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Monitoring and rendering of visual and photo-biological properties of daylight-redirecting systems

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Abstract

We previously developed a Camera-Like Light Sensor (CLLS) to record images using a novel High Dynamic Range (HDR) imaging vision sensor. The device was equipped with customized filters for adapting the camera's spectral sensitivity to both photopic and circadian sensitivities. Here, we aim at investigating photometric and circadian metrics to assess and simulate the potential of light on non-visual functions. The CLLS was used to monitor luminance and circadian weighted radiance (L_{ec}) over time in two test rooms, equipped with different daylight re-directing devices: venetian blinds (VB) and optical louver systems (OLS). Additionally, a computer simulation was performed for the two test rooms using the software RADIANCE: false colour images were used to demonstrate distribution of luminance and absolute values of L_{ec}. Circadian weighted irradiance (E_{ec}) was also computed at different positions corresponding to the gaze directions of a seated office worker. From our results, the VB provided overall higher illuminance compared to the OLS, but when a virtually seated observer was facing desk, the OLS provided larger circadian weighted irradiance in the afternoon. Our results illustrate the use of simulations for circadian metrics, which will be applicable in the future to predict the potential impact of light on non-visual functions for daylighting optimization in buildings.

Keywords: Non-visual effects; Camera-Like Light Sensor (CLLS); Monitoring; Simulation; Daylighting systems

1. Introduction

Lighting simulations are deployed during the early building design phase in order to ensure sufficient indoor lighting availability and quality for visual purposes. Physically-based rendering programs for computer simulations have been widely used for that purpose, such as RADIANCE which is applied based on as a backward ray tracing technique (Larson and Shakespeare, 1998). The simulation results obtained with RADIANCE are considered to be accurate for daylighting assessments (Maamari et al., 2003; Mardaljevic, 1999; Ulbricht et al., 2005; Thanachareonkit, 2008) and annual daylight simulations can be performed in order to predict the annual distribution of daylight provision for buildings mounted with different daylighting systems (Reinhart and Herkel, 2000; McNeil and Lee, 2013; Nabil and Mardaljevic, 2005).

Abbreviations: CLLS, Camera/Like Light Sensor; E_{ec} (W/m^2), circadian weighted irradiance; L_{ec} (W/m^2 sr), circadian weighted radiance; VB, venetian blinds; OLS, optical louver systems; HDR, High Dynamic Range.

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To optimize daylighting strategies in buildings, several daylighting metrics and photometric variables are used to assess indoor lighting conditions. Most of the lighting criteria aimed at complying with requirements for related visual tasks. It is also known that besides visual aspects, light also influences circadian, physiological and behavioural effects in humans: the so-called "photobiological" or non-visual effects of light. Many lighting properties have an influence on occupants' physiology and behaviour, for example on mood, alertness, health and well-being (Cajochen, 2007; Chellappa et al., 2011; CIE, 2004; Münch et al., 2012; Münch and Bromundt, 2012; Rea et al., 2008; Wirz-Justice and Fournier, 2010). In order to account more specifically for these non-visual effects of light, appropriate metrics must be used to assess when measuring light.

Photometric variables are commonly used to assess the light properties in the visible range, i.e. from 380 to 780 nm; they are weighted by the sensitivity of rods and cones for humans, according to the CIE luminous efficiency function or $V(\lambda)$ curve (CIE, 1978). On the other hand, the circadian sensitivity function or $C(\lambda)$ curve was introduced in order to assess light properties important for impacting on the non-visual effects of light (Gall and Bieske, 2004; Thapan et al., 2001; Brainard et al., 2001). The $C(\lambda)$ curve is based on the relative sensitivity by a new class of photoreceptors located in the retinal ganglion cells, the so-called intrinsically photosensitive retinal ganglion cells (ipRGC) (Lucas et al., 2014). The ipRGCs are known to convey many non-visual functions such as circadian rhythms, the pupil light reflex, and hormonal secretion (Lewy et al., 1980; Cajochen et al., 2005; Lucas et al., 2001; Foster, 1998; Czeisler et al., 1986). Prior research showed larger nocturnal melatonin suppression in humans with narrow-bandwidth blue light (446–477 nm) (Thapan et al., 2001; Brainard et al., 2001), indicating that melatonin suppression is an indirect sensitivity marker of ipRGCs function. A few research groups have already suggested circadian sensitivity curves (Gall, 2002; Rea, 2002; Bellia and Bisegna, 2013; Kozakov et al., 2008) based on melatonin suppression data in humans, first published by Brainard et al. (2001) and by Thapan et al. (2001). Recently, a few novel devices have been developed for measuring light fluxes in circadian metrics based on the existing circadian sensitivity curves (Bierman et al., 2005; Figueiro et al., 2013; Hubalek et al., 2006).

In two previous publications (Borisuit et al., 2013; Borisuit, 2013), we introduced a Camera-Like Light Sensor (CLLS) to monitor the distribution of circadian weighted radiance (L_{ec}) (Gall and Lapuente, 2002). The key advantage of the CLLS is its great acquisition of speed performance (Borisuit et al., 2012). With customized filters, the CLLS was adapted to the spectral sensitivity of human eyes expressed by the $V(\lambda)$ function according to CIE (CIE, 1978) as well as to the $C(\lambda)$ function, introduced by Gall (2002). The CLLS was used to assess luminance and L_{ec} distribution over time in realistic office spaces, and was used in an experiment with human subjects for visual comfort assessments a working day (Borisuit et al., 2013, 2012; Borisuit, 2013).

Beyond measurements on circadian metrics, a few authors have previously reported lighting simulations with respect to the human circadian system. Geisler-Moroder and Dür (2010) presented the distribution of circadian action factor a_{cv}, the ratio between $C(\lambda)$) and $V(\lambda)$ values for office lighting conditions, obtained using RADIANCE. Pechacek et al. (2008) proposed a method to assess the circadian efficacy of a given light source (such as daylight) by multiplying the known relative radiometric spectrum with an assumed $C(\lambda)$ curve in order to provide a "circadian-e quivalent" lux [unit: W-C(λ)] of the light source. Minimum and maximum "circadian-equivalent" illuminance thresholds were considered as "benchmark" for non-visual aspects of each light source (mainly for daylight as D55, D65 or D75) (Andersen et al., 2011); the threshold values were used in DAYSIM, a computer software based on RADIANCE, in order to predict alerting levels as a proxy of health with respect to light spectrum, intensity and timing of light.

In this study, we investigated the distribution of circadian weighted radiance in two test rooms equipped with different daylight-redirecting systems. The CLLS was used to monitor circadian weighted radiance. Additionally, several lighting simulations of the two test rooms were performed; circadian weighted radiance of the test rooms was also computed and compared with the CLLS monitoring results. Firstly, computer models of two test rooms mounted with different daylighting systems were built and the photometric variables of the two models were compared with physical measurements. Secondly, the luminance and luminance ratio of the models were compared with the images obtained by the CLLS equipped with $V(\lambda)$ filters. A comparison of the distribution of L_{ec} (rendered by simulation) with data monitored by the CLLS equipped with $C(\lambda)$ filters was then carried-out. Lastly, the two different daylighting systems were investigated and qualitatively compared.

The computer simulations carried out in this study followed the RGB approximations method by using RADIANCE, as suggested by Geisler-Moroder and Dür (2010). This study targeted to use absolute values of circadian weighted radiance and irradiance. This is not the same procedure as in previous studies where the circadian stimulus, (= the ratio of $C(\lambda)$ and $V(\lambda)$ values Geisler-Moroder and Dür, 2010) and the "circadian-equivalent" lux were investigated (Pechacek et al., 2008; Andersen et al., 2011, 2013). Circadian weighted irradiance was used to compare the potential of a certain light source for non-visual effects provided by two different daylighting systems. This study also served to confirm the reliability of daylighting simulations to assess circadian metrics. For this purpose, we compared the simulations with our CLLS monitoring over time. The daylight flux reproduced by the simulation was determined at different positions in the rooms and over time, in order