A Survey Study of Occupants' Visual Satisfaction on an Automated Venetian Blind based on Sky Luminance Monitoring and Lighting Simulation

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Abstract

Smart daylighting control can contribute to energy savings in artificial lighting, space cooling and heating loads in buildings. Although various shading automation systems have been proposed to foster the utilization of daylight in buildings, the performance of which is limited by a number of factors, including insufficient glare protection, disturbing movement of slats, privacy issues, and difficulty in installation and commissioning. This paper investigates the performance of a novel decentralized shading system based on real-time sky luminance monitoring and on-board lighting simulation, in the perspective of occupants' visual satisfaction. A subjective study was conducted with 34 young subjects in a daylighting testbed during the winter when the solar elevation angle was low and occupants were subject to discomfort glare from the sun during the period. According to the survey results, the automated shading system was able to reach 89% satisfaction from the occupants regarding daylight provision, 87% satisfaction on the discomfort glare protection, and 86% satisfaction of the occupants on the quietness of shading movements.

Keywords: Automated shading, Visual comfort, Discomfort glare, Subjective study, Daylighting control

1. Introduction

Studies have shown sufficient daylight exposure contributes to occupants' productivity and health (McArthur, et al., 2015) in buildings. However, excessive daylight ingress can overheat buildings during warm seasons and contribute to discomfort glare to occupants. Although shading devices are widely applied in buildings to adjust daylight penetration, the actual performance of a manual shading device is largely limited by users' low interaction frequency (less than once/day on average) (Mahdavi & Pröglhöf, 2009). Since daylight is dynamic with the variation of sky conditions including movements of clouds, frequent adjustments of shading devices are necessary to maintain daylighting for visual comfort inside buildings, but these are impractical for users to manage without distraction from their own tasks. As a result, shading devices commonly remain closed over long period of time and occupants rely on artificial lighting, even if the open position of shading could offer superb daylighting.

Well-designed automated shading systems have a potential to efficiently exploit daylighting in buildings, reducing peak cooling loads and artificial lighting and simultaneously improving occupants' visual comfort (Kuhn, et al., 2001). Early studies on shading automation were based on the incident solar radiation on windows or based on a ceiling mounted photo-sensor pointing at a task area (Rubinstein, et al., 1989) to control shading positions, stabilizing work-plane illuminance (WPI). Peak cooling load reduction of 28% was reported by Lee et al. (Lee, et al., 1999) during summer in Oakland, CA. However, in addition to the commissioning and calibration difficulty, the systems commonly neglect discomfort glare for occupants, which is a major rejection factor in practical applications. Newsham et al. (Newsham & Arsenault, 2009) used a camera to control roller blinds in an office room, which improved accuracy in controlling WPI and assessed discomfort glare compared with using photo-sensors. Motamed et al. (Motamed, et al., 2017) implemented two cameras with high dynamic range (HDR) image sensors to control the position of roller

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blinds based on fuzzy logics: one was mounted on ceiling, assessing WPI, and the other one was positioned at an occupant's sitting position, assessing glare risk. Although cameras have been extensively used for shading control in a laboratory environment, privacy issues introduced by placing cameras in building interiors and their installation complexity remain impeding factors for their practical applications (Newsham & Arsenault, 2009). In the control of Venetian blinds, the 'cut-off' angle strategy is commonly employed to determine the slat angle of Venetian blinds to exclude direct sun rays based on the sun profile angle (Kuhn, 2006), despite the inefficiency in preventing discomfort glare from the specular inter-reflections between slats (Karlsen, et al., 2015). Katsifaraki et al. (Katsifaraki, et al., 2017) investigated the control of Venetian blinds according to daylighting simulation results based on weather data, sky luminance model and geometric model of the room. However, the discomfort glare from surrounding reflections were not considered, since the ambient landscape was difficult to model. In addition, a close-by weather station or an unshadowed roof for installation of weather sensors is needed for the simulation-based control, which can be unavailable for decentralized systems.

This paper investigates the performance of a novel automated Venetian blind (Wu, et al., 2019a) employing an embedded photometric device (EPD) to control daylighting based on real-time monitoring of the sky (and landscape) luminance distribution with high resolution and on-board lighting simulation, as a decentralized system with reduced installation difficulty. It circumvents the privacy issues, since the imaging system of the controller points at the outdoor space. The previous studies (Wu, et al., 2019a) demonstrated its performance in efficiently maintaining WPI and mitigating discomfort glare from both the sun and surrounding reflections according to results of physical measurements as reference. In this paper, a subjective study was performed in a daylighting test module with 34 young subjects experiencing the automated shading system, which evaluated the daylight provision, glare protection, shading motion and occupants' view outwards.

2. Methods

A daylighting test module (interior dimension $6.4 \times 2.9 \times 2.6\,\mathrm{m}^3$) located in Lausanne (46˚31′04″N, 6˚33′53.6″E), Switzerland was used for the subjective study on shading control, as shown in Figure 1. The module was equipped with a unilateral façade facing the south reaching a 0.62 window-to-wall ratio. The façade was fitted with an external Venetian blind of which each metallic slat had a sinusoid profile to diffuse daylight.

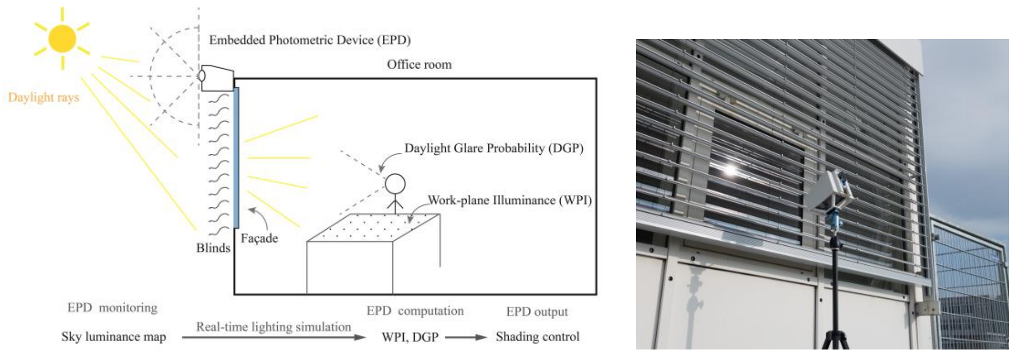

Figure 1 a) Work-flow diagram of the daylighting control b) Prototype of the automated Venetian blinds

Acting as both the sensor and controller, the embedded photometric device (EPD) developed by Wu et al. (2019b) was positioned in front of the daylighting test module with its axis of lens in the orthogonal plane of the façade. The EPD was mainly composited of a field programmable gate array (FPGA) processor and a calibrated imaging system, which was capable of real-time monitoring of the sky (and landscape) luminance distribution and on-board lighting simulation for a building interior. After optical correction, the spectral response of the EPD was close to the photopic luminosity function V(λ) with a spectral correction error f_1' of 8.9%. Employing a high-speed shutter, the EPD spanned a wide luminance detection range (150 dB) within 0.55 seconds exposure time, covering the luminance of the sun orb, the sky background, clouds, and landscape objects during daytime. Based on the generated luminance map of the exterior space (the sky and ground fraction) and a geometric model of the building, the EPD was able to perform the daylighting simulation for the building interior employing back-ward raytracing algorithms. Although it was positioned in front of the blinds for shading control in this study, the EPD can be alternatively integrated into the head rail of the blinds as a compact control system.

For the shading control as illustrated in Figure 1 a), two daylighting metrics were calculated on-board including the work-plane illuminance (WPI) and daylight glare probability (DGP). The WPI was defined as the average horizontal illuminance on the desk at 0.8 m height and 1.5 m distance to the façade. DGP (Wienold & Christoffersen, 2006) is a metric quantifying discomfort glare level regarding occupants' visual comfort, which is associated with the luminance magnitude and contrast within occupants' visual field. The DGP was calculated at occupants' sitting position at 1.2 m height and with view directions oriented 45˚ towards the façade from both sides (east and west). 15 different shading positions were evaluated including the fully retracted position, fully extended slats inclined at 72˚ to the vertical plane (horizontal slats), slats inclined at 67˚, 62˚…, and 0˚ (fully closed). Regarding shading control, an optimization process was employed to determine the optimal shading position. The WPI was constrained between 500 lux and 2000 lux: the lower bound was to maintain sufficient daylighting according to the European Lighting Standard EN 12464 (Comité Européen de Normalisation, 2002), and the upper bound was to prevent excessive solar heat gain during warm seasons. The DGP was limited below 0.35 (within imperceptible level) for occupants' visual comfort. In order to preserve users' view outwards, the objective of the controller was to find the largest opening of the shading position regulating daylight within constraints. The EPD took approximately 6-9 min to perform luminance monitoring and on-board lighting simulation and finally determine an optimal position for the Venetian blinds. In this study, the EPD operated at 15 min intervals to control shading positions from morning to evening. Readers can refer to (Wu, et al., 2019b) about the specification of the EPD and (Wu, et al., 2019a) regarding details of the shading control.

From Jan. 22nd to Feb. 13th, 2019, 34 young subjects (26 males, 8 females) volunteered to participate and assess the performance of the automated shading system in the daylighting test module. Every two subjects seated opposite to each other on the left and right side of the room respectively, as shown in Figure 2. Occupants were able to sense glare from the left or right view perspective towards the window, which was also simulated by the shading controller. The EPD performed sky luminance monitoring, lighting computation, and adjustment of shading positions every 15 min (without manual override). Subjects performed activities, including reading, writing, and typing, as office workers during three hours either in the morning or afternoon. At the end of each hour, they filled in a questionnaire as illustrated in the Appendix, to show their level of visual satisfaction on the daylighting environment controlled by the shading system. Questions were answered with scores ranging from 1 to 5 about occupants' level of satisfaction or dissatisfaction on perspectives including daylight provision, discomfort glare sensation, system response, and view outwards. The average elevation angle of the sun at noon was 25˚ during this period, when it was challenging for a shading system to prevent discomfort glare, since the sun was visible from at least one of the two occupants' visual field during the experiment without occlusion of the shading or clouds.

Figure 2 Occupants sitting at the two sides of desks experiencing the daylighting performance of the automated blinds

3. Results

Based on the survey results, the average mark of each question and its corresponding 95% confidence interval were calculated and illustrated in Figure 3. Bars with four different colors denote questions from different perspectives, including daylight provision, discomfort glare and contrast sensation, system response, and view outwards. To outline results clearly, the mark of each question was transformed and normalized to 1 in order that a higher mark represents a more positive answer. According to the results, Question 2 “The lighting in this room is comfortable” receives a 0.89 average mark. Actually, Questions 1-4 receive relatively high ratings between 0.85 and 0.93 on average, which indicates majority of the occupants were satisfied with the daylight provision or WPI with sufficient daylighting to perform reading, writing, and typing tasks. The result of Question 3 (0.93) also reflects that automated shading prevented excessive daylight ingress (or SHG). A minor portion of subjects also showed inclination on a higher level of WPI, which is suggested by the lower bound of the 95% confidence interval of Question 4 “Sufficient light for proper reading/writing/typing”, due to the variance of users’ preference and sensitivity to light. Regarding discomfort glare sensation, Question 6 “I had no glare feeling” has a rating of 0.87, which suggests the majority of occupants’ glare sensation was either imperceptible or below perceptible level. It also indicates the shading system managed to occlude glare sources in winter with the relatively low solar elevation angle, which is suggested by the result (0.85) of Question 7 “Shading blocked the glare source successfully”. Since the actuator of shading was improved with smooth motions by a step motor and a reduction gearbox (Wu, et al., 2019a), Question 9 investigates occupants’ distraction from shading movements. Its rating (0.86) indicates occupants’ satisfaction on the reduced noise level and smooth motions of shading adjustment. Although outwards view was generally preserved for occupants, according to Question 10 (0.76), advices including using narrow slats were received to improve view outside. Moreover, the relatively low rating (0.73) of Question 8 “Shading responded quick enough according to variation of weather condition” suggests the performance of the shading can be further improved by the increasing the computation speed and operating frequency (15 min), to enhance the performance under a partly cloudy sky with rapid motions of clouds, which can occlude the sun and move away within minutes.

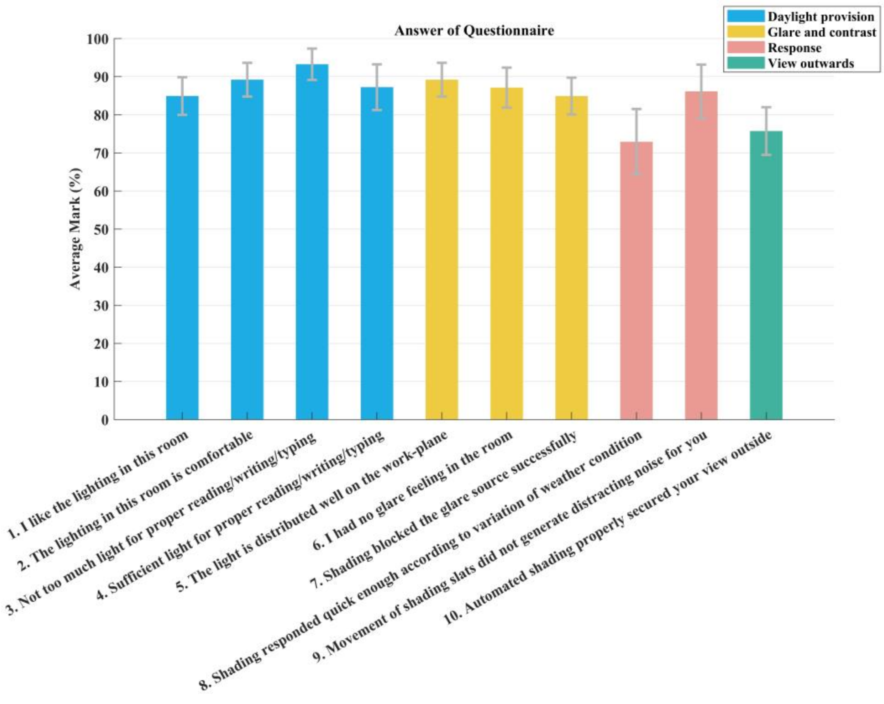

Figure 3 Survey results of occupants’ visual satisfaction

The survey also enquired about occupants’ additional comments (or suggestions) on the performance of the automated shading system. Certain occupants also compared its performance with their past experience on a conventionally automated exterior Venetian blinds based on solar irradiance in the “Rolex

Learning Center" (RLC), an open-plan library in the EPFL campus. The provided comments span a wide range of opinions and are categorized as follows, in an order from positive to negative feedbacks (comments were reproduced verbatim but not edited for proper grammar):

- Overall daylighting satisfaction:

– I think that the shading system was better than standard shading system. The distribution of light on the work-plane was very pleasant.
– During the three hours, you can really see the difference in terms of shading. During [10:30, 12:00], the system responded very well.
– At the end of the experiment when the shading system was turned off, we could see the difference! The system is very useful and works well. The work (at hand) is much better with this shading system.

- Glare protection:

– Good shading system, way much better than the one in "Rolex Learning Center". The glare is stopped directly whenever there is too much of it.
– I barely could notice the glare, compared to what I usually notice at the Rolex Learning Center (RLC).
– The glare feeling was completely imperceptible from my point of view. I felt really at ease, the lighting was just perfect as well as the level of noise.

- Slat motions:

– Comparison with the Rolex Learning Center (RLC): the system in the RLC makes more noise than this one. The movement of shading slats of the experience is softer (more gentle) than the one of the RLC. So this shading changes very slowly (more comfortable while studying.)
– When compared to conventional shading systems, the major improvements one can notice are the fact that the system makes no noise, and that changes (slat movement) are not sudden, but rather gradual (smooth).
– Overall the lighting is consistently comfortable. Minor adjustment is quiet which almost cannot be distinguished without paying extra attention to the shading.

- Systematic response (15 min intervals):

– The system responded quickly enough matching the weather condition without making noise.
– Sometimes the automated shading reacts slowly according to the variation of weather condition. Generally, I think that the automated shading is really interesting and permits to have a great lighting without doing anything (without override).
– Prefer, the shading to respond more quickly.

- Daylight provision:

– I would not mind a bit more light to read or write but for the computer screen it is adequate.
– The brightness may be marginally increased.

- View outwards:

– Everything was smoothly controlled for the lighting. But it is true that there the view is not always secured, but this is a defect compared to the efficiency of the automated shading.
– Regarding Question 10, it would be nice to have a sort of transparent shading system with a protective film to control the intensity of the light.
– Smaller plates to have a better view of the outside and let a bit more luminosity come inside.

4. Conclusion

Well-designed shading systems have the potential to efficiently exploit daylighting in buildings, reducing cooling load and artificial lighting and improving occupants' visual comfort, which could positively influence the health and productivity of users. In this paper, a subjective study was carried out to evaluate the daylighting performance of an integrated automatic Venetian blinds based on real-time sky luminance monitoring with high resolution and on-board daylighting simulation. The automated shading system avoids privacy issues, since its imaging system points outdoors (for the sky and landscape), and reduces installation and commissioning difficult compared with convention shading systems, since indoor sensors and connection wires are unnecessary as an integrated decentralized system and a relative coordinate is established on the imaging component.

34 young subjects participated the study to experience the daylighting environment regulated by the shading system in winter when the average solar elevation angle was approximately 25˚ and occupants were vulnerable to the discomfort glare from the sun. The automated shading system operated from morning to evening at 15 min intervals under clear, partly cloudy and overcast sky conditions, and the occupants assessed daylighting performance and filled in a questionnaire at the end of each hour according to their sensation. The survey results showed 89% satisfaction from the occupants regarding daylight provision or work-plane illuminance (WPI), 87% satisfaction on the protection of discomfort glare, and 86% satisfaction of the occupants on the quietness of shading movements. Furthermore, the participants provided comments and suggestions to the automated shading system. A portion of occupants also compared the performance of the novel shading system with that of a conventional shading system installed in the campus library based on solar radiation according to their past experience, which showed noticeable merits in glare protection and quietness of slat motions. According to the feedbacks, certain occupants also showed variances of lighting sensitivity and inclinations of large view outwards and quick response of the controller. In the future, advanced computational hardware and simplified algorithms will be investigated to shorten the computation time of the controller to improve its performance under rapidly changing sky conditions. Adaptive learning features will be employed to cater the lighting sensitivity of different users to further increase their acceptance.

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Appendix

Gender: M/F Date: __/__ M/A

__/3 **Survey on Visual Comfort** L/R

1) I like the **lighting** in this room:

No 1------------2------------3------------4------------5 Yes

2) Generally, the **lighting** in this room is comfortable:

No 1------------2------------3------------4------------5 Yes

3) There is **too much** light for proper reading/writing/typing (on the desk):

No 1------------2------------3------------4------------5 Yes

4) There is **not enough** light for proper reading/writing/typing (on the desk):

No 1------------2------------3------------4------------5 Yes

5) The light is **poorly distributed** on the work-plane (desk):

No 1------------2------------3------------4------------5 Yes

6) I had the **glare** feeling in the room:

Imperceptible | Perceptible | Acceptable | Uncomfortable | Intolerable

7) Did the automated shading **blocked** the **glare** source successfully:

No 1------------2------------3------------4------------5 Yes

8) Did the shading **respond** quick enough according to variation of weather condition:

No 1------------2------------3------------4------------5 Yes

9) Did the movement of shading slats generate distracting **noise** for you:

Imperceptible 1------------2------------3------------4------------5 Intolerable

10) Did the automated shading properly secure your **view** outside, while providing optimal daylight:

No 1------------2------------3------------4------------5 Yes

Comments/Suggestions:

Sky type: C / Tn / Tk / O