ASSESSMENT OF CIRCADIAN WEIGHTED RADIANCE DISTRIBUTION USING A CAMERA-LIKE LIGHT SENSOR

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ABSTRACT

Suboptimal light distribution in a room can cause visual discomfort and glare. Next to rods and cones, perception of light is also governed by a third class of photoreceptors, important for circadian rhythm regulation and non-visual functions such as alertness, mood and hormonal secretion. These receptors show greatest sensitivity in the blue part of the visible light spectrum. In order to assess light distribution with respect to non-visual sensitivity functions, we aimed at validating a new device to create light distribution maps with a circadian weighted radiance (L_{ec}) which accounts for this difference in sensitivity.

We utilized a camera-like light sensor (CLLS) to assess the distribution of L_{ec}. For this purpose, we equipped the device with customized filters to adapt the camera's spectral sensitivity to circadian sensitivity, similarly, as we had previously reported for the photometric calibration with the same device [1]. After spectral calibration and circadian weighted radiance calibration, we validated the CLLS in real scenes. The results showed that circadian luminance maps of a room can be efficiently assessed in a very short time (i.e. within 100 ms) under electric lighting as well as under daylighting conditions. We also used the CLLS to compare the L_{ec} values between two rooms, equipped with different daylighting systems such as LightLouver^{TM} and standard venetian blinds. Our results showed different dynamics of luminance and L_{ec} in the course of the day with highest values at noon. We also found higher luminance and L_{ec} values in the test room with the venetian blinds, when compared to the room equipped with LightLouvers^{TM}.

Taken together, the validation of circadian luminance maps under real dynamic lighting conditions offers new possibilities to integrate the CLLS into advanced (day-) light sensors systems. This would allow to instantly adapting ambient lighting conditions with respect to tailored biological user needs.

Keywords: Light distribution, circadian weighted radiance, daylighting system, camera

INTRODUCTION

Conscious light perception via rods and cones is important for visual functions, visual comfort, glare and contrast in humans; it also depends on luminance distribution. A decade ago, a new class of photoreceptors in the retinal ganglion cells has been described, mainly responsible for non-conscious light perception to regulate circadian functions, the pupil light reflex and hormonal secretion. One important indirect marker for activity of these cells in response to light is suppression of the pineal hormone melatonin during night time. It has been shown that this light induced melatonin suppression is greatest in response to blue light exposure (446-477 nm) [2,3]. Sensitivity to different wavelengths of light was tested and subsequently a specific circadian sensitivity function created. This function is called C-lambda curve ($C(\lambda)$) [4] and differs from the V-lambda curve which reflects the photopic eye sensitivity ($V(\lambda)$).

Several new tools assessing (photopic) luminance maps were developed within the last ten years [5-8]. We recently described the different calibration processes of the camera-like light sensor (CLLS), developed by the Centre Suisse d'Electronique et de Microtechnique, and demonstrated its potential in creating luminance maps in real scenes under highly dynamic daylight conditions [1]. In order to also evaluate light distribution from an observer's perspective at the eye level, and with respect to non-visual functions, we intended to create light distribution maps with a circadian weighted radiance (L_{ec})[4]. We used our CCLS, equipped with customized filters enabling to adapt the camera's spectral sensitivity to the C(λ) function. We finally compared the distribution of L_{ec} using circadian luminance mapping under electric and daylighting conditions at different times of day.

METHODS

Spectral sensitivity calibration

In our previous work, the CLLS was calibrated based on the photometric sensitivity function (V(λ))[1] and corrected also for vignetting effects. The aim of this project was to use the CLLS device for circadian luminance maps: we thus first performed the spectral calibration with respect to the circadian sensitivity function (C(λ)). Narrow-bandwidth monochromatic light beams were used as a reference light source. The CLLS captured the photos of the light beams at 470 nm with different intensities. Simultaneously, we measured L_{ec} of the emitted light beams with a calibrated spectrophotometer (Specbos 1201, JETI, Jena, Germany). We then correlated the values obtained from the CLLS and the L_{ec} from the spectrophotometer. The camera provided a single value per pixel on a greyscale (in arbitrary units from 0 to 1024 digits); we used an exponential function ($R^2 = 0.9986$) in order to fit the greyscale and the respective L_{ec} (W/sr.m^2).

The same CLLS measures and those of the spectrophotometer were then taken at a constant light intensity, while modifying the wavelength of the light beam in 5 nm steps from 380 to 780 nm. The relative raw spectral sensitivity of the CLLS and the circadian sensitivity curve taken from the literature [4], are shown on Figure 1a). This sensitivity curve is based on the action spectrum for light-induced melatonin suppression, performed by Brainard *et al.*[2], and Thapan *et al.* [3] with a peak at 464 nm.

To implement customized filters in the camera, we calculated their optimal thickness to correct for the spectral response of the CLLS. We then performed the same steps as described above to determine if the filter corresponds to the circadian sensitivity function (Figure 1b). In order to assess the error between the relative spectral sensitivity from the CLLS and the circadian sensitivity (4), we applied the CIE standard error (F') of the V(λ) function [9] on the modified formula for C(λ) [see equation (1)]. We obtained a standard error of 10.4% for C(λ) by using the modified formula:

$$f' = 0.93584 \int_0^\infty \left| \; s(\lambda)_{rel} - C(\lambda) \; \right| \; d\lambda \% \qquad (1)$$

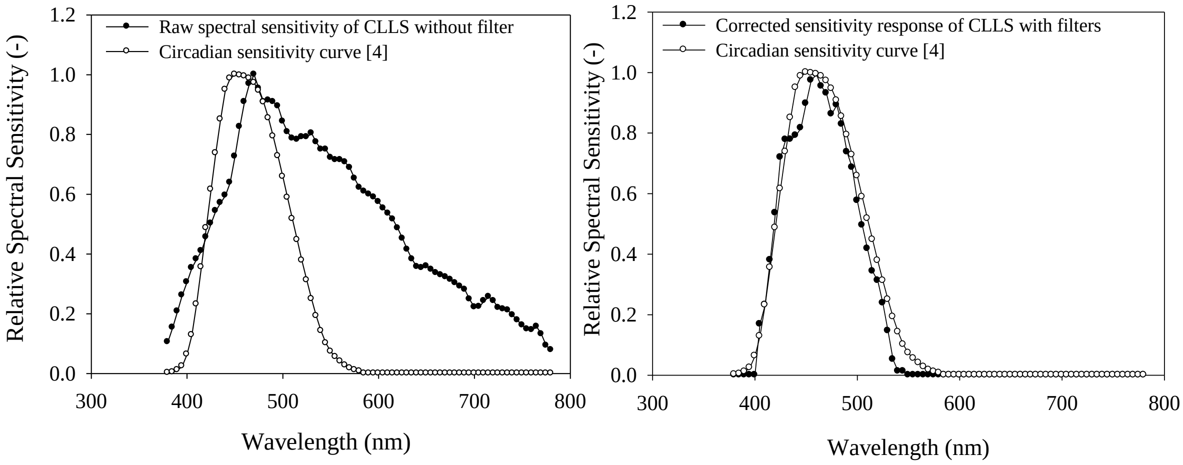

Figure 1a-b: Relative spectral sensitivity assessment of the CLLS; 1a) Relative raw spectral sensitivity of the CLLS (normalized data; black circles) and circadian sensitivity function (C (λ)[4]; white circles). 1b) Corrected spectral sensitivity response of the CLLS, equipped with filters (black circles) and circadian sensitivity function C (λ) (white circles [4]).

Circadian weighted radiance calibration

To perform the photometric calibration, a total of 83 measurements (from 0.04 cd/m^2 to 23’871cd/m^2) were made by using simultaneously the CLLS and a luminance meter (Minolta LS-110) as the reference sensor. Polychromatic white light from a 1000 W Xenon lamp and a 1200 W metal halide spotlight were used as reference light sources for the photometric calibration. The camera and the calibrated spectrometer monitored the emitted radiance values: the camera provided the associated pixels on a greyscale (in arbitrary units from 0 to 1024 digits); the luminance meter gave the corresponding luminance (cd/m2). The best fit between the pixel greyscale values and their associated luminance was determined [10] by using two different functions: for greyscale values which were lower than 425 (arbitrary units), we used an exponential function (R^2=0.97); for greyscale values higher than 425 (arbitrary units), a polynomial function was used (R^2=0.98; Figure 2). Both functions were finally implemented in the CLLS software.

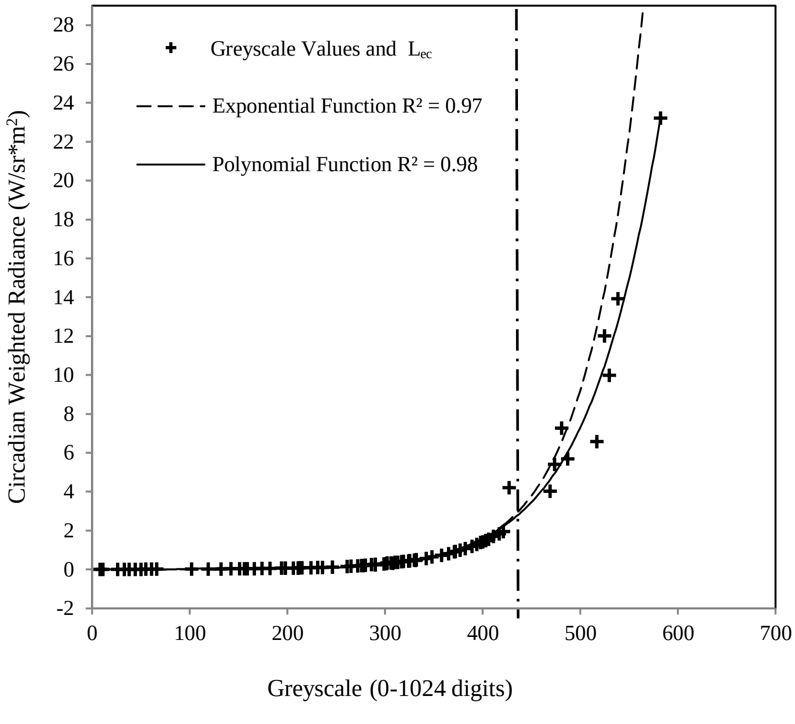

*Figure 2: Correlations between pixel greyscale values (arbitrary units from 0-1024) and associated luminance (W/sr*m^2). The black crosses indicate measurements taken with the CLLS and the spectrophotometer; the solid line indicates the regression line for the two functions (R^2=0.97 and R^2=0.98). The vertical dashed line depicts the border for the two regression functions at greyscale value 425 (arbitrary units).*

RESULTS

Circadian weighted radiance mapping

We tested the CLLS in an office room located in the LESO solar experimental building on the EPFL campus (Ecole Polytechnique Fédérale de Lausanne, Switzerland). We used 20 different room elements as targets for measurements (Figure 3). A set of pictures was taken under electric lighting conditions (2 x 36 W fluorescent tubes; 3000K) and under daylight conditions (clear sky). The L_{ec} values of the room elements were simultaneously assessed by the spectrophotometer and by the CLLS. Both data sets were then compared with the luminance meter values, as shown on Figure 4. The coefficients of determination (R^2) between L_{ec} measured with CLLS and the spectrophotometer across all room elements were: 0.96 for electric lighting and 0.91 for daylighting.

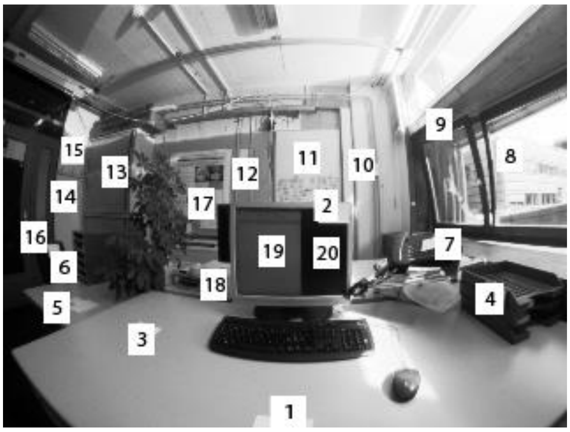

Figure 3: Locations of different room elements for the validation of the CLLS. 1=desktop, 2=PC screen, 3=desktop left side, 4=desktop right side, 5= second desk left side, 6 = chair, 7= telephone, 8= window, 9 upper window, 10 = back wall 1, 11 = white board, 12=back wall 2, 13 = closet, 14 = wall left side, 15= door, 16=bottom of the door, 17= poster, 18=behind PC screen, 19=document on PC screen, 20=black wallpaper on PC screen.

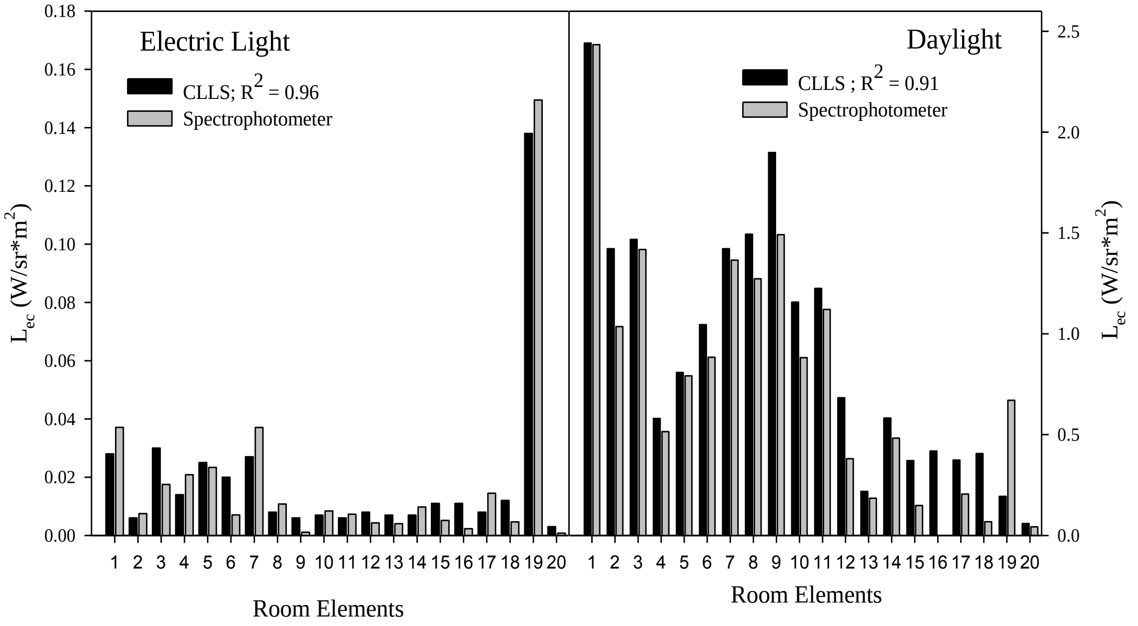

Figure 4: Luminance mapping derived from L_{ec} values of different office room elements (see Figure 3). The data points were extracted from CLLS (black bars) and the reference luminance measurements (spectrophotometer; grey bars). Left: assessment under electric lighting conditions; right: assessments under daylight conditions.

Circadian weighted radiance mapping at different times of day

After these calibration steps, the CLLS was tested in two test rooms at the Lawrence Berkeley National Laboratory (LBNL; CA, USA), during a short term stay of the first author. The two rooms (A and C) are equipped with standard venetian blinds (room A) and Light Louvers™ (room C). Both daylighting systems were located in the upper part of the windows, whereas the lower parts of the windows were completely covered. A set of pictures was taken with the CLLS at 9AM, 12PM and 3PM. Luminance and L_{ec} were measured for the same reference points in both rooms (walls, windows, task area, and ceiling). The ratio of L_{ec} and luminance (L_{ec}/L) was then determined to assess the circadian efficiency of the light distribution in the room: a higher ratio indicated a higher circadian efficiency. A total of 84 measurements were taken under clear sky conditions; extracted luminance, L_{ec} and ratio on log-transformed values were analysed with 2-way rANOVA with factors 'time' and 'room'.

We found higher luminance and L_{ec} in room A (venetian blinds) than room C (LightLouver^{TM}) for all three time points. For both rooms, luminance and L_{ec} were higher at 12PM than at 3PM and lowest at 9AM (Figure 5a-b, 'room' x 'time'; $p<0.05$). The ratio of L_{ec}/L was overall higher in room A than C ($p<0.05$; main effect of 'room'); the ratio for both rooms was higher at 3PM than 9AM ($p<0.05$; main effect of 'time'). First comparisons between two different locations in the room (near by the window and deeper in the room) did not reveal any difference in circadian efficiency of light distribution ($p>0.20$).

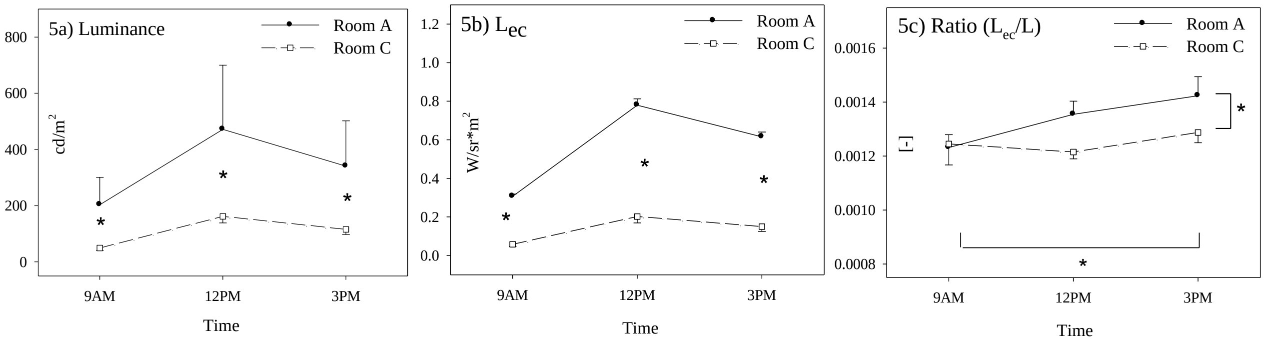

*Figure 5a-b: Photopic luminance (5a) and L_{ec} (5b) for room A (black circles) and C (white squares) at 9AM, 12PM, and 3PM. The Ratio between L_{ec} and Luminance was higher in room A than C; and larger at 3PM than 9PM; *=$p<0.05$; mean ± SEM).*

DISCUSSION

The CLLS was successfully calibrated and tested in real scenes: the calibrations resulted in high correlations with a reference device. The validation in real scenes revealed that the correlation of L_{ec} between CLLS and values monitored with spectrophotometer was high for constant electric lighting conditions and daylighting conditions under clear sky. The room equipped with standard venetian blinds provided higher luminance and L_{ec} than the room equipped with LightLouver^{TM} throughout the day, with highest values at noon. The most likely reason for the dynamics of luminance and L_{ec} is due to the change in the angle of incoming sunlight. Interestingly, circadian efficiency was highest at 3PM: one reason for this might be that the different angle of daylight did not provide only different light levels, but also accounted for changes in the spectral composition of daylight.

One important question remains: what does a higher or lower circadian efficiency mean? It can be used as a proxy for biological functions. Future experiments should also test other variables, for example circadian efficiency of light for human alertness, mood or performance.

The first experimental assessments of circadian weighted luminance maps of two complex fenestration systems were also carried out in this work: the latter provided different circadian weighted light distributions. Therefore it will be important to further analyse those systems also with respect to circadian weighted luminance at different locations in the room and at varying times. Using the CLLS for circadian luminance mapping is thus innovative in particular for the assessments of light with respect to non-visual biological functions in architectural settings.

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REFERENCES

1. Borisuit, A, Münch, M, Deschamps, L, Kämpf, J, Scartezzini, JL: A new device for dynamic luminance mapping and glare assessment in buildings. Proc. of the SPIE 2012 Optics+Photonics Conference conference. San Diego, 2012.
2. Brainard, GC, Hanifin, JP, Greeson, JM, Byrne, B, Glickman, G, Gerner, E, Rollag, MD: Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. Journal of Neuroscience. Vol.21(16) pp 6405-6412, 2001.
3. Thapan, K, Arendt, J, Skene, DJ: An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. Journal of Physiology. Vol.535(Pt 1) pp 261-267, 2001.
4. Gall, D: Circadiane Lichtgrössen und deren messtechnische Ermittlung. Licht. Vol.11-12 pp 1292-1297, 2002.
5. Bellia, L, Cesarano, A, Minichiello, F, Sibilio, S: Setting up a CCD photometer for lighting research and design. Building and Environment. Vol.37(11) pp 1099 - 1106, 2002.
6. Inanici, M: Evaluation of high dynamic range photography as a luminance data acquisition system. Lighting Research and Technology. Vol.38(2) pp 123 - 134, 2006.
7. Beltrán , LO, Mogo , BM: Assessment of luminance distribution using HDR photography. Proc. of the 2005 ISES Solar World Congress conference. Orlando, FL, USA, 2005.
8. Borisuit, A, Scartezzini, JL, Thanachareonkit, A: Visual comfort and glare risk assessment by HDR imaging technique. Architectural Science Review. Vol.53(4) pp 359-373, 2010.
9. CIE: CIE Technical support. Methods of characterizing illuminance meters and luminance meters - Performance, characteristics and specifications. Vol. CIE 069-1987, Vienna, CIE Central bureau, 1987.
10. Andersen, M: Innovative bidirectional video-goniophotometer for advanced fenestration systems. Ecole Polytechnique Fédérale de Lausanne (EPFL), 2004.