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Daylighting & Electric Lighting (Green Lighting)

On the integration of Non-Image-Forming effects of light on venetian blinds and electric lighting control

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Abstract

Light induces important "Non-Image-Forming" (NIF) effects on human physiology and behavior, such as improvement of alertness, cognitive performance and mood. Considering these effects in office lighting can improve well-being and productivity of the occupants. This study introduces and evaluates NIF effects of light on humans within a Building Automation System of an office environment. Real-time luminance mapping is assessed by novel HDR vision sensors; the monitored data is used for a smart user-centric controller of the indoor electric lighting and sun shadings. A preliminary evaluation of this advanced controller was carried out during one week in a single-occupied office in the LESO solar experimental building at the Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland. The system demonstrated to have sound capabilities in satisfying visual comfort conditions and well-being for the office's occupant.

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Keywords: Building Automation; Daylighting and Electric Lighting Control; HDR Vision Sensor; NIF Effects of Light; Visual Comfort.

1. Introduction

Several research studies showed that exposure to light has significant effects on human physiology and health [1], [2]. It has been demonstrated that the latter can directly boost alertness and cognitive performance; it can also improve our mood, while a lack of proper entrainment of our biological rhythms can cause sleep disorders, fatigue, performance problems, hormone and metabolic disorders: this is known as "Non-Image-Forming" effects. Light is the most important time cue for resetting our circadian clock [3]. In modern society, people spend around 90% of

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their time in buildings, thus indoor lighting condition plays an important role in determining inhabitants' mood and health, as well as visual comfort. Considering NIF effects in lighting for working environments, such as offices and administrative buildings, can significantly improve well-being, performance and productivity of employees and workers. So far, these effects have not been considered in building automation mainly due to their unknown and complicated nature, as well as lack of proper lighting and control technology. The objective of this study is to assess the performance of a shading and electric lighting controller that takes NIF effects of light into account and is aiming to improve the well-being and visual comfort of the users in an office environment. It must be considered as preliminary investigations before carrying-out subjective users surveys as well as in situ monitoring to determine the controller performance regarding energy savings and human comfort. With respect to a reference case, the advanced controller is expected to allow achieving significant energy savings as well as to improve users' visual comfort and performance and productivity at the workstation.

The magnitude of NIF effects of light on humans depends on different characteristics of the light flux, such as intensity (measured by the way of pupilar illuminance), timing, spectrum, duration/pattern and light history. Exposure to light for healthy humans during night causes alerting effects (non-visual responses), which are strongly correlated with the degree of "melatonin suppression" [4][5]. Melatonin is the "sleep hormone" released by the pineal gland during the biological night. Different studies showed that light can boost alertness also during daytime [6][7] when melatonin concentration is negligible, denoting that the alerting effect of light is not necessarily correlated with melatonin suppression. Moreover, the timing of light exposure plays a crucial role in determining the magnitude of NIF effects [8]: in other words, the alerting response elicited by exposure to light would vary with the time of the day.

The Standard DIN SPEC 67600 [9] defines some guidelines for "biologically effective illumination". For offices, the recommended minimal vertical illuminance at the eyes level is 250 lux with a Correlated Colour Temperature (CCT) of 8'000 K in the morning (8h00-10h00), 200 lux with a CCT of 3'000 K during lunch break (12h00-13h00) and evening hours (18h00-20h00), whereas the illuminance shall correspond to the requirements of the visual task during the rest of the day. The WELL Building Standard [10] includes recommendations for the built environment to promote and improve human health and well-being. For work areas, at least 250 equivalent melanopic lux ("melanopic illuminance" is defined as a biological representation of irradiance [11]: it is the irradiance weighted with the sensitivity curve of the photopigment melanopsin) shall be present at 75% or more of workstations, in a vertical plane facing forward, 1.2 m above the finished floor (to simulate the view of the occupant). This luminous level shall be present for at least 4 hours per day every day of the year.

2. Methodology

2.1 HDR vision sensor

The assessment of the lighting environment in an office room was carried out by means of two HDR vision sensors manufactured by the Swiss Center for Electronics and Microengineering (CSEM) (Figure 1-b). The sensor is equipped with a fish-eye lens and organic filters that allow to adapt its spectral sensitivity to photopic response of the human eyes, expressed by the V(λ) function. Furthermore, it has been calibrated photometrically (to convert the generated greyscale images in luminance maps) and geometrically (to take into account vignetting effects, i.e. drop of response at the image's corners). In summary, the HDR vision sensor is capable of generating accurate real-time luminance maps and assessing visual properties of a lit science; discomfort glare expressed by glare indices, such as the Daylight Glare Probability (DGP) [12] , can also be monitored by this device and was used in the present study.

2.2 Test bench

The control system was installed and tested in a south-facing office room at the second floor of the LESO solar experimental building on the EPFL campus: the space is usually occupied by a single user. The office room is set-up with both a conventional double glazing on the lower part, and an Anidolic Daylighting System (ADS) on the upper part [13]. The windows are equipped with motorized venetian blinds provided by the Swiss company Griesser ("Lamisol" and "Grinotex" metal blinds). They can be managed via manual switchers located in the office; they can also be controlled automatically through a KNX communication network. The lighting fixture consists of a floorstanding luminaire providing both direct and indirect light fluxes. The system is dimmable and can also be managed both via a KNX system or manual switchers. One sensor is placed on the computer screen facing in the same viewing direction as the occupant while sitting at his desk (as in Figure 1-a). Luminance distribution, as well as potential discomfort glare sources within the field of view, are recorded by the sensor in order to assess the vertical (pupilar) illuminance E_v and the DGP by means of an embedded software. The second sensor is installed on the ceiling: the luminance of the pixels located on the work plane are extracted; the work plane average horizontal illuminance E_h is determined assuming a lambertian surface (more details in [14]). A greyscale image captured by the second sensor is illustrated on Figure 1-c.

a) b) c)

Figure 1. a) The testbed: one of the sensors is placed on the computer screen, oriented in the same view direction of the user; b) The novel HDR vision sensor developed by CSEM; c) Greyscale image captured by the HDR vision sensor mounted on the ceiling.

2.3 Dynamic Lighting Pattern

The current knowledge on NIF effects, as well as the recommendations for lighting mentioned in section 1, have been taken into account in the Dynamic Lighting Pattern (DLP) illustrated in Figure 2-a. In the early morning and afternoon the impact of NIF effects is more pronounced [15][16], therefore “circadian criteria” are applied: a minimum E_v is required, with a larger tolerance on DGP. During the rest of the day, when light does not have noticeable NIF effects, priority is given to visual comfort, meaning that the constraint applied to DGP is stricter and only a minimal value of E_h on the work plane is required. More detailed information about the DLP can be found in [17]. The proposed lighting pattern represent the target for the control system in the office room: in other words, the controller will track these set-points knowing the time of the day and will manage shadings and electric lighting accordingly.

a) b)

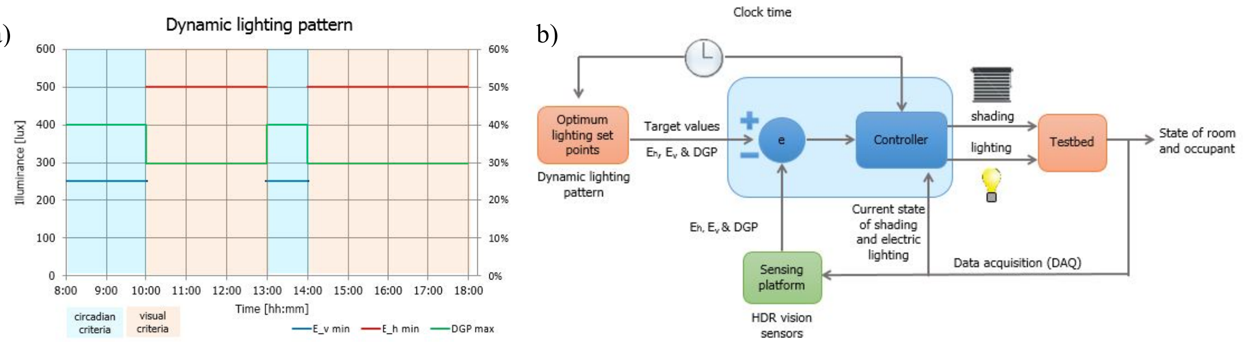

Figure 2. a) Dynamic Lighting Pattern where E_v_min is the minimal required vertical illuminance, E_h_min is the minimal required horizontal illuminance on the workplane and DGP_max is the upper threshold for Daylight Glare Probability; b) Scheme of the control system.

2.4 Shadings and Electric Lighting Controller

An automated control system for venetian blinds and electric lighting was designed based on the room geometry and the sun course. Ideally, the controller must avoid direct sunlight to reach the user and its work plane when glare risks may be expected (assessed by the HDR vision sensor located on the computer screen). In the same time, it must provide sound lighting conditions in the room by activating and adjusting electric lighting when daylight is not sufficient for that purpose. The controller is responsible to determine the optimal setting for the shadings and the electric lighting system, e.g. to set the slat angle and the position of the venetian blinds as well as the dimmed electric power for the lighting according to the DLP set-points (see Figure 2-a). The conceptual scheme of the system is illustrated on Figure 2-b. The time clock is used to sample the DLP reference curve and is used by the controller to determine the sun profile angle. Data acquired by the HDR vision sensors is continuously processed and used as an input to the controller. The difference between the DLP set points and the monitored data are used to determine the controller's actions regarding the shadings or the electric lighting. The bottom blind management is based on a simple analytical equation that considers the room geometry and sun altitude with the aim of protecting the work plane from direct sunlight. Due to the ADS presence in the upper window part, a more complex approach was used to set-up the upper blind fuzzy logic control rules. Since it is assumed that the discomfort glare is induced by direct sunlight entering through the window, priority of regulation was given to one of the two blinds depending on the current sun elevation angle. When needed, the electric lighting power is adjusted after the blinds movement in order to prioritize the use of daylight, and thus save electric lighting energy. The dimming power depends on the 'lacking' work plane illuminance and is used to reach the required level; the latter is determined by means of an empirical curve obtained through the method explained in [13]. Finally, the current states of the shading and electric lighting system is continuously recorded to avoid too frequent and/or small amendments according to a patent pending algorithm [18]. Besides visual comfort criteria, thermal considerations are also taken into account: during summertime, the controller lowers the blinds to avoid that large solar gain lead the indoor temperature to exceed a threshold of 26°C, whereas in winter the blinds are closed during night time to mitigate the thermal losses through the building envelope.

2.5 Preliminary experiments

The control system was commissioned from April the 14th and the 21st in an office room of the LESO solar experimental building. The occupant - a 35 years old male subject – provided his own feedback on the controller's performance in terms of visual comfort by the way of a short online survey: this subjective evaluation of the controller actions are mainly focused on the glare sensation, lighting provision and shadings movements (questions and answers are listed in *Table 1*).

3. Results and discussion

The two diagrams of Figure 3 illustrate monitored data acquired during two typical days, characterized by clear sky conditions. For both days in the morning, a DGP increase overpassing the 30% DGP threshold can be observed leading to the lowering of one or two blinds. Due to the shading movement, the DGP decreases underneath the comfort-discomfort limit and do the horizontal and vertical illuminance in the office room. In the evening, blinds are opened following the decrease of Eh underneath a minimal value. Electric lighting is switch on only after 17:00, when daylight is not sufficient to reach the required level on the work plane. The boxplots of Figure 4 illustrate the DGP, Eh and Ev variables monitored by the HDR vision sensors during the experimentation period (6 days). Regarding DGP, the data 75th percentile is always lower than the threshold that was set in-between 30% and 35% DGP (depending on the time of day); it indicates that the controller is effective in maintaining the discomfort glare index within the desired limits. As far as horizontal and vertical illuminance are concerned, a wide range of values was monitored. However, for most of the day, both Eh and Ev were kept above the minimal required levels thanks to the available daylight. The user feedback was recorded daily by means of a short online survey. Since he was not present in the office during the whole experimentation period, his answers for the two typical days illustrated in Figure 3 were recorded.

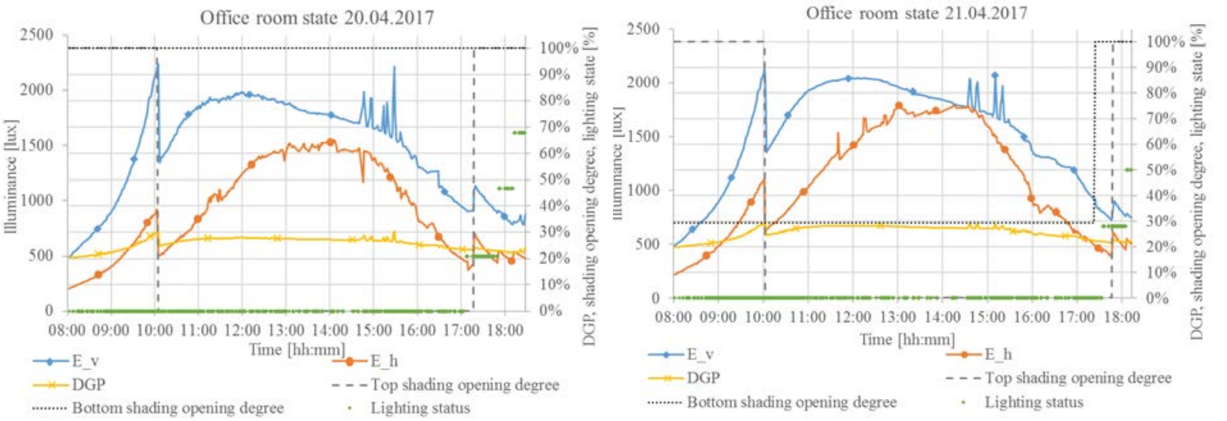

Figure 3. Results from data acquisition of two representative days. The diagrams show E_h, E_v and DGP assessed by the HDR visior sensors, as well as the shadings' positions and the lighting state during the working day (measurement error is approximately 15%).

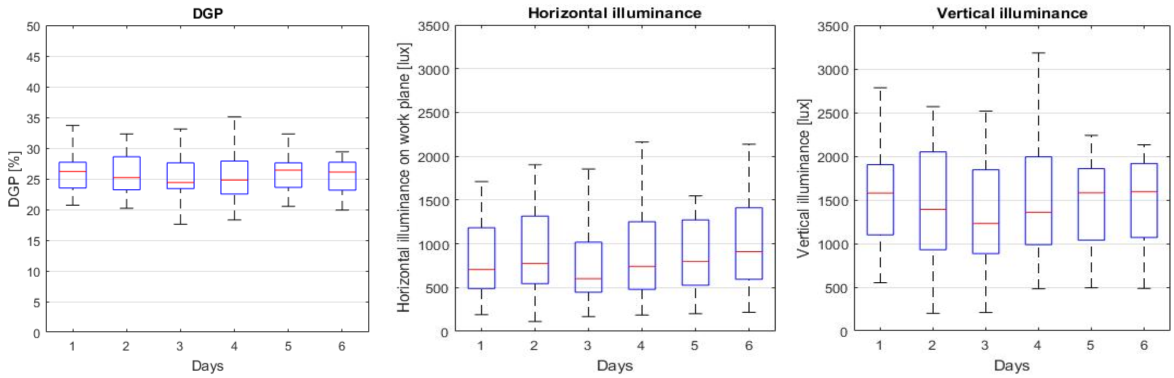

Figure 4. Boxplots of DGP, E_h and E_v data registered during the 6 days. Outliers are not shown in the plots.

Question	**Globally, the lighting in this room is comfortable**	**There is enough light to read/work properly**	**There is too much light to read/work properly**	**Glare is...**	**The shadings move…**
Options	1 – 5 (1=no, 5=yes)	1 – 5 (1=no, 5=yes)	1 – 5 (1=no, 5=yes)	• Imperceptible • Perceptible • Acceptable • Inacceptable	• Not frequently • Frequently, but that does not disturb me • Very frequently and that disturbs me
20/04/2017 14:59	5	5	1	Imperceptible	Not frequently
21/04/2017 10:41	5	5	1	Imperceptible	Not frequently

Table 1. User's feedback via online questionnaire. Questions are described in the upper part of the table (grey background) and answers are listed in the two lines below. The user was not present during the whole week so he was not able to answer the questionnaire every day.

Table 1 summarizes the questions and answers of the online questionnaire: the lighting was rated as comfortable, the glare imperceptible, and the blinds and electric lighting did not move too frequently. Globally, the user expressed a good acceptance of the integrated lighting control system.

4. Conclusion

An automated control system of venetian blinds and electric lighting was set-up in order to take the NIF effects of light on occupants of an office room into account. A Dynamic Lighting Pattern (DLP) was designed and used as a target for the user-centric lighting control system. The controller was tested during one week in the framework of preliminary experiments; all data monitored by the sensors as well as the user's feedback were recorded. Longer on-site experimentations are necessary to draw further conclusions; the novel smart controller demonstrated however his capabilities in terms of glare protection, daylight sufficiency, and limitation of shading and electric lighting adjustments. Satisfying visual comfort conditions and well-being for the office's occupant were moreover delivered in the meantime.

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