# INTEGRATING NON-VISUAL EFFECTS OF LIGHT INTO LIGHTING SIMULATION: CHALLENGES AHEAD

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## ABSTRACT

Lighting is a major influential factor that affects human health and sense of wellbeing in the built environment. Since 2002, when the first reports on the discovery of a novel type of photoreceptor were published, a new field of study started to emerge at the intersection of photobiology and architecture. This novel photoreceptor is considered the primary mediator of non-visual responses to light in humans while the classical photoreceptors, rods and cones, are responsible for vision. Daily changes in the light spectrum and intensity impact a range of circadian, physiological and behavioral functions, including sleep quality, mood, alertness and cognitive performance. This new understanding on how light affects human physiology has sparked a growing interest in the role of lighting design on health and wellbeing. This paper discusses the challenges ahead in integrating non-visual effects of light – mediated by the novel photoreceptor – into a computer-based lighting simulation framework.

*Keywords*: Non-visual effects, Light, Wavelength, Spectral sensitivity, Lighting design, Simulation

## 1 INTRODUCTION

In addition to stimulating vision, light induces a range of circadian, physiological and behavioral, or 'non-visual' responses in humans. These effects are primarily mediated via novel intrinsically photosensitive retinal ganglion cells (ipRGCs) that contain the photopigment melanopsin. Considering that ipRGCs are more sensitive to blue light than scotopic and photopic vision, the current recommendations for lighting, which are based mainly on visual criteria, may not provide the necessary amount and type of light to synchronize important physiological and behavioral rhythms to the 24-hour day, such as alertness and cognitive performance.

The importance of lighting simulation is growing with increasing complexity of building design and higher performance requirements regarding energy consumption and wellbeing of individuals. New methods, created at the interface between photobiology and architecture, predicting the non-visual response to light are needed to support design decisions. The challenges ahead in integrating non-visual effects of light into a lighting simulation framework are not only related to the questions: How does the non-visual system work? How should we quantify light in terms of non-visual effects of light? They also include considerations about occupants' behavior in buildings in order to predict the amount of light received at the eye with respect to dynamic changes in the lighting environment.

## 2 PROPERTIES OF LIGHT AND THE NON-VISUAL SYSTEM

Physical aspects of light exposure are important in predicting the effects of a light stimulus on non-visual responses. Researchers have identified wavelength, intensity, pattern, history and timing of light exposure as some of the important factors that control the non-visual light response in humans.

### 2.1 Wavelength

The human eye has five types of photoreceptors: rods, short-, medium- and long-wavelength cones and ipRGCs. The photoreceptors' spectral sensitivity to light of different wavelength is not constant and is commonly described with a spectral sensitivity curve. Figure 1(a) shows the photopic efficiency function, *V(λ),* which corresponds to the spectral sensitivity of cones operating when light is plentiful, and the scotopic efficiency function, *V'(λ),* which describes the spectral sensitivity of rods operating when light is very limited. A non-visual efficiency function has not been standardized but a few suggestions have been made as a temporary solution. The circadian efficiency function, *C(λ)*, was proposed by Gall and Bieske [1] using the effects on nocturnal melatonin suppression as the indicator of spectral sensitivity based on measured data from Brainard et al. [2] and Thapan et al. [3]. Maximal circadian response to light ($\lambda_{max}$) occurs around 460 nm, illustrated in Figure 1(a). As a complement to *C(λ)*, Enezi et al. [4] proposed a melanopic spectral efficiency function, $V^Z(\lambda)$, peaking close to 480 nm, based upon the spectral sensitivity of melanopsin. Their methodology was validated against experimental data collected in nocturnal rodents.

## 2.2 Intensity

The intensity of light is an important quantitative measure but cannot be used exclusively to describe the characteristics of the visual or the non-visual system. It has been shown that there is a nonlinear intensity-response relationship between nighttime light exposure and various non-visual responses, including melatonin phase shifting, melatonin suppression and subjective alertness [5, 6]. The results demonstrated that ~100 lx could stimulate a half maximum response. Although the intensity-response curves are useful to obtain information about the magnitude of non-visual responses, they are only available in detail for relatively long-duration exposures and for limited light sources. Further, there are no data to estimate the intensity-response relationship for daytime light conditions to date.

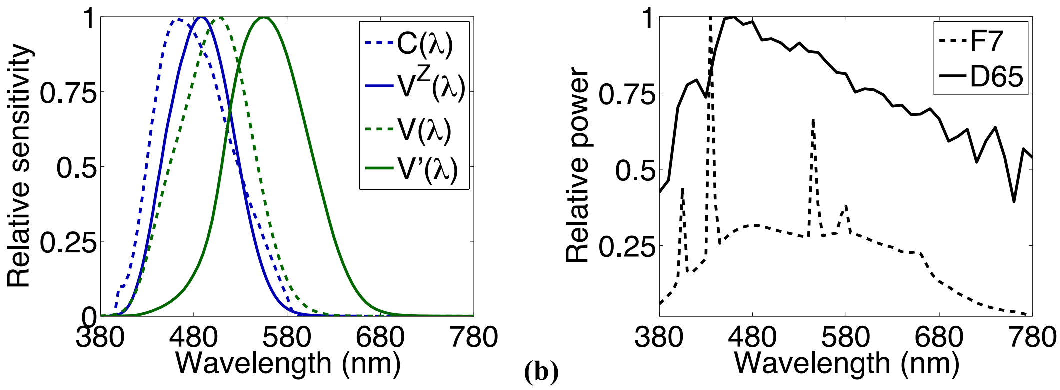


**Figure 1 – (a) The relative spectral sensitivity of *C(λ)*, $V^Z(\lambda)$, *V'(λ)* and *V(λ)*. The ipRGCs are more sensitive to light at short wavelength with a peak sensitivity that is blue-shifted ($\lambda_{max} \cong 480$ nm) relative to the photopic ($\lambda_{max} = 555$ nm) and the scotopic ($\lambda_{max} = 507$ nm) visual systems. (b) The SPD of F7 fluorescent lamp and D65 standard CIE illuminants.**

## 2.3 Pattern

Light exposure does not need to be continuous to have an effect on the non-visual system. In real-world situations, exposure to light of different intensities is typically intermittent. Experimental studies have shown that frequent changes in light stimuli over time between dim light and bright light pulses may have a greater impact on the non-visual system than was previously recognized. When intermittent bright light occupied only 23% of the total experimental time, ~70% of the response of continuous bright light was observed [7]. It appears that the ipRCGs cannot track short-term temporal patterns in light stimuli and are slower to activate than rods and cones [8].

## 2.4 History

The non-visual system adapts its responses to changes in light intensity and spectral composition over much longer time period than the visual system. Current response depends on the past and can extend over several hours, even days. Duration and intensity properties of past light exposure affect both spectral and intensity sensitivity of the non-visual system. Prior exposure to bright light can reduce the amount of non-visual responses [9, 10]. It has been shown that subjects exposed to 90 lx show 68% increase in melatonin suppression response when previously exposed to 1 lx as compared to subjects previously exposed to 90 lx [11]. Moreover, recent findings suggest that cone photoreceptors contribute identically to non-visual responses at the onset of a light exposure and at low-light intensity, whereas ipRCGs appear to be the primary non-visual photoreceptors in the response to long duration and bright light exposure [12].

### 2.5 Timing

The human non-visual system is responsive to light throughout the waking day, as described by a phase response curve (PRC) [13, 14, 15], which predicts maximum phase advances in the late night, maximum phase delays in the early night and minimal shifts during midday light exposure. PRCs do not exist for the alerting effects of light but light during both the day and night can increase subjective alertness. The effects of bright light (5,000 lx) on subjective alertness were found to be independent of its timing [16], but there may be time-of-day differences in non-visual responses to lower intensities of light (less than ~1,000 lx).

## 3 INTEGRATION INTO PRACTICE

Lighting design is a vast topic of enormous complexity. Lighting design methods used to assess visual function and comfort, based on wavelength- and time-independent calculations, cannot be directly applied to evaluate non-visual responses to light. The following two sections discuss the wavelength-dependent effects (Section 3.1) and the time-dependent effects (Section 3.2) concerning practical application and integration into a computer-based simulation framework.

### 3.1 Light as a function of wavelength

Illuminance is a standard measure for quantifying light and is widely used in lighting practice to quantify the brightness of a space and the stimulus to the visual system. The luminous flux is quantified by weighting the measured radiance flux of different wavelengths according to the spectral sensitivity of the visual system using the photopic $V(\lambda)$ function, see Figure 1(a). At constant radiance, the wavelength of 555 nm has the greatest brightness in photopic conditions. Although illuminance can be calculated or measured precisely, it is important to note that it only represents the visual effects of light under particular conditions and is not suitable for quantifying the non-visual effects of light. The individual contribution of rods, cones and ipRGCs to non-visual responses may differ with intensity and duration of a light exposure and it seems that the non-visual responses to light cannot be predicted using a single spectral sensitivity function.

A spectral power distribution (SPD) of a light source shows the amount of light as a function of wavelength and is a useful tool to compare light sources graphically. The term full-spectrum is often used to describe the spectral quality of different lamps, but electric light and daylight have very different spectral power distributions. Fluorescent full-spectrum lamps do not present the different wavelengths of the spectrum evenly. Figure 1(b) shows the relative SPD of a 6500 K full-spectrum fluorescent (CIE F7). In comparison to the relative SPD of a typical noon daylight (CIE D65), the daylight shows a smooth curve while the electric light shows spikes at different wavelengths throughout the spectrum.

Access to daylight in buildings has long been linked with good health and wellbeing, though electric lighting is more often used to conduct experimental research compared with daylighting. This is probably mainly due to the fact that daylight is constantly changing and hard to control. There is evidence that daytime exposure to blue-enriched electric light improves alertness, performance and sleep quality in office settings, when it is appropriate [17] but evening exposure to light-emitting diodes (LED)-backlit computer screen may also increase alertness and cognitive performance at an inappropriate time and thus may lead to problems with sleep initiation and quality [18]. Another study reported a decrease in alertness with blue window glazing while bronze and neutral glazing of similar degree of light transmittance had almost no effect on alertness level [19]. Differences in results between electric and daylight studies underline the need to increase our understanding of how spectral composition of light affects human non-visual responses.

A spectral representation is the only accurate way to model the interaction of light with colored surfaces and objects, but spectral computations are expensive. The spectral sensitivity of the human eye comprises the wavelength range from 380 nm to 780 nm, therefore sampling the spectrum at 5 nm intervals results in 80 samples that must be stored and processed for every rendered pixel. One of the main challenges of integrating non-visual effects of light into a lighting simulation framework is to adapt the existing methods and tools to the requirements of the visual and the non-visual system. Furthermore, there are two apparent difficulties to be overcome when using spectral models in rendering systems. One is the difficulty of interactively designing a spectral description of a desired color. The other is the difficulty of converting existing and useful libraries of RGB triplets into equivalent spectral representations for modeling non-visual responses, where simple RGB data are insufficient.

### 3.2 Light as a function of time

As architecture mediates the boundary between the outside environment and the human body, it becomes the most effective element in providing building occupants access to natural light. Daylighting simulation software tools are designed to evaluate visual requirements and comfort taking into account the stochastic fluctuations linked to the climate and to the behavior of the building's occupants. The evaluation usually compares simulated light intensity values on a horizontal plane with static threshold values. Most current daylighting simulation tools remain limited to time-independent (static) calculations such as the daylight factor, where fewer offer the capability to carry out annual calculations. The non-visual response must be evaluated based on dynamic threshold values, which depend on wavelength, intensity, pattern, history and timing of light exposure received at the eye, and ultimately the retina. Since the non-visual system responds relatively slowly to a light stimuli and adapts to changes in light intensity and spectral composition over much longer time periods than the visual system, lighting simulation software tools cannot be applied directly to evaluate the non-visual response to light. Challenges arise because the lighting simulation software has to provide a full spectral description of a light exposure at small time intervals. This extra computational effort may be the main barrier to integrating non-visual effects of light into practice.

At present, there is no methodology to predict the non-visual effects of light on humans depending on both dynamic and spectral characteristics of light exposure. Pechacek et al. [20] developed a method to study the impact of key architectural decisions on achieving static circadian-equivalent threshold values based on vertical illuminance at the eye level. The research was the first to incorporate these new discoveries into a preliminary lighting simulation framework. The study was extended and modified by Andersen et al. [21], where the 24-hour day was divided into three-day periods for distinguishing between the timing effects of a light exposure. The question that a model must answer is how the non-visual system remains sensitive to changes in light intensity over a wide range, which cannot be achieved using static threshold values. As a solution to the problem, we have proposed a modular model structure to predict the response of the non-visual system to the wavelength, intensity, pattern, history and timing of light [22]. Further research is needed to refine and validate model predictions, and to assess the reliability and adequacy of the model to effectively inform design decisions.

In addition to dynamic and spectral properties of light, movements of humans must be simulated to account for the amount of light received at the eye. The investigation of how lighting simulation can be extended beyond conventional methods to address behavior of occupants in buildings is ongoing. For a proof-of-concept, we applied four different strategies to generate light exposure patterns based on occupants' spatial behavior [23]. The results confirmed that the use of a space is an important factor, which strongly relates to the (temporal) pattern property of light discussed in Section 2.3. The challenges associated with measuring human non-visual responses and behavior in realistic settings continue to be a barrier for developing a computer-based lighting simulation framework that can predict the non-visual effects of light.

## 4 CONCLUSION

The link between lighting design and health outcomes is only starting to be established. Research in photobiology on the impact of light on human physiology and health is in its early stages, but is progressing rapidly. It has informed us about how light of different wavelength and intensity affects our capacities to respond to light dependent on time-of-day, and how exposure to dynamic lighting conditions influences such capacities. These findings offer the means to advance and validate novel additional guidelines to assess how architectural spaces might affect human health and wellbeing. Before integrating this new knowledge into a design support tool, more experimental work is needed outside the controlled laboratory settings that address the dynamics of human non-visual responses with respect to our daily light exposure. New approaches created at the interface between photobiology and architecture should continue to develop and be continually updated based upon accumulating measurable evidence.

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