help inform the design process of buildings regarding their potential for daylight exposure and associated psycho-physiological effects. This workflow is a first attempt of defining a tool that could help improve building occupants’ health, well-being, and productivity related to light. This is done by guiding towards a relevant combination of architectural features. The simulation workflow was applied to a simple case study - an existing classroom-, and an extreme variation of this classroom with blue floor and wall finishes (i.e., base case vs. blue variant). The workflow outputs showed differences between the two scenarios in terms of psychophysiological functioning, under both clear and overcast sky conditions. It is expected that, by comparing multiple variants of a design project, this workflow helps to indicate which variant has the most positive impact on occupants’ alertness.

Due to the relative infancy of the field of non-visual responses to light, the workflow should be used as an informative tool for design decisions rather than as a prediction tool. On one hand, the spectral simulation tool, Lark, shows an error that typically ranges between ±20% in spectral irradiance [3]. Lark does not account for the change in spectral content over the sky dome, considering a global sky SPD, which has been related to increased errors [20]. On the other hand, the nrR0 model was shown to be unable to predict specific values of alertness accurately [8]. In their current state, both the rD and R0 outputs of the model are also difficult to interpret and relate to real-world effects. In addition, and unlike other light-driven models of alertness, the nrR0 model only relies on light exposure to predict alertness, without considering any irregular sleep-wake cycles (e.g., shift work) in the equation. Future work is therefore needed, both in terms of refinement of prediction models and accuracy of spectral simulation tools, to improve the reliability and applicability of such simulation workflow.

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