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Daylighting & Electric Lighting (Green Lighting)

Toward proper evaluation of light dose in indoor office environment by frontal lux meter

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Abstract

The wearable Brazilian illuminance meter “OcuLux” provides the opportunity to monitor continuously pupilar illuminance for indoor environment. The device is calibrated to evaluate the illuminance in lux for the range of 0 to 3500 lux with 23% of precision. This sensor was worn for 19 days in an office room of the LESO solar experimental building at EPFL (Lausanne, Switzerland), equipped with Anidolic Daylighting System (ADS) as well as a conventional window, to assess the light dose received by a human subject (30 year old female). The results showed that: i) the light dose is lower than the recommended values for most of the time; ii) in spite of asymmetrical workstation orientation, the light dose received during the morning and in the afternoon are comparable and iii) the impact of day length and sky condition on the light dose at the pupillary level is considerable.

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Keywords: Indoor office environment; human cecntric lighting; light dose at pupillary level; non-image-forming effects of light; visual comfort

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1. Introduction

Light is an important external cue for adjusting humans' circadian rhythm or internal clock: this is known as Non-Image-Forming (NIF) effects of light [1], [2]. People nowadays spend more than 90% of their lifetime in an indoor environment. In this situation, the light-induced circadian rhythm entrainment differs considerably from the natural stimulation, especially for people working far away from building facades or during nighttime. Lack of proper entrainment of circadian rhythm due to insufficient light stimulation is responsible for serious health issues, like sleep deprivation and depression; it reduces productivity and alertness, an undesirable socio-economic burden for the country. Proper assessment of the light flux received by the eyes of building occupants is an important step toward characterizing and mitigating this issue.

It was showed, under controlled conditions [3], that 30 minutes of exposure to a bright daylight near windows (with a pupillary illuminance ranging from 1000 to 4000 lux) was almost as effective as a short nap in reducing normal post lunchtime drowsiness in healthy subjects. Several authors contributed to determine the sensitivity threshold of the circadian system: they demonstrated that the human circadian pacemaker phase shifts are responding to relatively low illuminance levels for a broadband spectrum white light source (~100 lux at the cornea or 300-500 lux on the horizontal plane). Later on, it was shown that a pupilar illuminance ranging from 50 to 100 lux can affect the circadian system of humans in laboratory settings [4].

For guaranteeing visual performance, the standard EN 12464-1 recommends a horizontal illuminance of 300-500 lux on the work plane; the Handbook of Industrial Engineering asserts that in offices illuminated by overhead luminaires the ratio between vertical and horizontal illuminance must be in the range of 0.3 to 0.5 [5]. Therefore, a minimum vertical illuminance of 150-250 lux (500*0.3 and 500*0.5) should be provided to the office occupants.

A study [6] performed using an Actiwatch-L light dosimeter, placed around a subject's neck as a medallion for the purpose of the experiment, suggests that the illuminance level as low as 40 lux measured in a vertical plane (~200 lux in the horizontal plane) during three evening hours (between 10PM and 1AM) can induce a phase shift of the human circadian pacemaker. It was observed moreover [7] that employees experiencing more light (day- and artificial light) during office hours show lower fatigue levels and higher sleep quality than other. However, evaluating the indoor lighting conditions from a fixed point of view and monitoring photometric quantities, such as the horizontal and vertical illuminance, might not necessarily reflect the light level received in reality by the building occupants.

This article presents the methodology and the results issued from the use of a front head-mounted illuminance meter in a south-facing office room of the LESO solar experimental building on the EPFL campus in Lausanne, Switzerland. This device was calibrated first by the way of a reference illuminance meter. In a second step, a human subject wore the sensor during 19 days while she was performing typical office tasks, in order to assess her pupillary illuminance level at a workspace.

2. Methodology.

2.1. Experimental setup

The experiments were carried out in a south-facing office room located on the ground floor of the LESO solar experimental building in EPFL main campus (Lausanne, Switzerland; latitude: 46°32' N, longitude: 6°36° E, a.s.l.: 410 m). The treated floor area of the office room is equal to 15.7 m^2 and the room height to 2.8 m (Fig. 1 (a)). Two LED-based ceiling luminaires are fitted in the office room, which is used a test bed; the characteristics of each of them are the following: (i) Luminous flux: 2400 lm, (ii) Energy consumption: 23 W, (iii) Correlated Color Temperature: 4000 K and (iv) Color Rendering Index: 80.

The Unified Glare Rating (UGR) sensed by the room occupants is expected to be lower than 19 [8]. There is a conventional e-coated double glazing on the lower part and an Anidolic Daylighting System (ADS) [9] on the upper part; this system collects direct and diffuse daylight issued from the sun and the sky vault through a zenithal collector, composed of a compound parabolic reflector protected by a double glazing [10]. There are two external motorized fabric blinds controlled by manual switches located in the room or through a KNX communication network [11]. The office room has standard office furniture and two main workstations.

During the experiment, the shading system and the artificial lighting were automatically controlled, to guarantee the visual comfort for the occupant (by minimizing glare risks) and sufficient illumination on the workstation (by optimizing the work plane illuminance). The subject, on the other hand, was allowed to manage manually the shadings using the switches located in the room in order to tune the lighting conditions.

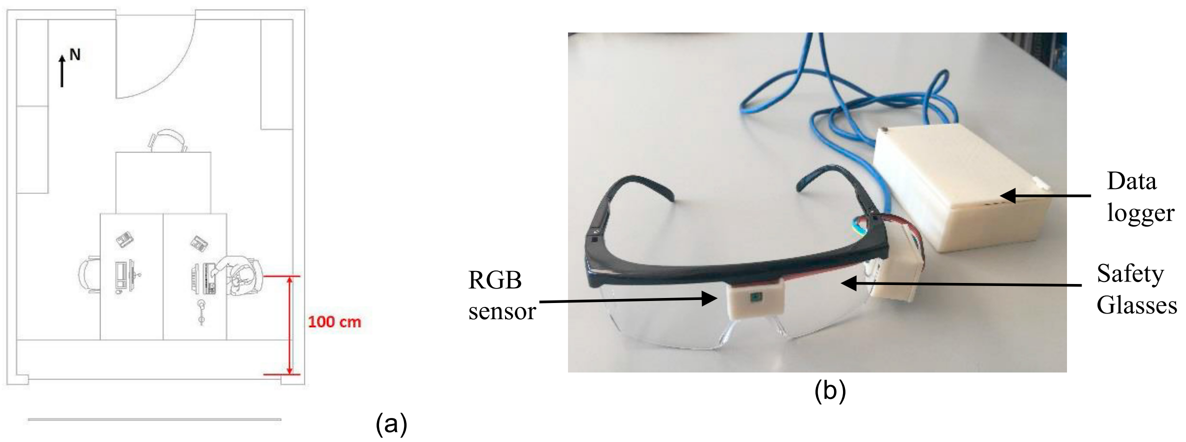

Fig. 1: (a) West-facing workstation occupied by the subject during the measurement campaign (plan to the scale); (b) "OcuLux", wearable sensor evaluating real-time frontal illuminance.

2.2. 'OcuLux' device

In this experiment, a Brazilian device named 'OcuLux' (Fig. 1(b)) inspired by the Swiss German 'LuxBlick' device developed by Hubalek at the ETH-Zürich was developed [12]. This wearable device has two parts: (i) safety eyeglasses with a RGB sensor in the center point and (ii) a data logger. The data logger contains an electronic circuit, which is connected to the Arduino NANO, a Real Time Clock (RTC), a Micro SD Card Reader and a 9V battery. The monitored data stored in the logger can be transferred by the way of a USB cable to a PC computer for further analysis and visualizations. The RTC allows for recording at a given time step and keeps the cadence independent of the 9V battery. In this way, it is possible to replace the battery during an experiment without compromising the RTC settings and data logging process.

The S9706 RGB sensor (Hamamatsu Photonics, Tokyo, Japan) converts the incident light flux into 12-bit digital signals. An amplifier is used for each RGB photodiode elements arrayed in a mosaic pattern, allowing simultaneous accurate measurements of the RGB components of the incident light flux [13]. An integration time of *30ms* is chosen to avoid a RBG sensor saturation at 5000 lux.

The 'OcuLux' was mainly designed for indoor lighting environments where the illumination conditions are typically lower than outdoor. There is no direct sunlight reaching the sensor the sun shading control system being designed to optimize visual comfort by avoiding glare sensations. For this reason, we opted for the *high* photosensitivity setting of the device during the subjects' experimentation. On the other hand, it is obvious that the RGB sensors provide only an estimation of the real physical illuminance as the visible spectrum being only sampled at 3 predefined wavelengths; the peak sensitivities of the three RBG 'channels' are located at 465, 540 and 615 nm for blue, green and red respectively. In order to improve the precision of these measurements, a calibration process limited however to indoor daylighting conditions (clear and overcast sky) without direct sunlight, was applied by comparing the latter with a reference illuminance meter (T-10 by Konica Minolta, Japan).

The sensor digital output RGB_{raw} span from 0 to 4095 digits (12 bit data, ranging from $2^0 - 1$ to $2^{12} - 1$). Using the photosensitivity parameters issued from the sensor's catalogue ($S_r = 5.8, S_g = 4.1, S_b = 1.9$), the digital output was translated into RGB_{linear} values. In the next step, the relative luminance values are derived from $the\ RGB_{linear}$ values using the following luminosity equation:

$$Y = 0.2126R + 0.7152G + 0.0722B \tag{1}$$

Finally, through a calibration process, the luminance values (Y) are transformed using a conversion factor using the illuminance values measured by the reference illuminance meter. The relative discrepancy is equal to 23% for values measured in the range of *0 -2500 lux*. The sensor is saturated for illuminance, which are larger than 3500 lux.

The hourly light dose [lux.h] is calculated by integrating the measured illuminance over a one hour period. A daily light dose is made of the sum of hourly light doses.

2.3. Experimental protocol

A 30 years old female human subject with normal vision (no corrective glasses) wore the 'OcuLux' device for 19 full days from 8AM to noontime and 1PM to 5PM. The experimental study was carried out between October 2016 and January 2017 spanning different sky conditions (overcast, partly cloudy and clear sky). The position and the orientation of the subject is illustrated in Fig. 1 (a) placed closed to the window side. She maintained a normal work rhythm and kept a scheduled diary. She observed that she did not experience any discomfort glare and that the work-plane illuminance is appropriate for paper-based and VDT-based tasks. The samples with light saturation were discarded; the total duration of this 'in-situ' experimentation was about 128 hours.

3. Results

An example of data monitored during a workday is illustrated in Fig. 2 (a). Since the office occupant is facing west, she is exposed to sunlight after the middle of the morning; peaks are caused by views towards the office window located in southern direction. The figure shows that after 10AM the illuminance recordings at the subject's eyes were primarily ranging between 1000-1500 lux in the morning and 1000-1700 lux in the afternoon; it decreases at the end the day due to sunset.

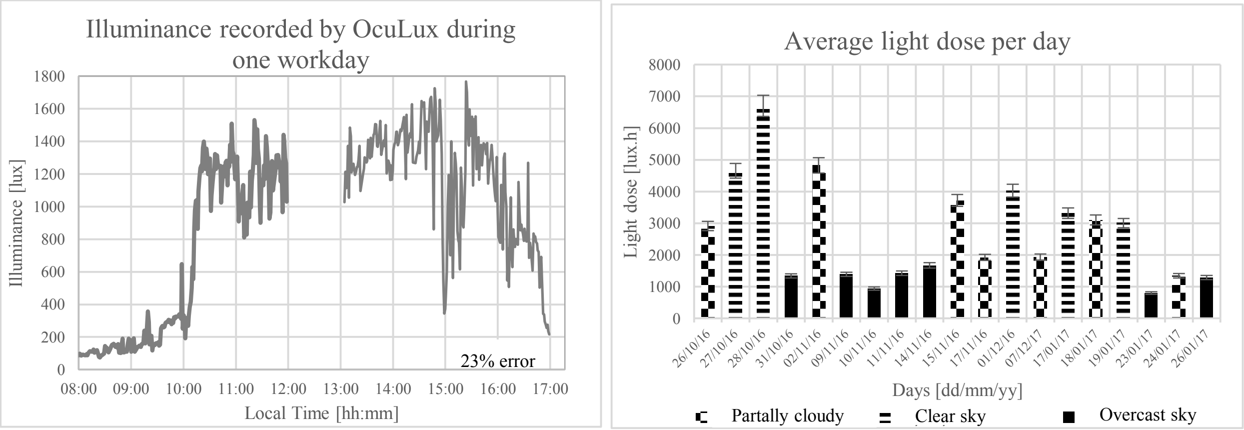

Fig. 2. (a) Example of illuminance recording by OcuLux for the office occupant during a workday in October 28, 2016 under clear sky; (b) Average light dose [lux.h] received by the user during the days with more than six hours of data.

One can observe that the daily light dose, received by the subject during cloudy days remains below 800 [lux.h]. For partly cloudy skies the occupant is experiencing a light dose ranging between 1300 and 4800 [lux.h]; it comprises between 3000 and 6700 [lux.h] for clear skies (Fig. 2 (b)).

It was expected that the light dose in the afternoon would be larger than the one in the morning, as the workstation is facing west. However, Fig. 3 (a) shows that there is no statistically significant difference between the light dose received on average in the morning and in afternoon. The similarity is very likely due to the management of the sun shadings, either by the subject herself or by the controller, in order to optimize the visual comfort and reduce glare sensations. This fact shows that the use of daylight in an indoor environment is limited by visual comfort constraints for a given position/orientation, meaning that the daylight flux can accordingly not exceed a certain limit.

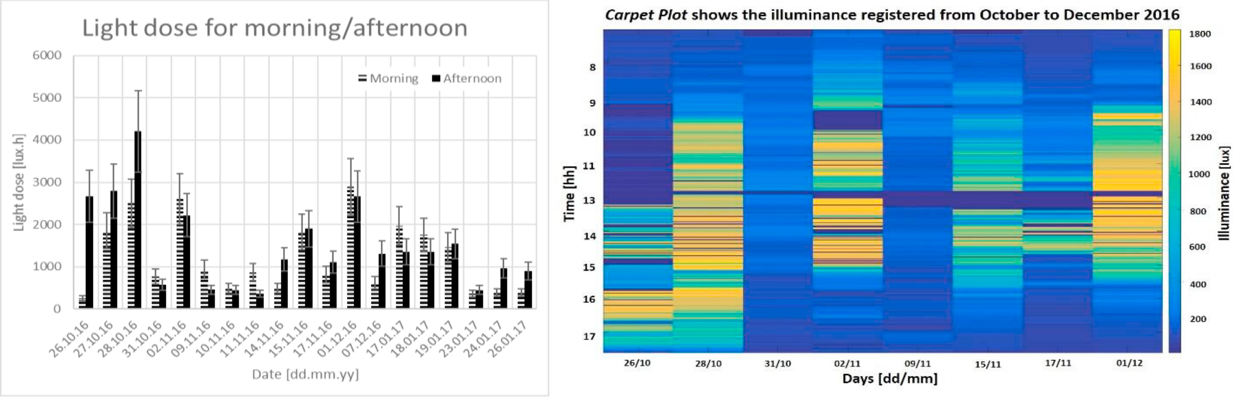

Fig. 3: (a) Light dose divided per morning/afternoon periods; (b) Carpet plot of the pupilar illuminance for representative days

The carpet plot in Fig. 3 (b) shows the relationship between the monitored pupillary illuminance, the duration of the day and the weather conditions for typical days in October and December 2016. The yellow lines refer to illuminance values larger than 1200 lux, blue lines to values lower than 600 lux. The absence of yellow and green lines indicate the occurrence of an overcast sky (e.g. October 31 and November 9). During partly cloudy days, an increase of illuminance values from 10AM to 3PM (e.g. November 2) can be observed. The predominant presence of yellow lines outlines days with a clear sky (e.g. October 28 and December 01). In some days, the weather varied from an overcast to partly cloudy sky: this can be illustrated by yellow and green lines for some day (e.g. October 26, November 15). Although October 28 and December 01 present the same sky conditions, the duration of the day had an influence on the recorded illuminance: in a longer day the illuminance reached ~700 lux in the end of the afternoon without any use of electric lighting, while on December 1, the same illuminance was monitored only until 3PM.

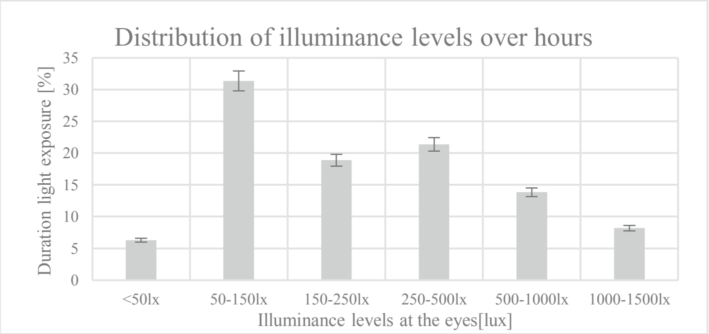

Fig. 4: Duration of exposure to different illuminance levels as a percentage per hour.

The distribution of illuminance values over hourly bins is shown in Fig. 4. Even if the required minimal vertical illuminance is expected to reach 150-250 lux, the figure shows that the subject was exposed to pupillary illuminance ranging from 50 to 150lx of pupilar illuminance during one third of the period. Records ranging from 150 to 250lx were observed during 18% of the time and between 250 and 500lx during 21% of the time. Values higher than 500lx were recorded during 13% of the time. As the data monitoring was performed during the fall/winter period in Central Europe, short days and large occurrences of overcast/partially cloudy skies lead to such lower illuminance records. It should also be considered that the subject performed activities both in a vertical plane (VDT screen) as well as horizontal one (paper-based tasks); leading to lower frontal illuminance in second case.

4. Conclusion

The use of a wearable front-head illuminance meter, such as ‘OcuLux’, provides a great opportunity for monitoring of the pupilar illuminance of human subjects without disturbances due to their head-movement. The LESO solar experimental building is equipped with Anidolic Daylighting Systems, which increase the daylight provision in the office rooms. By the way of this on-site experimentation, the average daily light doses received by a human subject during 19 days were monitored. We observed that the light dose is not considerably affected by the varying sun profile angle and that visual comfort constraints limit the daylight penetration in the room. The influence of the duration of the day and the weather conditions on the light dose was observed as significant. Finally, we found out that the monitored pupillary illuminance is lower than the one recommended by standards during wintertime, even if the subject did not complain about the illumination sufficiency. This finding shall however be confirmed by more extensive measurement campaigns with subjects of different sex, age and ethnic group.

As a future work, one can also utilize the ‘OcuLux’ as a reference device for opting the optimal position and orientation of a fixed illuminance/glare sensor. Such a sensor can provide valuable information to the building automation system regarding the lighting conditions in an indoor environment, guaranteeing a personalized visual comfort and mitigating the electric lighting demand.

Acknowledgements

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