Effect of Automated Dynamic Control of Interior Roller Shades on Daylighting and Energy Performance of South Facing Office Spaces

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ABSTRACT HEADING

Fenestrations are responsible for 4.3 quads of energy use annually for heating and cooling of US Buildings, 2.6 quads of which are from commercial buildings. Thus, these buildings can benefit from fenestration systems that further focus on maximizing energy efficiency and improving daylight harvesting, while maintaining occupant thermal and visual comfort. In this research, two types of motorized roller shades are tested in a full-scale commercial building laboratory with the goal of improved balance between visual and thermal comfort, and energy efficiency. The shading devices are controlled using multi-step custom algorithms, which use feedback from multiple illuminance sensors to automatically adjust both the height of the roller shades and the lighting levels using dimmable controls. Both daylighting and energy performance are assessed in three different sky conditions for a total of 1months between March and August 2017. Daylighting performance is measured using daylight glare probability and work plane illuminance values in three locations in each room; lighting energy savings is determined by comparing sub-metered energy use of two parallel test rooms, one of which serves as a baseline with no roller shades, and the other of which implemented the control strategies. The control strategies were developed to adjust the shading device to any arbitrary height and to minimize shade movement using variable interval logic. Overall, the control strategies reduced lighting energy use substantially, by approximately 50%, and maintained lighting levels at eye level within acceptable range 90% of the time. The results of this work include assessment of the lighting energy savings and occupant comfort from the use of the control strategy which indicates improvements in the occupant comfort-energy balance.

INTRODUCTION

Buildings consume approximately 40% of energy and 73% of electricity in the United States; 65% of total energy consumed by commercial buildings is from heating, cooling, and lighting applications ("US EIA" 2017). Solar heat gain from fenestrations are among the most variable and dominant factors influencing building energy demand (Lomanowski and Wright 2009) and can offer an energy saving potential of up to 3.9 quads (Apte and Arasteh 2008). At the same time, windows are also responsible for daylight availability in interior building spaces as well as influence visual and thermal comfort. Shading devices can help to control the amount of solar radiation and light entering the building to reduce overall building energy consumption and maintain occupant comfort while maximizing daylight availability. However, since most of the shading devices in use today are controlled manually, optimization of energy saving, occupant comfort and daylight availability is not always attained (Kim and Park 2012). To overcome this limitation, the shading devices which operate autonomously and react to the immediate environmental conditions, also called dynamic shading (Kim and Park 2012) could be used. Internal roller shades are among the most common shading devices commercially used.

Numerous studies have been carried out to evaluate potential impact of roller shades on building energy and occupant

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comfort. Many studies in the past have used daylight as well as energy simulation to study the potential impact of roller shades on built environment (Bourgeois, Reinhart, and Macdonald 2006; Athanassios Tzempelikos and Athienitis 2007; Wankanapon and Mistrick 2011; Shen and Tzempelikos 2012). Relatively fewer experimental studies, as compared to simulation studies, have been carried out to assess the impact of roller shades. Among the experimental studies some have focused on properties of static roller shades along with methods for modeling roller shades (Athanasios Tzempelikos and Chan 2016), some on manually-controlled roller shades and others on dynamic roller shades (Shen and Tzempelikos 2017; Xiong and Tzempelikos 2016). Chan and Tzempelikos (Konstantzos, Tzempelikos, and Chan 2015) performed an experiment using different control strategies to study the correlation of DGP with work plane illuminance and vertical illuminance. Experiments using model-based control for shade height and lighting level was carried out in (Xiong and Tzempelikos 2016) where they also introduced variable interval control logic to prevent occupant distraction from frequent movement of the shading device. Sadeghi (Sadeghi et al. 2016) used automatic control to prevent direct sunlight along with manual control and occupant interaction with shading and lighting control. Daylight-linked control which enables control of shading device based on only one transmitted illuminance from the window, aided by simulation to determine the correlation between the transmitted illuminance and work plane illuminance was performed by (Shen and Tzempelikos 2017). Lighting control has been used along with shading control to utilize daylight to reduce the amount of energy consumed for lighting application. Some studies have used continuous dimming for lighting control (Hoffmann et al. 2016; Iwata, Taniguchi, and Sakuma 2017) while other have used on/off control (Gunay et al. 2017; Huchuk et al. 2015).

Most of the experimental studies in the past are aided by simulation to perform the control of the roller shades. In this study, simple illuminance sensor based control algorithm is used to control the roller shades which can be applied without aid from simulation and can be used for rooms with different geometry, orientation and roller shades properties.In addition to this the control algorithm used in the study was integrated with existing Building Automation System (BAS) unlike past studies in which application of control algorithm was performed by standalone custom controller.

METHODOLOGY

Experimental Set-up

Full-scale testing of dynamic interior roller shades was performed at the Iowa Energy Center's Energy Resource Station (ERS), located in Ankeny, Iowa. The testing was performed using south-facing private office spaces, each with a floor area of 24.71 m^2 (266 ft^2) and ceiling height of 2.5 m (8.2 ft) from the finished floor level. Two identical test rooms were utilized; one was used as baseline without any shading devices or lighting controls (Test Room A), and second was equipped with internal roller shades and dimming lighting controls (Test Room B). Test Room A was equipped with double glazing windows with U-value of 3.12 (W/m^2.K), visible transmittance of 81% and shading coefficient of 0.85 while the Test Room B was equipped with double glazing with low-e coating with a U-value of 1.36 (W/m^2.K), visible transmittance of 65% and shading coefficient of 0.27. Apart from these differences, the two test rooms were identical in all other aspects including glazing type, temperature setpoints, simulated occupancy schedules, and sensor placement. Normalization testing was performed when both test rooms had identical glazing, and after the windows in Test room B was replaced with the low-e glazing; this testing was performed to ensure the performance of the two rooms was identical when identical glazing was installed, and to assess the imapcts of the low-e glazing on Test Room B. During the normalization testing for period of 5 days with low-e glazing on the Test Room B, no shading device and lighting control was used in the Test Room B for comparison with Test Room A. Next two types of roller shades were installaed and automated to test dynamic shading application. The properties of the shading devices are provided in Table 1.

Table 1. Properties of two different roller shades

Shading device	Openness factor	Visible transmittance	Solar transmittance	Solar absorptance	Solar reflectance	Color
Roller Shades 1	1 %	1%	1%	95%	4%	Charcoal
Roller Shades 2	3%	12%	17%	19%	64%	Oyster

Commercial-grade motors and controllers were used to adjust the height of the roller shades. Commands for height of the roller shades obtained from the custom control algorithm were sent utilizing a commercial grade controller connected to the existing direct digital control (DDC) building automation system (BAS). Each test room was equipped with 6 lighting fixtures, each fixture containing three U-shaped T8 fluorescent tube lamps sized at 31W. The lighting fixtures in the Test Room A were fully on during the test duration while the lighting fixtures at the Test Room B were dimmed to maintain work plane illuminance of 500 lux (46.45 ftc) at a height of 0.76 m (2.49 ft) from the floor and 2.5 m (8.2 ft) from the window. All six light fixtures were controlled as a group.

Following a typical occupancy and equipment schedule of an office building, occupied times were assumed to be from 8 am – 6 pm each day of testing. The test rooms were equipped with sheet metal androids to simulate internal heat resulting from occupancy of two people per room at a rate of 73.3 W (250 BTU/hr) sensible and 58.6 W (200 BTU/hr) latent per person. The computer workstation provided approximately 88 W of internal load in active mode (occupied), and 5 W in stand-by mode (unoccupied). Constant temperature setpoints of 21.1 °C (70 °F) for heating, and 23.3 °C (74° F) for cooling were used for both rooms. Each room was conditioned using a terminal variable air volume (VAV) box to which air was supplied from central air handling units. The VAV box changed the position of the damper to control the airflow to the test room required to maintain the test rooms at desired temperature of 23.3±0.14 °C. The test rooms were equipped with three work plane illuminance sensors, a ceiling illuminance sensor, a vertical illuminance sensor, a temperature sensor and a relative humidity sensor. The position of the interior illuminance sensors in the test rooms are provided in Table 2. Apart from these sensors the air flow rate, supply air temperature and relative humidity of the supply air was also measured. Exterior sensors utilized include global horizontal irradiation, direct normal irradiation, outside air temperature and relative humidity, as well as irradiation and illuminance on the external facade. The uncertainity of the sensors are provided in Table 3. All the measurements were monitored and recorded at 1-min intervals.

Table 2. Position of Interior Illuminance Sensors in Test Rooms

Sensor	Height from the floor	Distance from exterior window
Work plane illuminance	0.76 m (2.49 ft)	1 m (3.28 ft), 2.5 m (8.2 ft) and 4 m (13.12 ft)
Vertical illuminance	1.2 m (3.93 ft)	3 m (9.84 ft) facing window
Ceiling illuminance sensor	2.56 m (8.4 ft)	2.86 m (9.38 ft)

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Variable	*Unit*	*Uncertainity*
Temperature	°C	±0.14°C (± 0.25°F)
Relative Humidity	% RH	± 2%
Global horizontal irradiation	W/m²	± 0.5 %
Irradiance	W/m²	± 3 %
Illuminance	Lux	± 5 %
Solar beam intensity	W/m²	± 0.5 %

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3 w~~W~~ork plane illuminance sensors were placed along the centerline of the room; their ~~, whose~~ distances from windows and height above the floor are provided in Table 2. were used to evaluate the level of lighting on the work plane surface, which was used as parameter for daylight availability. Simplified daylight glare probability (DGPs) (Wienold 2007) was used as visual comfort criteria, and was calculated based on the measured vertical illuminance (E_v) at occupant eye height, using the empirical equation as follows:

$$\text{DGPs} = (6.22 * 10^{-5}) * E_v + 0.184 \qquad (1)$$

Shading Control Algorithm

The shading control algorithm was used to prevent visual discomfort to the occupant while maximizing daylight availability in the room. The roller shades were deployed to the minimum of work plane protection height (Athanasios Tzempelikos and Shen 2013) whenever external solar irradiation was greater than 150 W/m² (47.56 Btu/(hr.ft²). The shading device was modulated between this height and full-height of the roller shades with an objective of maximizing the daylight in the room while maintaining occupant comfort using a PI loop with a target vertical illuminance of 1830 lux (170 fc). A total deadband of 215 lux (20 fc), with half of the dead band on each side of target vertical illuminance was utilized to reduce the movement of the shades. The flow diagram for the control logic is provided in Figure 1.

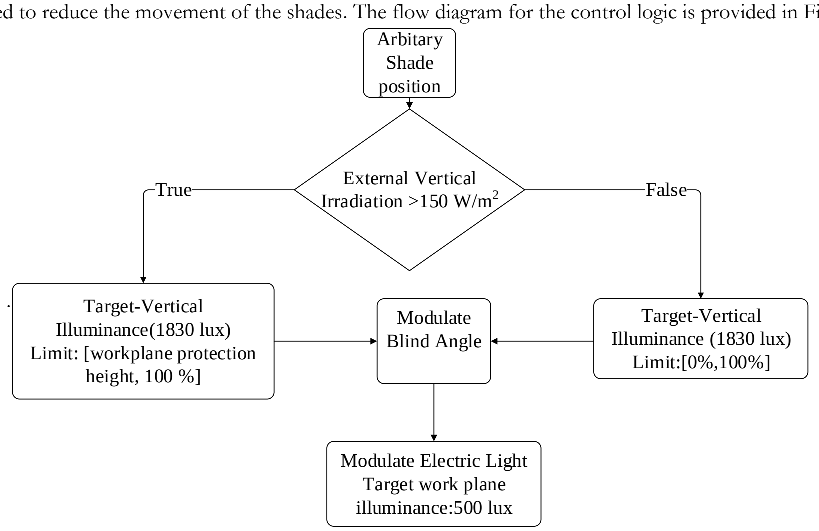

Figure 1 Control Strategy Flow Chart

In the control algorithm shown in Figure 1, the work plane protection height (*h*) which is the height of the bottom of the shade from the work plane surface needed to prevent direct sunlight from hitting the work plane area, is given as

$$h = \frac{a}{\cos(\gamma)} * \tan(\alpha) \qquad (2)$$

where, *a is* predefined distance of the work plane from the window*, γ* is surface solar azimuth and α is solar altitude. During the testing, the predefined distance of work plane from the window was set to be 2.25 m and the work plane illuminance sensor at the distance of 2.5 m from the window was used to monitor the illuminance condition at the work plane.

RESULTS

Lighting energy savings

Lighting energy savings from the application of shading and lighting control was assessed in comparison to the baseline case which was considered to be without the use of any shading devices and lighting controls. The summary of the daily lighting energy savings provided in Figure 2 is for 16 test days (7 days in spring and 9 days during summer) for RS1 and 15 test days for RS2 for occupied hours of 8:00 am to 6:00 pm. The '×' symbol in the boxplot represents the mean of the distribution while the horizontal line inside the rectangular box represents the median; the portion of the boxplots with colored rectangle represents the inter-quartile range. An average lighting energy savings of greater than 50 % and 2.5 kWh per day was obtained by using the control strategy for both the shading device. The variation in lighting energy savings ~~during various days~~is the ~~was a~~ result of variations in ~~different~~ sky conditions and the daylight availability during those sky conditions. For example sunny days with more daylight availability demanded less supplemental lighting energy to maintain the work plane illuminance level compared to overcast days ~~with~~which had low daylight availability.

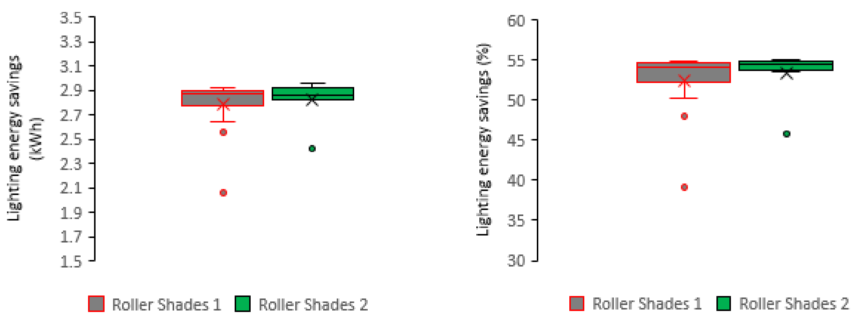

Figure 2 Daily lighting energy savings (a) in kWh and (b) in percentage

Visual Comfort

Simplified daylight glare probability (DGPs) calculated from measured vertical illuminance is used for assessment of visual comfort. The vertical illuminance measurement during occupied hours for 16 test days for RS1 and 15 test days for RS2 are used to calculate DGPs. Since the two test rooms were equipped with different types of windows, normalization test was run for duration of 5 days in which visual comfort on both rooms were assessed without using any shading device and lighting controls. DGPs<0.35 is considered imperceptible, 0.35-0.4 perceptible, 0.4-0.45 disturbing, and >0.45 intolerable level of glare, following the classification for DGPs used in (Suk and Schiler 2012). The DGP level for the normalization days with low-e glazing in the Test Room B is shown in Figure 3. The DGPs level for the baseline test room (Test Room A) and controlled test room (Test Room B) while using RS1 and RS2 are shown in Figure 4 and 5 respectively.

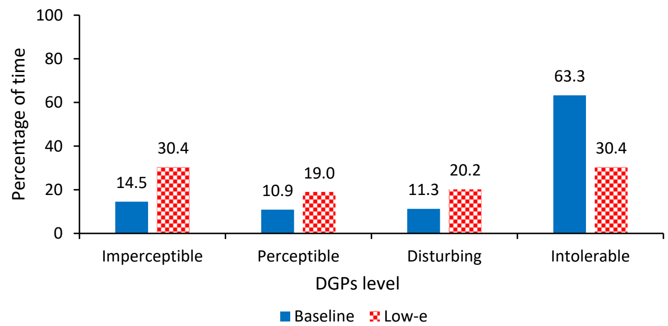

Figure 3 DGP percentage for Test Room A and Test Room B - normalization testing

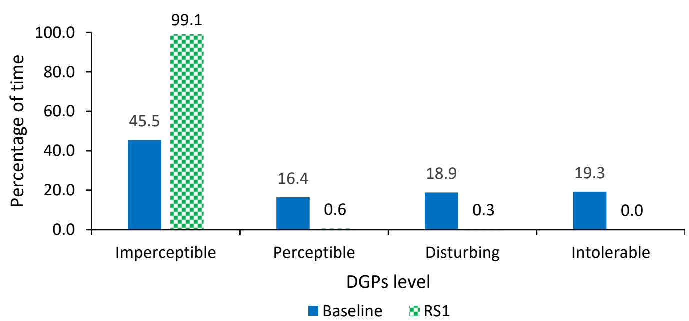

Figure 4 DGP percentage for Test Room A (baseline case) and Test Room B (RS1)

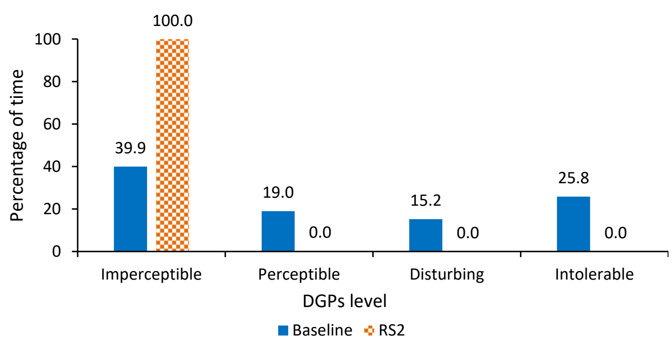

Figure 5 DGP percentage for Test Room A (baseline case) and Test Room B (RS2)

As depicted in Figure 3 although the use of low-e windows in the Test Room B slightly improved the visual comfort level compared to that of clear window in Test Room A, still without the use of a shading device visual discomfort level was at least perceptible about 70% of the time. While, as shown in Figure 4 and 5, the dynamic shading application utilizing both RS1 and RS2 improves the visual comfort to the occupant significantly. In both the cases utilizing the dynamic internal roller shades, the glare is at least perceptible more than 50% of the time for the Test Room A, while for Test Room B the glare is imperceptible more than 99% of time. Hence, the use of the dynamic shading utilizing the control strategy described in the methodology section ~~shows very good performance in terms of maintaining~~provides acceptable levels of visual comfort more than 99% of the time when DGPs is used as the visual comfort criteria.

CONCLUSION

Automated interior roller shades along with continuous dimming lighting control was tested in a full-scale experimental setup for two different types of roller shades. The control algorithm which can be used for varying room size, orientation and shading device with pre-determined work plane area and occupant position was utilized for controlling the roller shades utilizing custom control algorithm in the existing BAS. Both the roller shades showed lighting energy savings of more than 50 %. In addition to lighting energy savings the dynamic shading application using internal roller shades significant improvement in occupant visual comfort with DGP below 0.35 more than 99% of the time for both shading device. It was observed that, although low-e window slightly improved the visual comfort level, shading device was essential to obtain visual comfort for the majority of the occupied duration. Finally, based on data collected for two different types of roller shades with visible transmittance of 1% and 12% for total ~~test duration of~~of 30~~1~~ ~~months~~days of testing, we can conclude that the control algorithm describe above provides good performance for varying properties of roller shades from energy savings as well as visual comfort perspective when used with integrated lighting control for south facing office spaces.

This study provided the impact of dynamic internal roller shades on visual comfort and lighting energy usage. While the shading device performed very well when visual comfort is assessed in terms of DGPs, this metric might not be good enough to evaluate glare while sun is within direct field of view (Konstantzos, Tzempelikos, and Chan 2015). For such conditions cost effective control of roller shades which can incorporate DGP assessed using luminance condition of the room using High Dynamic Range (HDR) photography should be developed. In future, the impact of the control strategy on other factors such as daylight and heating, ventilation and air-conditioning (HVAC) energy consumption should be studied along with the impact of low-e windows on HVAC energy, since these windows are particularly used to reduce solar gain entering the building. In the field of dynamic shading, different shading devices and control algorithms and their impact on different types of buildings also needs to be studied to support broader use of this technology in the building sector.

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