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Occupant interactions with shading and lighting systems using different control interfaces: A pilot field study

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ABSTRACT

The paper presents a field study on human interactions with motorized roller shades and dimmable electric lights in private offices of a high performance building. The experimental study was designed to (i) extend the current knowledge of human-building interactions to different and more advanced systems, including intermediate shading positions and light dimming levels, and (ii) reveal behavioral characteristics enabled through side-by-side comparisons of environmental controls ranging from fully automated to fully manual and interfaces with low or high level of accessibility (wall switch, remote controller and web interface). The research methodology includes monitoring of physical variables, actuation and operation states of building systems, as well as online surveys of occupant comfort and perception of environmental variables, their personal characteristics and attributes (non-physical variables). The analyzed datasets provide new insights on the dynamics of interdependent human interactions with shading and electric lighting systems. Higher daylight utilization was observed in offices with easy-to-access controls, which implies less frequent use of electric lights and less energy consumption accordingly. Analysis of occupant satisfaction, in terms of comfort with the amount of light and visual conditions, based on datasets from offices with variable accessibility to shading and lighting control, reveals a strong preference for customized indoor climate, along with a relationship between occupant perception of control and acceptability of a wider range of visual conditions.

1. Introduction

Occupant behavior in office buildings can be classified as (i) occupant presence/absence or so-called *occupancy*, which can make a difference in required temperature set points, ventilation requirements and energy consumption and (ii) their interaction with the building through thermal and visual control systems and/or devices that affect plug loads; *human-building interactions*. Interactions with comfort delivery systems include opening or closing windows/doors [1,2] and/or turning on/off fans [3,4], changing thermostat set points [5,6], controlling electric lights [7–12], and moving window shades [13–21]. Researchers have explored human-building interactions in office spaces to reveal their energy impact and in some cases, correlations between occupant actions and monitored physical variables were developed for use in building simulation programs [1,2,17,19–24]. Some have attempted to infer occupant preferences from those interactions [5,25–27] and have reported individual differences in experiencing thermal environments. Field studies also conclude that maintaining acceptable visual comfort conditions for the majority of people is challenging, since the perception of glare/adequate light levels varies significantly amongst individuals [20,28–31]. Studies with shading/lighting automation systems suggest that occupants frequently override these systems, either indicating discomfort or implying their desire for customized indoor climate [10,32–36].

It is clear by analyzing previous studies that differences in building design (e.g., space layout, window size, orientation, glazing/shading type and properties) and indoor environmental control characteristics should be considered when comparing results. To investigate the triggers of interactions with shading and lighting systems, a wide range of indoor variables have been monitored in various campaigns around the world. These include

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indoor air temperature [12,17,19,21], horizontal illuminance [12,17–19,21], average and maximum window luminance [17,19], vertical illuminance on VDU screens [18], daylight glare index and probability [7], transmitted solar radiation [14,17–19], depth of solar penetration [14]; as well as outdoor variables such as outdoor temperature [3,21], incident solar radiation [12,13,15,18,37], horizontal and vertical global illuminance and irradiance [12,18], solar altitude [21], sunshine index, and sky conditions [9,16]. Occupants may use shading devices to alleviate both visual and thermal discomfort, which can be caused by temperature, solar radiation, glare, etc. and a wide range of physical variables has been considered to identify the main drivers of these interactions with significant variations in findings [38]. For example [15,16], claimed that indoor temperature and incident solar radiation cannot be a predictor variable for the window shade/blind deployment. This is while, elsewhere, these two variables were reported to be significant for occupant interactions with shading [12,14,17–19,21]. In other studies [18,24,39] only visual or illuminance considerations were used to connect to blind lowering or electric light on/off switching. Furthermore, occupation dynamics, HVAC system operation and automatic controls affect the way occupants interact with shading and electric lighting systems. For example, results from Ref. [17] revealed that the mean shade occlusion rate for offices with air-conditioning (A/C) was 30% compared to 49% for offices without A/C. Frequency and dynamics of shading/lighting interactions were significantly different between arrival, intermediate, and departure periods in relevant studies [7,20,39–41].

Seasonal effects have been studied to investigate potential differences in occupant behavior with respect to shading and lighting systems [12]. However, findings from some studies [20] reported that the effects of seasonal changes rely on other physical variables, such as indoor temperature or daylight levels, thus they were found statistically insignificant. These suggest that considering the right triggering variables, one might be able to describe human-shading interactions throughout the year. However, physical variables are not the only drivers of human-building interactions. Personal characteristics and attributes, i.e. non-physical variables that are not measurable with typical sensors, have also been reported to describe occupant interactions with building systems. For example, view and connection to the outside, privacy and perception of daylight as important factor for health have been reported as non-physical motivations for human interactions with shading and electric lighting [12,16,17,20,21,42,43]. Previous research has discussed the importance of cultural and social factors in the study of human-building interactions, highlighting the need for more and geographically broadly distributed office behavior monitoring campaigns [7,44]. Statistically high number of field studies have been conducted in several European countries [3,7,9,12,16,18,20–22] while studies in the United States are rather limited [17,26].

To summarize, in perimeter building zones, several physical or non-physical variables may affect occupants' visual perception and trigger their control actions –in these dynamic environments, understanding of stimulus–response relationships is a complex task. Motorized and automated shading systems have been implemented in high performance buildings, but there are only a few studies, mostly on venetian blinds, that investigate the performance of these systems and how people actually interact with them [10,18,20,33,45]. Studies with roller shades are quite limited, although these products are commonly used [35,36]. It is important to observe occupant interactions through the lenses of different environmental control options. Side-by-side experiments with controls ranging from fully automated to fully manual and interfaces with low-level of accessibility (wall switches) or high-level of accessibility (remote controllers, modular web interfaces), should enable better understanding of occupant behavior.

The main goal of this paper is to investigate how occupants interact with shading and lighting control systems in real offices with variable control capabilities. To this end, a field study with a large number of participants was designed and conducted in four adjacent private offices of a high performance building, equipped with motorized roller shades and dimmable electric lights. In particular, this study examines human-building interactions considering different environmental control setups with manual and web (cyber-physical) interfaces for shading and lighting operation. The results allow better understanding of the dynamics of human interactions with shading and lighting systems; correlating actions with indoor environment conditions, and most importantly, with visual perception and comfort; analyzing effects of non-physical variables; as well as demonstrating the impact of control interfaces that affect human interactions -and consequently, energy use.

2. Research approach

The field study was designed to address the following set of key research questions:

1. How do occupants interact with motorized roller shades and dimmable electric lights using different control interfaces (including manual operation modes and overrides on automated operation)? What are the resulting shade positions and electric light levels?

Low rates of shade movement for offices with manual (non-motorized) shading devices have been reported in previous research [7,14,15,17,18,37]. Although very few studies considered occupant interactions with motorized blinds/roller shades, they all showed higher shade movement rates compared to manual control [18,35,36,45]. It is also important to monitor the preferred intermediate motorized shade positions selected by occupants (and not only fully open/closed positions), which of course varies with office layout, orientation and sky conditions among other factors summarized in Ref. [38]. Studies focused on occupant interactions with electric lighting [7–11,28,39] considered lights on/off switching without considering intermediate light levels, in parallel with shading positions. In addition to the frequency of electric light adjustment, selected dimming levels should be monitored as well, associated with visual comfort sensation and the nature of the office task. In this study, we monitored and compared human interactions with motorized roller shades and dimmable electric lights using different control interfaces.

2. What are the underlying physical and non-physical variables for describing human interactions with motorized shading and electric lighting systems?

It is important to account for both physical and non-physical variables when developing probabilistic models of human-building interactions. Specific to the sensor network in each field study, a wide range of physical variables has been considered for modeling occupant interactions with shading or electric lighting systems [7,12–14,17–19,21]. Occupant behavioral models for use of shading devices and electric lights exist [7–9,17,20,21,24,39] but non-physical drivers are not incorporated within the structure of predictive models. Another important issue to consider when deriving models of human-building interactions is the existing endogeneity, if any, between the operation states of multiple building systems (dependent variables in statistical terms). Modeling efforts related to occupant use of window shades and electric lights inherently assume that these two environmental control systems are operated independently. This assumption, if found to be violated, can result in model inefficiencies [47]. A wide range of environmental variables was monitored in this study along with operation states of motorized roller shades and electric lights. This question embarks on highlighting those physical and non-physical variables that have a strong correlation with observed states of shades/lights and seem to support reasoning behind human interactions with these systems. Non-physical motivating factors for human-building interactions cannot be measured; therefore, online (web) surveys were designed and used to gather information from office occupants about their attitudes towards interacting with roller shades and electric lights.

3. What are the preferred visual conditions in offices with different shading and lighting control setups?

To depict the distribution of both total and daylight work plane illuminance, it is essential to examine if illuminance preferences vary with different control setups and if they are in agreement with standards and recommendations [48,49]. Daylight provision is desired in perimeter offices, and this hypothesis is investigated considering different control interfaces to seek thresholds of daylight illuminance, if any, for which occupants prefer daylight to artificial lighting. Apart from work plane illuminance considerations [46], the overall visual conditions in perimeter offices play an important role in occupant interactions with daylighting (shading) and electric lighting systems. Daylight discomfort glare is one of the triggers for actions, and available glare indices account for source luminance size and location, view direction and background luminance among other factors [31,50], with new research insights on design metrics [51]. Previous work has analyzed Daylight Glare Probability or DGP [54] for the case of roller shades [52,53], proposing alternate criteria for the case of low openness fabrics. Vertical illuminance and DGP were evaluated in this study in real office environments, along with variations among the different control setups.

4. What are the effects of shading and lighting control setups on occupant visual comfort and satisfaction with the indoor environment?

Field studies have shown that automation systems that exclude occupants from the control loop are not well received, and demonstrated the desire for a customized indoor climate and access to control [34–36,55]. They have also reported a strong relationship of occupants' perception of control over their environment with productivity [34,56]. Related research highlighted a distinct difference between the effects of perceived and utilized control [59] and the fact that satisfaction benefits are contingent upon controls being simple and well-maintained [34,42,43]. This is also pronounced in Ref. [60] where detailed statistical analysis has shown significant correlations between key thermal comfort and perceived control variables (ASHRAE RP-884 datasets) while conveying that occupants' understanding of controls plays a key role and simply having control over the environment is not enough to result in occupant satisfaction and comfort conditions. Some of the field studies have suggested that improved thermal satisfaction through perceived control is due to increased tolerance of wider ranges of thermal conditions [58,59]. Adaptive thermal comfort models also have the potential of making the comfort zone wider [61]. To date, there is no “adaptive visual comfort”, but several studies investigated respective concepts [62]. Studies on luminous environment have recognized the importance of occupant control perception and interface design [31,63] but the details of occupant behavior remain to be investigated. Overall, it is believed that providing occupants with easy-to-use controls over comfort delivery systems would make them more eager to act for improving their comfort. Our main hypothesis is that occupant satisfaction (or dissatisfaction) with visual conditions is probabilistically tied to visual perception and expressed via interactions with respective indoor environmental controls. It also depends on behavioral factors as well as on building design and operational features (office control setup). This research question investigates this hypothesis using data from web surveys, designed to provide an initial understanding of occupant satisfaction with the visual environment and subjective productivity under different control setups.

3. Field study details

3.1. Building description

Four identical south-facing private offices (3.3 m × 3.7 m × 3.2 m high) in a new high performance building located in West Lafayette, Indiana, were selected for the purpose of this study. The building was awarded LEED Gold certificate in 2013. A Building Management System (BMS) is available through the installed Tridium JACE controllers and Niagara/AX software framework, which in addition to a variety of internet-enabled features gives the ability to monitor, control, and automate all the building systems regardless of manufacturer or communication protocols. Fig. 1 shows the arrangement of the monitored offices. The offices have one exterior curtain wall façade with 54% window-to-wall ratio, and a high-performance glazing unit with a selective low-emissivity coating (visible transmittance: 70%, solar transmittance: 33%). The windows are equipped with dark-colored motorized interior roller shades that have a total visible transmittance equal to 2.53% (measured with an integrating sphere) and an openness factor of 2.18%. The low openness factor combined with the low visible transmittance was a decision to reduce daylight glare [53], while the dark color is associated with clearer view to the exterior [64]. Each office has two electric lighting fixtures with two 32-W T5 fluorescent lamps (total of 128 W). During the field study, the temperature in each office was well kept within ±0.5 °C of the set point using feedback from two sensors installed close to the person. This is only important for ensuring that there were no other thermal impacts potentially affecting human interaction with shading.

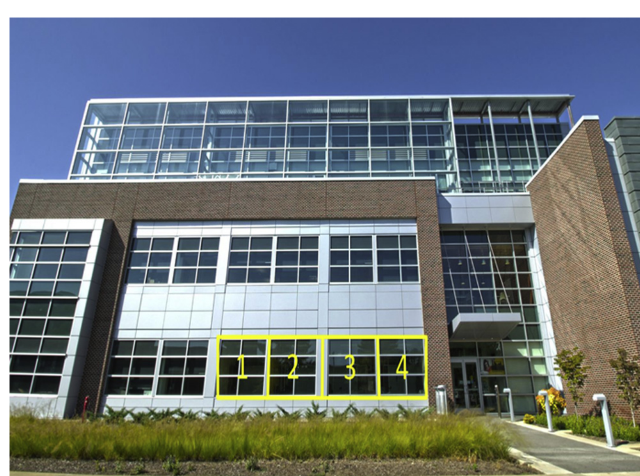

Fig. 1. The four offices used in the study.

3.2. Experimental procedure

The field study was conducted over a period of 40 days (9:00 am–4:00 pm), covering a wide range of sky conditions (Appendix A) and solar paths between April 1st and June 15th 2015 (including 22 sunny days, 10 cloudy days, and 8 mixed sky days). Overall, 147 office occupants participated in the field study (98 males and 49 females). Participants were students and staff (between 20 and 40 years old) not familiar with this research. Each office was occupied by one participant every day. All participants were asked to perform their usual workload (computer-related work, reading, writing, etc.) during the day and answer four short web-based questionnaires, which were sent by e-mail and combined with phone alarm reminders at specific times during the day. They were free to take breaks or leave the office if they needed to (e.g. attend meetings, classes etc.). To enable side-by-side comparisons, contextual factors such as monitor type and size, monitor position, seat position, sensor positions, office desks, and other furniture were identical in the four offices. The only difference was the control interface provided to participants for interacting with shading and electric lighting systems. At the beginning of the day, details regarding the environmental control setups were explained thoroughly to each participant in order to help them become quickly familiar with the setup. Participants were advised to interact with electric lights, shading system, and thermostat as they usually would, and to avoid any direct contact with the monitoring instrumentation. The instrumentation was installed so there was no interference with the occupant regular position and task. To eliminate any bias in the results, each person participated in the monitoring campaign only for a single day in one office setup. This sampling method enabled a large number of participants, which is necessary for the purpose of this study, and did not require the installation of experimental equipment in a large number of offices. During the preliminary phase of the field study (before starting the main monitoring campaign), the impact of test duration, in terms of the number of days that human test-subjects stay in the office, was examined and representative results are discussed in Appendix C. The occupants showed consistent behavior in all consecutive days and our findings support the conclusions made in previous studies [9,10,14,13,15,24,37,39,41]: Even though occupants behave differently, they use their lighting and blind controls consciously and consistently. In addition, comparisons of our findings in terms of daily human-shading interactions with those reported in previous studies [35,36,45] that investigated motorized shade movement rates in office spaces (reported in Section 4.2.1) indicate good agreement, despite of the differences in the duration of stay of the occupants in the offices. Similarly, good agreement is found with results reported in Refs. [7,10,14,20] regarding the significance of occupation dynamics for interactions with shading and lighting systems. Therefore, it is anticipated that the results of this study are representative of typical office occupants. The field study with human subjects was approved by the Institutional Review Board (IRB Protocol #: 1503015873).

3.3. Office control setups and interfaces

Four different arrangements (control setups) were considered to investigate human-building interactions with shading and lighting in the offices:

- **Setup 1:** Manual control with low level of accessibility (wall switches)

In this setup, participants used commercially available wall switches (Fig. 2) to control motorized roller shades and electric lights. Participants could open/close roller shades or turn on/off electric lights with a single button push (top and bottom), or they could choose intermediate shade positions or light dimming levels (both in 25% increments) by pressing middle increase/decrease buttons respectively.

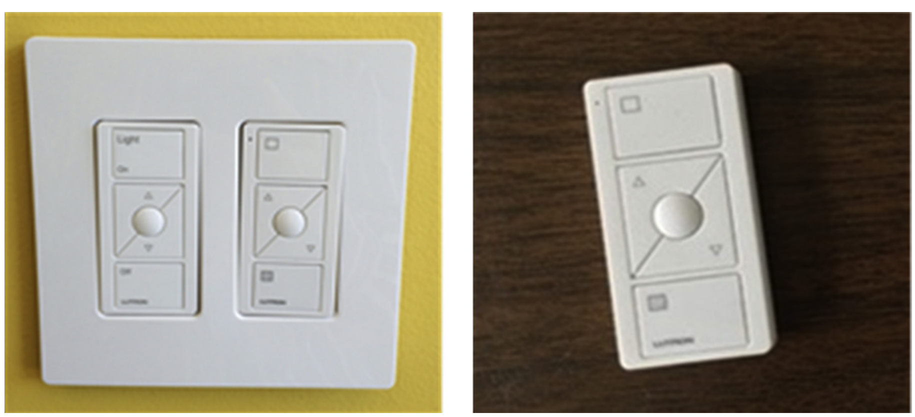

Fig. 2. Wall switches for manual control of electric lights and roller shades (left); remote controller for shading control in setup 4 (right).

- **Setup 2:** Manual control with high level of accessibility (web interface)

In this setup, participants used a modular web-based graphical interface (designed by the authors) to control shade position and electric lighting levels. Usability tests of the interface were performed in a preliminary study before starting the main monitoring campaign. Fig. 3 presents the graphical interface in its final design form (note that occupants were also able to change thermostat set points but this aspect is outside of the scope of this paper). Participants could use sliders or click on buttons to control roller shade position (right side) and electric light levels (left side) in 25% increments.

As shown in Fig. 3, other important features were designed on the interface. These include comfort sliders for capturing the level of comfort with the amount of light and visual conditions, as well as a four-scale reasoning slider in the middle to capture non-physical motives of human-shading interactions. The selection of non-

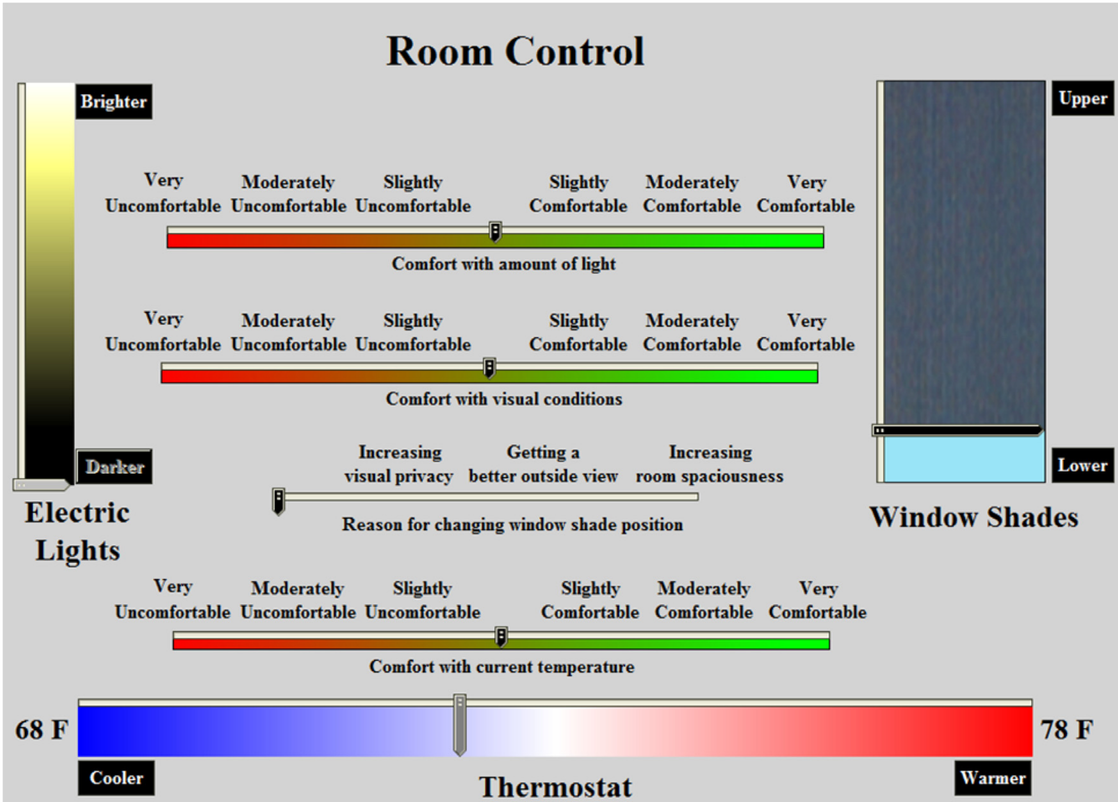

Fig. 3. The modular web-based graphical interface for environmental controls in setup 2.

physical triggers included on the interface was based on a preliminary study before the main monitoring campaign, which was done with a small group of participants. This revealed that "increasing visual privacy", "getting a better outside view", and "increasing room spaciousness" were the most important non-physical drivers of human-shading interactions.

The interface features and the way data was collected is important for understanding the triggers of human interactions. This was achieved by collecting information when those interactions occur, i.e. participants moved the comfort sliders right before taking any action. In addition, they only moved the reasoning slider before moving the shades, based on one of the indicated reasons; otherwise, the slider would remain untouched. The sliders incorporated a snapping feature, which was designed to bring the slider back to its default position (in the middle for comfort sliders and at the left end for the reasoning slider) three minutes after each movement. All comfort votes and actions were continuously monitored.

- **Setup 3:** Fully automated control

In this setup, occupants did not have any control over their environmental conditions. Roller shades were controlled automatically to prevent direct sunlight on the occupant/work plane, but allowed direct light on the floor, up to 1 m from the window. In addition, there were adjustments for low light and high brightness conditions. This operation depends on the solar path and the room orientation [65,66]; having intermediate positions is better than fully opening/closing shades, since it allows more daylight and outside view. Electric lights were automatically controlled in order to always provide 500 lux on the work plane, using a commercially available ceiling daylight sensor.

- **Setup 4:** Automated control with manual overrides

In this setup, shading and lighting were automatically controlled as in setup 3, but occupants could override the shade position using a remote controller (Fig. 2). The controller had buttons for completely opening/closing shades as well as for continuous intermediate positions, by holding the increase/decrease buttons and releasing them once the desired position was reached. The automatic control was disabled for 15 min after each override and then enabled again. Upon arrival in the morning (9:00 am), the room air temperature was 22 °C in all offices. Occupants could precisely control the room temperature in all manual setups (using a wall switch in setup 1 and the web interface in setups 2 and 4) -the Variable Air Volume (VAV) system in each office was fine-tuned for that reason. In setups 3 and 4, the initial shading position upon arrival was set automatically following the control logic described above, and electric lights were initially turned off. In setups 1 and 2, where there was no automatic control, different initial conditions for the roller shade position and electric light levels were implemented over the course of the study. However, to enable side-by-side comparison between setups 1 and 2, the same initial conditions were used in these two setups every day.

3.4. Instrumentation, physical data acquisition and communications

This section presents the data acquisition framework designed to investigate occupant interactions with shading and lighting systems. This includes the sensors used to monitor physical variables and the communication protocols for actuation and operation status of the building systems. The following physical variables were monitored during the field study:

- Shade position, electric light levels, and room temperature set point: shading and lighting systems in the building are connected to a lighting control hardware. VAV boxes, with thermostat set-point information, are connected to thermal systems controllers. Both control hardware communicate with the building's JACE controllers through the Niagara framework [67] and BACnet protocol.
- Occupancy: wireless vacancy sensors connected to lighting controller were used to monitor and store the state of occupancy in each room and as mentioned above, lighting control hardware communicates with building JACE controllers and Niagara framework. All other sensors described below were connected to data acquisition input modules, and through a wireless connection, to the main data acquisition (DAQ) controller, which communicates with JACE controllers through the Niagara framework and Modbus protocol.
- Work plane illuminance: measured using one LI-COR 210-SL photometric sensor in each office. Facing upwards, the sensor is located on the desk and in a central position of occupant working area. Occupants were advised to keep the sensor unobstructed. All illuminance sensors have an accuracy of 3%.
- Work plane daylight illuminance: calculated from the difference between measured total work plane illuminance and work plane illuminance due to electric lighting (the latter measured separately at night).
- Vertical illuminance (near eye level): measured using LI-COR 210-SL photometric sensors mounted vertically (on the camera) adjacent to the occupant's head (30 cm away) to capture representative values without obstructing their actions.
- Transmitted global solar radiation through window: measured using a LI-COR 200-SL pyranometer vertically mounted on the inside of the glazing, facing outside. The sensor has a resolution of 0.1 W/m^2 and accuracy of 3%.
- Transmitted illuminance through window: measured using a LI-COR 200SL photometric sensor vertically mounted on the inside of the glazing, facing outside, next to the pyranometer.
- Average window and background luminance: a calibrated dSLR camera (Canon T2i) equipped with fisheye lenses (Sigma 4.5) was mounted at 30 cm from the occupants' head in each office to capture the luminance distribution within their visual field, using HDR imaging. To avoid manual operation and occupant distraction, a firmware [68] was used with the cameras to automate the shooting sequence. To extract the average luminance of the visible part of the window, the respective area was masked from the HDR images using Adobe Photoshop and then used as input for Evalglare [69] marking the area of interest as a glare source. This enabled the software to output the average luminance of the area of interest, in addition to the average luminance of the entire visual field. Due to the large number of data throughout the experiment, automation scripts were created for running all the necessary image-processing routines involved. Further details are presented in Appendix B.
- Daylight Glare probability: DGP is calculated by processing the HDR images in Evalglare. There were some differences in terms of focus area between different subjects as some participants were also using their laptop screens along with the monitors provided. Therefore, the glare source identification method was based on the average luminance of the entire visual field rather than the task areas.
- Indoor air temperature: two shielded J-type thermocouples (resolution of 0.01 °C, 0.4% accuracy) were mounted in each office at seating height and on two sides of occupant regular work position. The average reading of the two is used to reduce the influence of spatial temperature distribution.

Fig. 4 shows a typical layout with part of the monitoring instrumentation described above. The seating position of the occupant, with partial window view (wall-facing office layout), which represents a typical setting for office environments, along with the location of sensors and control devices are shown in Fig. 5. Fig. 6 presents the framework of sensor integration to Building Management System (BMS). Measurements of relative humidity, globe and room air temperature were included to ensure proper equipment operation. Using proper communication protocols, all sensor readings were discovered in Niagara framework and recorded every five minutes; DGP and luminance data were measured every 15 min.

3.5. Occupant surveys

Two types of web-based survey questionnaires were designed in order to capture data that are not measurable with sensors. Survey-A includes questions about both human-building interactions and occupant satisfaction with indoor environment and was completed four times a day. A six-point scale from "very uncomfortable" to "very comfortable" was used, while a seven-point Likert scale was utilized for questions related to satisfaction with window view and overall lighting conditions. Survey-B refers to personal characteristics and attributes. Survey questionnaires were sent to participants at specific times during the day. Occupants were reminded to answer the web surveys by phone alarms set in the morning. Table 1 presents a summary of the survey questions.

4. Results

This section presents the experimental data from the monitoring campaign structured to address the set of key research questions presented in Section 3.1.

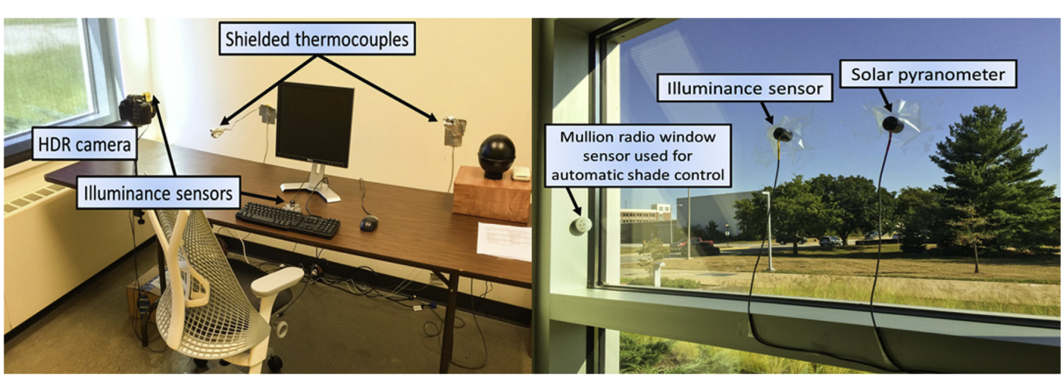

Fig. 4. Typical layout of monitoring instrumentation in each office.

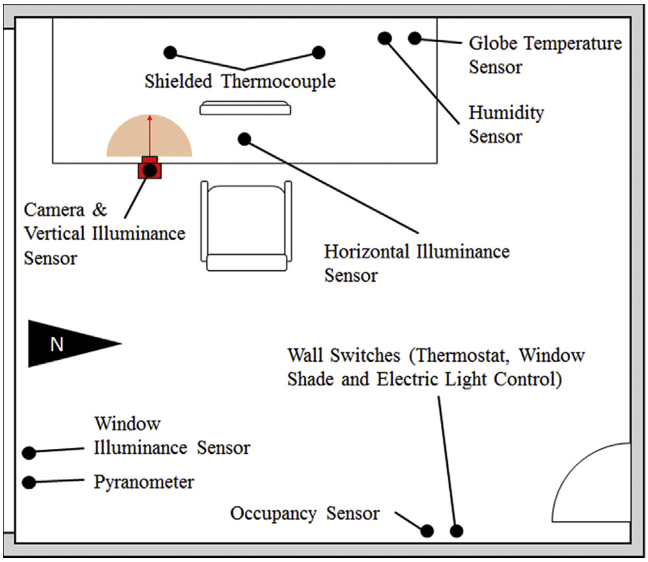

Fig. 5. Schematic view of identical offices showing occupant's seating position, location of sensors and control devices.

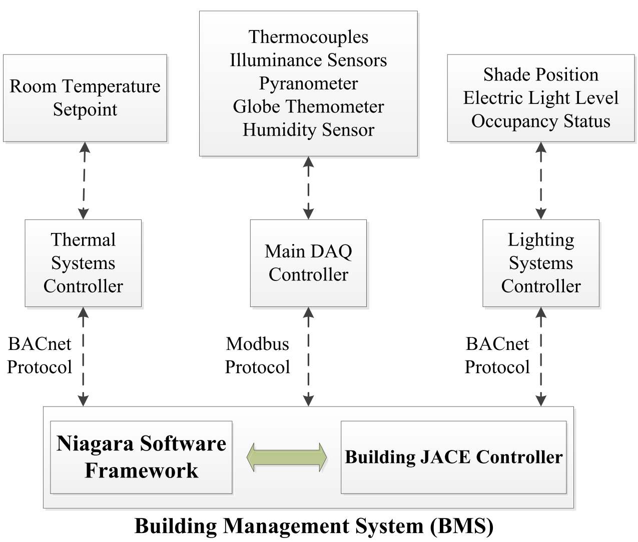

Fig. 6. Sensor integration to BMS.

4.1. How do occupants interact with motorized roller shades and dimmable electric lights using different control interfaces (including manual operation modes and overrides to automated operation)? What are the resulting shade positions and electric light levels?

4.1.1. Interactions with motorized roller shades

Table 2 presents the summary of test cases under different sky conditions and metrics for interactions with motorized shades for each control setup. It should be noted that setups 1 and 2 were examined throughout the whole period of the field study with the same outdoor conditions. To increase the number of observations in control setup 2, this setup was sometimes used in multiple offices during the field study, resulting in 54 cases with different participants. Setup 4 was evaluated for a shorter period. For the results presented in Table 2, the same percentages of sunny/cloudy/dynamic days were considered for setups 1, 2 and 4, representing statistically equivalent conditions in order to enable meaningful comparisons.

A total number of 53 shading adjustments were recorded when occupants had to use the wall switch (setup 1) to control the motorized roller shade (1.36 shade adjustments/day on average). These results are in agreement with other studies [35,36,45] that investigated motorized shade movement rates in office spaces. A significantly higher number of interactions (2.63/day) was observed when the web interface was used (setup 2), proving that the ease of control access results in increased interactions with motorized shading (or more generally, reduces the effort required to control/improve indoor environmental conditions). This is also the reason why the shade movement with wall switches presented here is still higher than what has been reported in studies with non-motorized manual shading devices, operated by turning a rod, pulling a chain or cord [7,13–15,17,19,21,22]. Raising and lowering could happen in 25% increments with setups 1 and 2; but with setup 4 (overrides to automated control), all intermediate positions were available using the remote controller. The rate of occupant overrides (2.24/day on average) in this case is an indication of the desire to have personalized control over the luminous environment.

Fig. 7 (top) shows the frequency of shade positions selected with control setups 1 and 2. Motorized shades remain in intermediate positions for a considerable amount of time; therefore, studies investigating only fully open/closed positions may not be adequate. This is more pronounced in setup 2 (web interface with easier access) where occupants tend to fine-tune their environmental conditions through a higher number of interactions with shading and selection of intermediate positions. Consequently, control interfaces play an important role in both the number of interactions and selected shade positions, which have a profound effect on energy use.

4.1.2. Interactions with dimmable electric lights

The frequency of selected light levels is depicted in Fig. 7 (bottom). On average, occupants adjusted their electric lights 1.33 times per day using wall switches and 1.52 times per day using the web interface. Higher frequencies of intermediate light levels with setup 2 show the desire towards improving environmental conditions when exposed to easy-to-access and high-level personalized controls (web interface). Moreover, for both interfaces, the high frequency of keeping electric lights off and interacting with motorized shades implies that occupants prefer natural light —nevertheless, this statement should be interpreted cautiously as shading interactions might be triggered by other non-physical variables (e.g. visual privacy, outside view), rather than desire for daylight as explained in Sections 4.2 and 4.3.

4.2. What are the underlying physical and non-physical variables for describing human interactions with motorized shading and electric lighting systems?

4.2.1. Physical variables and considerations for modeling human interactions

Human interactions with shading and lighting systems are governed by a combination of variables (physical and non-physical) rather than a single variable, some of which might be affecting each other's attribute in explaining the interactions (dependent variable in statistical terms) within a network structure. Table 3 presents Pearson correlation coefficients between nine physical variables and corresponding changes in the operation states of roller shading and electric lighting based on the data collected from control setup 1 and 2 (results for the two setups were similar to each other, therefore only one correlation coefficient is shown for each variable). It indicates that indoor illuminances and solar penetration depth show the strongest correlations with shading and lighting

Table 1
Summary of survey questionnaires.

Questions	Answer options
Survey A	
1a) Did you lower/close roller shades during last section?	Yes/No
1b) If yes, what was the reason for that?	To increase visual privacy To reduce overall brightness of workspace To reduce glare on computer screen To reduce glare on the desk To reduce glare on the floor To reduce glare from the sun (directly into my eyes) To reduce heat from sun Other (please specify)
2a) Did you raise/open roller shades during last section?	Yes/No
2b) If yes, what was the reason for that?	To get a better outside view To increase room spaciousness To increase level of daylight in workspace To get heat from sun Other (please specify)
3a) Did you adjust electrical lights during last section?	Yes/No
3b) If yes, what was the reason for that?	To reduce overall brightness of workspace To reduce glare on computer screen To reduce glare from electrical lights (directly into my eyes) To reduce heat from electrical lights To save energy To increase level of lights in workspace To make interior surfaces (walls, ceiling etc.) almost as bright as window Other (please specify)
4) How comfortable are you with current amount of light?	1. Very uncomfortable, 2. Moderately uncomfortable, 3. Slightly uncomfortable, 4. Slightly comfortable, 5. Moderately comfortable, 6. Very comfortable
5) How comfortable are you with current visual conditions (e.g. glare, reflections, and contrast)?	1. Very uncomfortable, 2. Moderately uncomfortable, 3. Slightly uncomfortable, 4. Slightly comfortable, 5. Moderately comfortable, 6. Very comfortable
6) How satisfied are you with your current window view?	1. Very dissatisfied, 2. Moderately dissatisfied, 3. Slightly dissatisfied, 4. Neutral, 5. Slightly satisfied, 6. Moderately satisfied, 7. Very satisfied
7) Please describe the current lighting condition at your workspace	1. Very dark, 2. Dark, 3. Slightly dark, 4. Neutral, 5. Slightly bright, 6. Bright, 7. Very bright
Survey B	
1) In general how important is it for you to have a clear view to outside?	1. Least important … 5. Most important
2) In general how important is it for you to have visual privacy?	1. Least important … 5. Most important
3) Overall, how would you rate your today's work productivity?	1. Poor, 2. Fair, 3. Good, 4. Very good, 5. Excellent
4) What is your gender?	Male/female

Table 2
Observed shading system events.

	Control setup 1 (wall switches)	Control setup 2 (web interface)	Control setup 4 (automated shades/remote controller overrides)
Total number of tests	39	54	25
Tests during sunny days	21	31	14
Tests during cloudy days	10	11	5
Tests during mixed sky conditions	8	12	6
Total number of human-shading interactions	53	142	56
Average number of daily human-shading interactions	1.36	2.63	2.24
Number of shade raising events	31	61	30
Number of shade lowering events	22	81	26

interactions. However, due to multicollinearity issues, these variables cannot be included in the same modeling framework. Moreover, despite the high inter-correlation, their attributes need to be further investigated in presence of other significant variables (e.g., direct solar radiation or occupation dynamics and non-physical variables) within a multivariable modeling framework. To investigate the existence of endogeneity between the operation state of shading and electric lighting, Fig. 8 explores the interaction between their usages, considering aggregated datasets from control setups 1 and 2. The figure presents selected electric light levels for each roller shade position and shows that increased electric light levels are more frequently selected with lower shade positions (and vice versa). Table 4 shows the Pearson correlation matrix for the operation state of shading, electric lighting, and thermostat. Results for the thermostat set point adjustment were considered, showing independent operation with the shading and electric lighting, which confirms the quality of the experimental dataset used in this paper. Overall, electric lights and roller shades are operated interdependently. This should be considered when developing predictive models to describe the human interactions with shading and electric lighting systems whether modeling their operation state directly or occupant actions on the systems (raising, lowering, etc.) as the interdependent operation can be reflected on human actions as well.

The effects of occupation dynamics and control access on shading and lighting actions are depicted in Fig. 9. The first ten

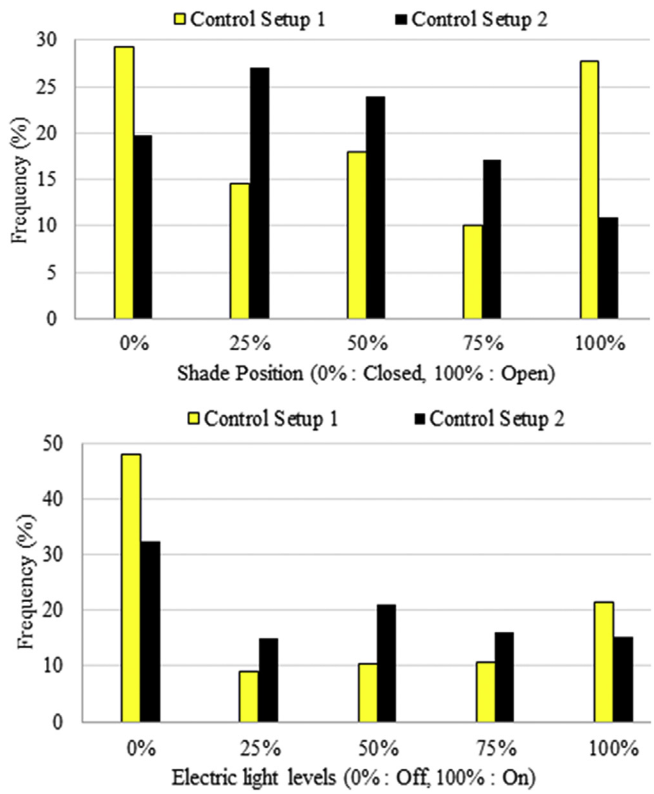

Fig. 7. Frequency of selected shade positions (top) and electric light levels (bottom) with control setup 1 (wall switches) and control setup 2 (web interface).

minutes after arrival and the last ten minutes before the departure were selected as threshold limits for arrival and departure time intervals. The same threshold was used for determining events before and after intermediate absences. Based on these results, a considerable portion of shading and electric lighting adjustments in both setups occurs outside the intermediate time interval with continuous occupation (49% with setup 1 and 35% with setup 2 for shading interactions; and 65% and 42% for electric light interactions respectively). Among the occupation dynamics outside the intermediate time interval, arrival and departure times show the highest frequencies of shading and electric lighting interactions in both setups 1 and 2 (orange and blue in small pies) except for departure shading interactions in setup 1. This is in agreement with findings of previous studies [7,10,14,20] and suggests that occupation dynamics is a significant variable for interactions with shading and lighting systems, and should be considered in relevant models. In addition, the results of Fig. 9 imply that the type of control interface, -or "ease-of-access"- should be considered as another important variable. Occupants using a web interface (setup 2) interact more with both shades and lights during intermediate time intervals with continuous occupation, compared to setup 1 (wall switches). This finding demonstrates the importance of human-building interface design, which should be incorporated in predictive models for human-building interactions.

4.2.2. Survey results: reasons for interactions with shading and lighting and non-physical variables

Fig. 10 illustrates the reasons for shading interactions based on the data collected from the survey type-A (Table 1) with setups 1, 2 and 4. Reducing overall brightness and increasing daylight levels were the main reasons for lowering and raising roller shades respectively with all control setups. Reducing glare on computer screens and desks are also two other frequent shade-lowering reasons, which can be also described by physical variables (e.g. glare indices or luminance values). Significant and relatively high Pearson correlation for these physical variables (Table 3), shows a good agreement between outcomes of survey type-A and monitored behaviors. With control setup 4 (overrides to automated shading operation), a higher rate of actions to reduce brightness was observed, due to the fact that shades automatically reset their position 15 min after each override, allowing 1 m of sunlight on the floor —which seemed too bright for the occupants.

The desire to increase visual privacy was another significant motive for lowering/closing window shades. Achieving a better outside view, as well as increasing room spaciousness were also reported by participants as reasons for window shade raising/opening events —these are all non-physical variables. Connection to the outdoors, directly related to shade position, is an important but not adequately studied aspect of the visual environment [70–73], especially for the case of motorized shades, which affect the amount and clarity of outside view [64]. For that reason, questions related to outside views were included in survey type-A, while some more general questions were answered once per day in survey type-B. Fig. 11 presents a distribution of survey type-B results relevant to connection to the outdoors. More than 60% of the participants prefer to be close to windows; the great majority want to have a window, while only 3% of the participants specifically stated that they want to face the window. These results, combined with other studies focused on the spatial characteristics of visual discomfort [53,62,70–72] support the fact that people are satisfied with partial window views (i.e., wall-facing layout in offices), which decrease visual discomfort sensation while still provide adequate daylight.

To examine the effect of outside view and visual privacy, Fig. 12 illustrates boxplots of selected shade positions with control setups 1, 2, and 4 versus occupant's self-reported level of importance of clear outside view and visual privacy (importance level of one is excluded due to low frequency). An average line as well as error bars are also shown. Higher unshaded portions are selected by participants to whom having a clear view is more important; and

Table 3
Pearson correlation between physical variables and the operation state of shading and electric lighting.

	Work plane illuminance	Work plane daylight illuminance	Vertical illuminance at eye level	Average window luminance	Average luminance of visual field	DGP	Transmitted global solar radiation	Transmitted direct solar radiation	Solar penetration depth	Room temperature
Roller shades	−0.453[a]	−0.401[a]	−0.427[a]	−0.326[a]	−0.293[a]	−0.367[a]	−0.143[c]	−0.248[b]	−0.487[a]	−0.078[d]
Electric lights	−0.151[a]	−0.336[a]	−0.264[a]	−0.234[a]	−0.262[a]	−0.243[a]	0.088[d]	0.023[c]	−0.335[a]	0.091[b]

[a] Statistical significance at 0.001.
[b] Statistical significance at 0.05.
[c] Statistical significance at 0.1.
[d] Not statistically significant.

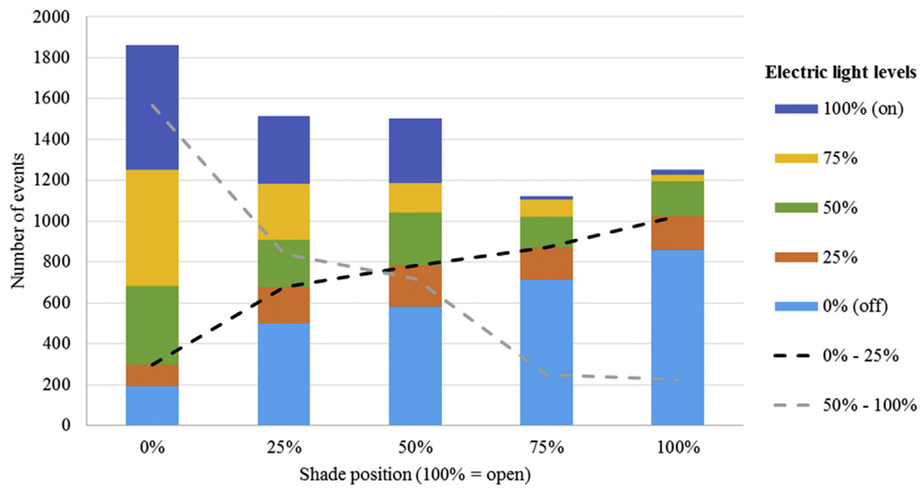

Fig. 8. Interdependency between occupant interactions with the motorized roller shade and electric lights.

Table 4
Pearson correlation between the operation states of building systems.

Variable	Roller shade position	Electric light level	Thermostat set point
Roller shade position	1.000[a]	−0.423[a]	0.005[a]
Electric light level	−0.423[a]	1.000[a]	0.110[b]

[a] Statistical significance at 0.001.
[b] Statistical significance at 0.05.

lower shade positions correspond to participants who reported visual privacy to be of high level of importance. Therefore, the impact of non-physical variables —such as visual privacy and outside view-on the dynamics of human-shading interactions is noticeable.

Among the reasons for adjusting electric light levels (Fig. 13),

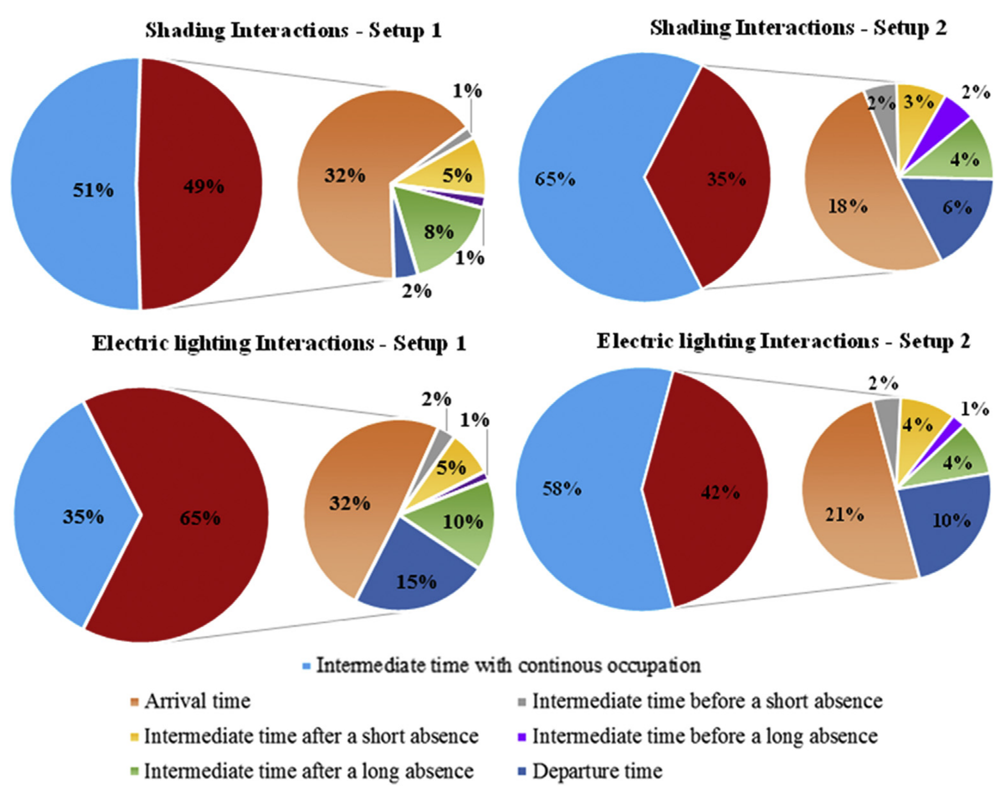

Fig. 9. The effect of occupation dynamics on interactions with motorized shades (top) and electric lights (bottom), comparing control setups 1 (wall switches) and 2 (web interface). In the big pie charts, the blue area demonstrates the overall portion of the intermediate time with continuous operation. For the remaining portion of time, a more detailed overview can be observed in the smaller pie charts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

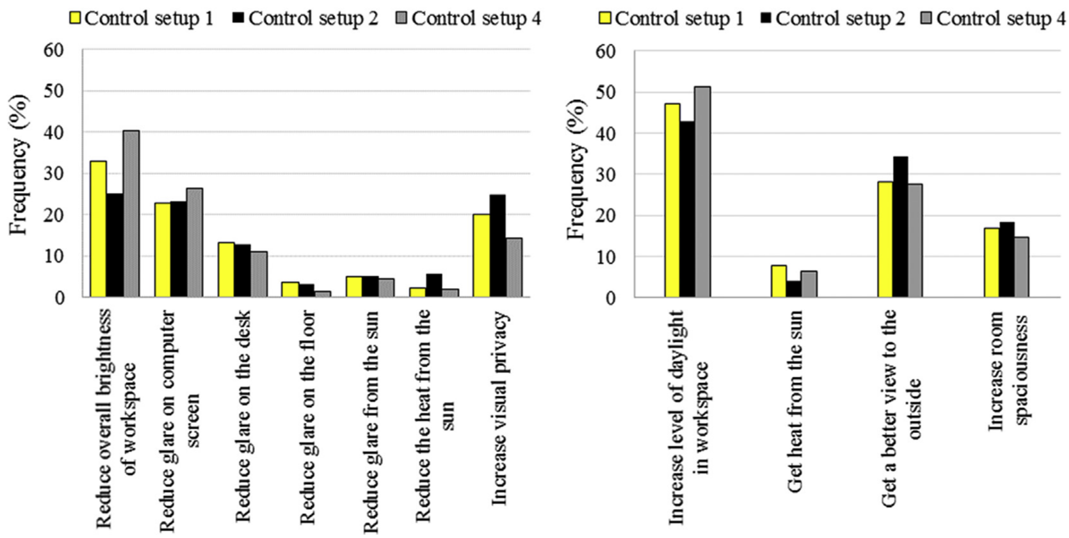

Fig. 10. Survey results: reasons for lowering/closing roller shades (left) and raising/opening roller shades (right) with control setups 1, 2 and 4.

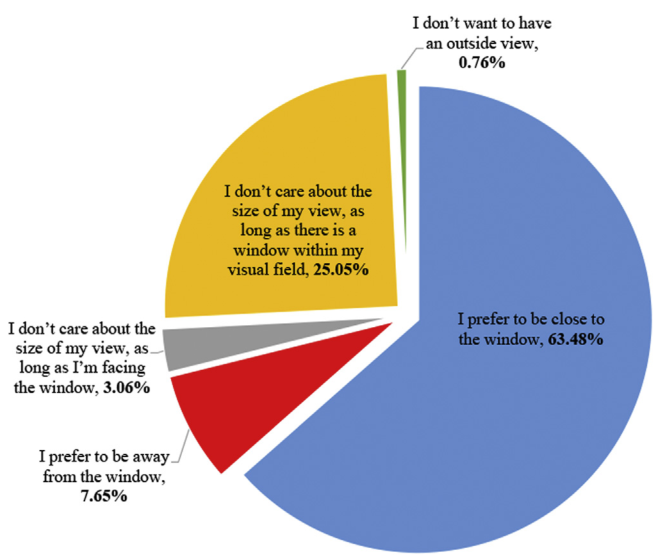

Fig. 11. Survey results related to outside view and connection to outdoors.

participants reported increasing and reducing the light level in workspace, as expected. Saving energy and making interior surfaces brighter were also noticed in both setups 1 and 2. Most of the reasons for interactions can also be represented by physical variables, except for "saving energy".

4.3. *What are the preferred visual conditions in offices with different shading and lighting control setups?*

Fig. 14 (top) shows the distribution of total work plane illuminance for all control setups during the monitoring campaign. Setup 3 represents fully automated control and visual conditions, which are not associated with occupant interactions. The rest of this section focuses on setups 1, 2, and 4 where indoor illuminances would result from occupant interactions with shading and electric lighting systems. It is clear from the results that work plane illuminances up to 1000 lux are preferred for all control setups. This is while outdoor conditions during the field study were bright enough to achieve higher values (Appendix A) but people preferred to control shades and lights to follow the frequency distribution of Fig. 14. Although there is a difference in the dynamics of

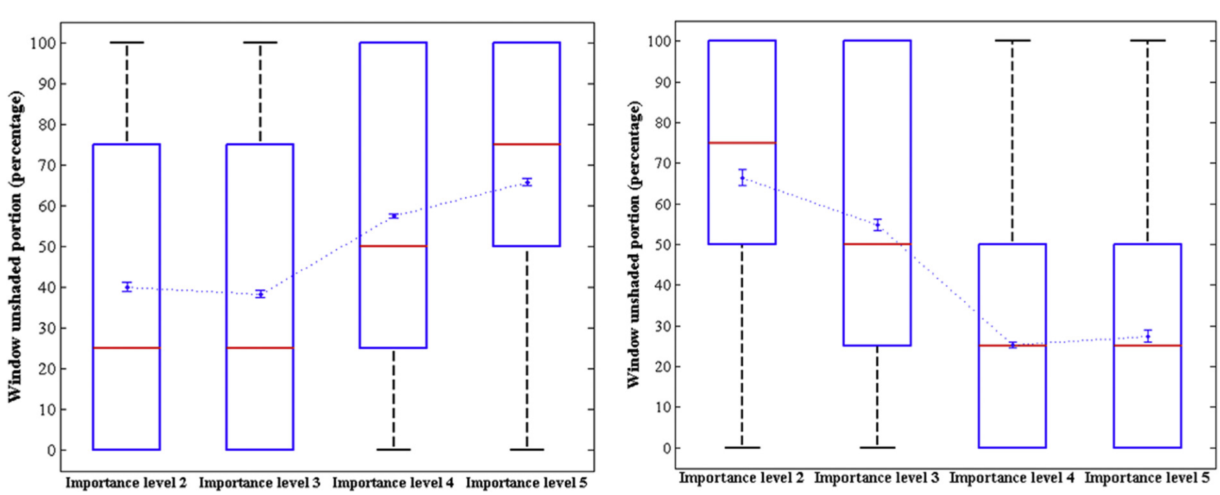

Fig. 12. Survey results for different shade positions (window unshaded portion) related to different importance levels of outside view (left) and visual privacy (right).

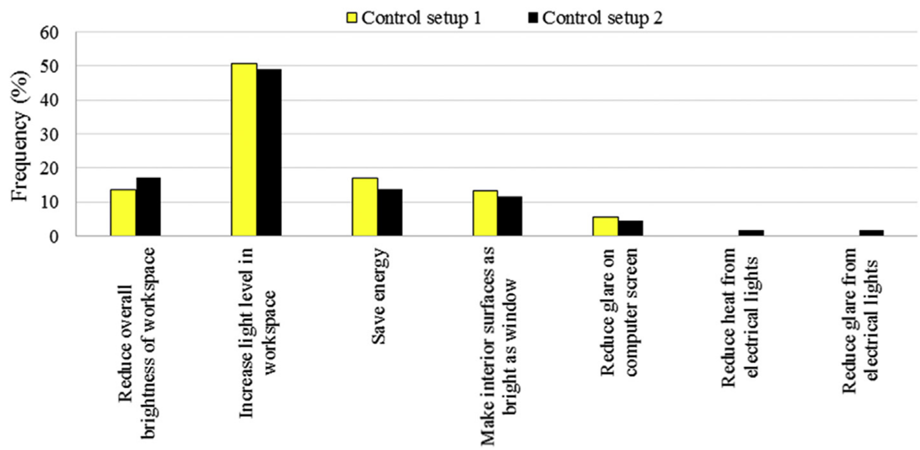

Fig. 13. Survey results: reasons for adjusting electric light levels with control setups 1 and 2.

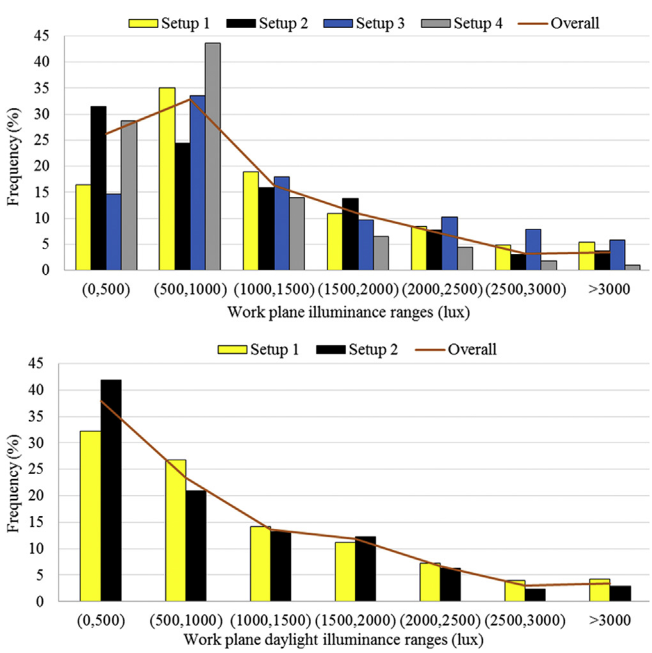

Fig. 14. Frequency distribution of total work plane illuminance (top) and work plane illuminance from daylight (bottom) for different control setups.

interactions between setups 1 and 2, as described earlier, the general illuminance preferences were within similar ranges between all setups. In other words, occupants seek similar preferences using different dynamics. The only difference between setups 1 and 2 is that occupants using the web interface (control 2) preferred total illuminances up to 500 lx over higher illuminances; the opposite was observed for occupants using wall switches (control 1), as well for the remote control overrides (control 4). Overall, work plane illuminances higher than 1000 lux are less frequent, while values higher than 2000 lux are rare.

Fig. 14 (bottom) shows the distribution of daylight illuminance for control setups 1 and 2, showing that occupants preferred daylight illuminances within the range of 100–2000 lux for almost two-thirds of the times (72% in setup 1 and 65% in setup 2). This confirms findings of previous studies [74], generally supporting simplified comfort criteria such as useful daylight illuminance bins. Daylight illuminance was investigated for different levels of electric lighting. With setup 1, on average, the daylight illuminance was 1675 lux for low levels of electric light (0% and 25%) while it was 700 lux for higher levels (50%, 75% and 100%). The respective average with setup 2 were 1852 lux and 564 lux. The easier access with the web interface of Setup 2 results in a wider range on average values, implying more use of daylight.

To further assess occupant preferences when controlling electric lights using different interfaces, electric light dimming levels were correlated with daylight illuminance levels for setups 1 and 2 (Fig. 15). Office occupants tend to choose natural light (low electric light levels) if a preferable range of daylight is available to them, as expected. However, the way that they interact with electric lights depends on the control interface with implications on lighting energy use. Fig. 15 shows that higher electric light levels (>75%) are used when daylight levels are less than 1000 lux with setup 1 (wall switches). For higher daylight values, low electric light levels are

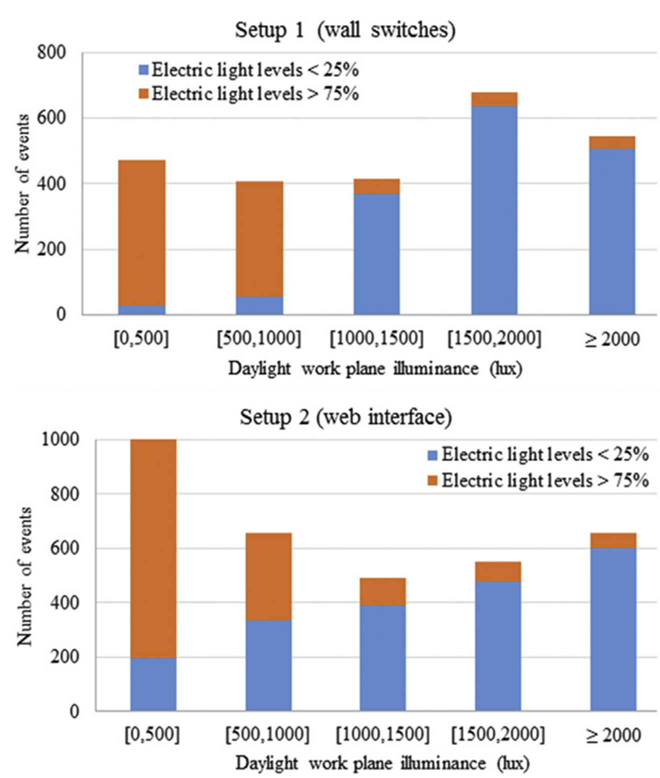

Fig. 15. High and low electric lighting levels correlated with daylight illuminance levels for setups 1 (top) and 2 (bottom).

preferred. This behavior occurs around 600 lux (daylight levels) when a web interface is used (setup 2). These results emphasize the significance of interaction dynamics using different control interfaces and show that there is a noticeable impact on light energy use.

To assess the potential impact of daylight discomfort glare, the DGP index was calculated by post-processing luminance distributions with the different control setups. Fig. 16 demonstrates distributions of DGP resulted from shading and lighting settings selected by occupants with all control setups. Noticeable glare is supposed to occur for DGP values higher than 0.35 [54]. The average value of DGP was 0.2 (M = 0.2, S.D = 0.07, n = 916) in setup 1, 0.16 (M = 0.16, S.D = 0.08, n = 1468) in setup 2 and 0.2 in setup 4 (M = 0.2, S.D = 0.04, n = 678). DGP values are mostly between 0.15 and 0.25 in all setups with occupant controls and rarely exceed 0.35. Note that the shades have a low openness factor and visible transmittance, and that the sun is not within the field of view of the occupants for a significant amount of time —nevertheless, sunlight enters the space when the shades are partially open during sunny days. Experiments with lower sun angles might show higher discomfort values, however occupants are expected to interact more with shades to reduce glare in that case; moreover, alternate glare criteria might be more suitable for cases with roller shades of low openness factors [53]. Vertical illuminance on the eye of the observer is also a critical metric associated with discomfort [51,53,75]. Through the simplified DGPs index, vertical illuminances over 2760 lux indicate noticeable glare. The findings of this field study show that occupants prefer much lower values (Fig. 17) for all the control setups.

4.4. *What are the effects of shading and lighting control setups on occupant visual comfort and satisfaction with the indoor environment?*

Data from web surveys during the field study are analyzed to provide an initial understanding of occupant satisfaction with the visual environment under different control setups. Fig. 18 presents boxplots of votes for comfort (a) with amount of light (b) with visual conditions (c) with outside view and (d) a subjective assessment of productivity, for all different control setups. Average lines along with an error bar for the mean value are also shown for each case. Overall, the lowest comfort votes occur when there is no occupant control (setup 3), indicating that there is a preference for customized indoor climate and a relationship between occupants' perception of environmental control and productivity (Fig. 18d). Comfort votes are significantly improved when occupants are allowed to override the automated system (setup 4), while controlling lights and shades manually through wall switches or a web interface (setups 1 and 2) show the best performance. However, the effect of ease of access (control interface) on comfort experience and productivity was not found to be significant, at least for the comfort votes presented here. The average line and non-

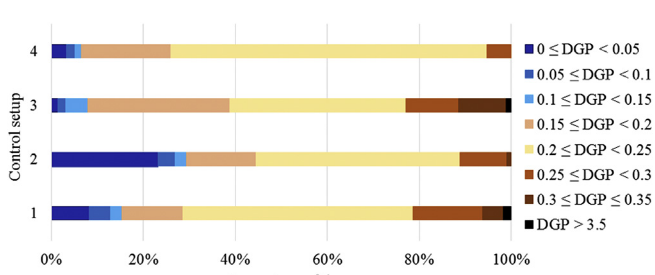

Fig. 16. Measured DGP index with different setups during the course of field study.

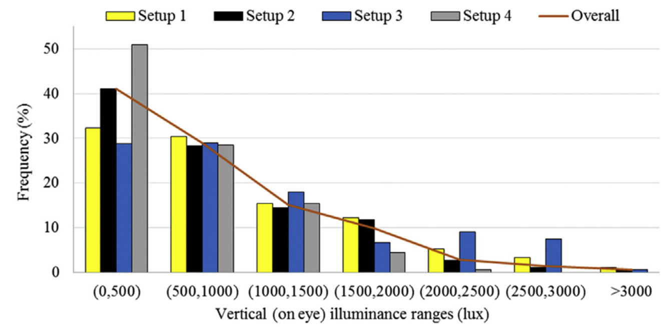

Fig. 17. Frequency distribution of vertical illuminance (at the eye level) for different control setups.

overlapping confidence intervals of mean in Fig. 18a rank control setup 2 as the highest comfortable in terms of light adequacy, followed by setups 1, 4, and 3. Except for a few votes considered as outliers, participants were mostly comfortable with the amount of light in control setups 1, 2, and 4. This is also true for comfort votes with visual conditions in control setups 1 and 2 (Fig. 18b). Comfort votes are high mainly because occupants had full control over their visual environment (motorized shades and controlled lights) and partially because they had about one third of the window within their visual field (when looking at the computer screen) with no significant glare issues reported. Very high illuminance values were rarely experienced in this field study —as should happen in well-designed, occupant-controlled indoor environments.

The distribution of comfort votes based on data gathered with the graphical web interface (setup 2) at the moments of shading or electric lighting interactions are shown in Fig. 19. The lower levels of comfort at moments of actions is obvious. "Comfortable" votes still exist because some of the actions were due to discomfort with only one of the visual conditions/amount of light or even none of them in cases when participants used the reasoning slider to report non-physical variables as the reason for their interaction.

Fig. 20 presents the distribution of "perceived" lighting conditions for each control setup, based on responses on a seven-scale question in survey type-A (Table 1, question 7). The perceived conditions with control setup 3 (fully automated shades) and setup 1 (manual wall switches) are almost the same. But lower comfort votes with the amount of light for control setup 3 (Fig. 18a) imply that lack of personalized controls can result in lower comfort levels even under the same range of perceived physical conditions. This is also clear from Fig. 21, which shows the level of comfort with amount of light in control setups 1 and 3, disaggregated by values of work plane illuminance greater and less than 2000 lux. It is clear that in setup 1, participants remained comfortable for the whole range of work plane illuminance. In setup 3, on the other hand, comfort level drops dramatically for work plane illuminance values greater than 2000 lux. These results, along with similar physical conditions observed for setups 1 and 3 in Fig. 14, tend to suggest that in setup 1, occupants reported to be comfortable almost for the whole range of experienced work plane illuminances only because they had full control over their luminous environment. These results present "occupants' access to environmental controls" as an important parameter to be accounted for when evaluating visual comfort.

5. Conclusions

The paper presented a field study to investigate occupant interactions with motorized shading and dimmable electric lighting systems in private offices of a high performance building. Four different control setups were explored ranging from fully manual to

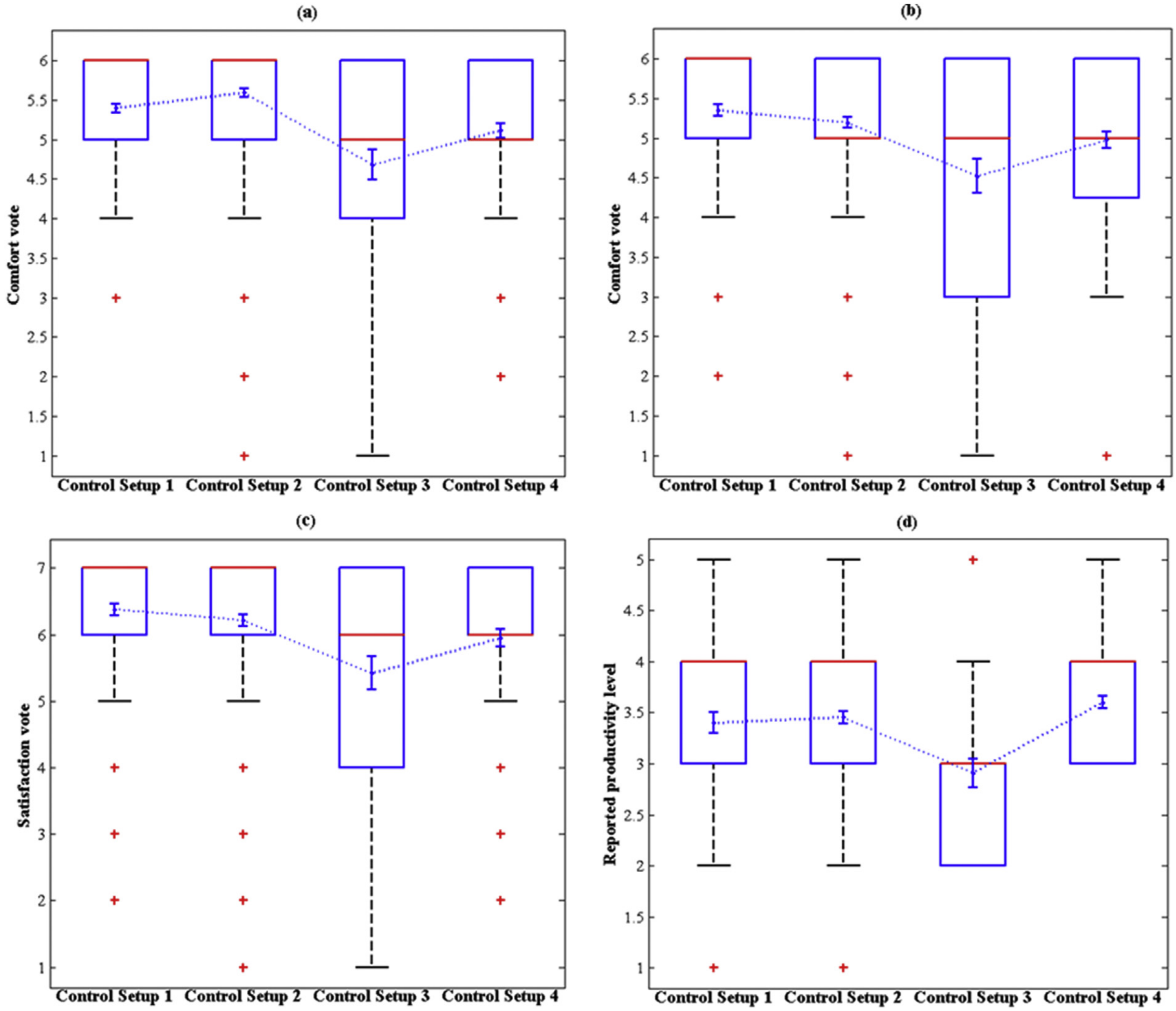

Fig. 18. Comfort vote distributions with (a) amount of light (b) visual conditions (c) satisfaction with outside view and (d) subjective productivity, for different control setups.

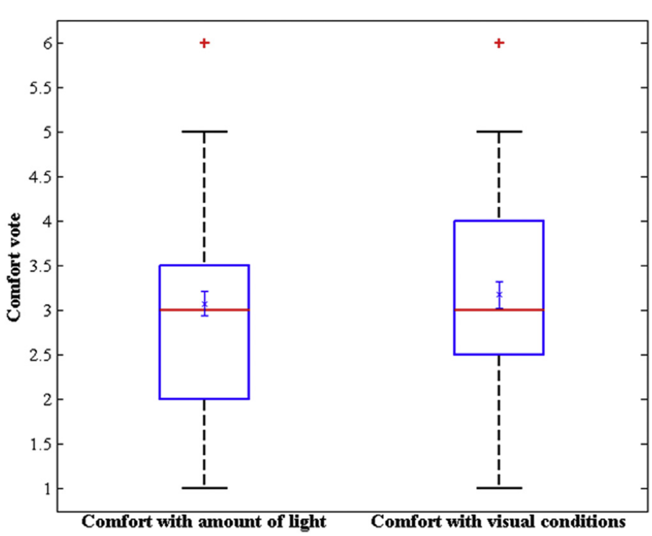

Fig. 19. Comfort votes at moments of actions with setup 2.

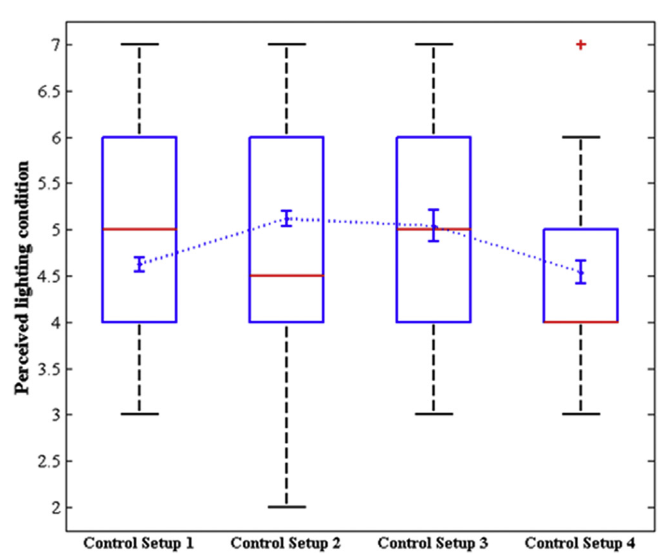

Fig. 20. Perception of lighting conditions with different control setups.

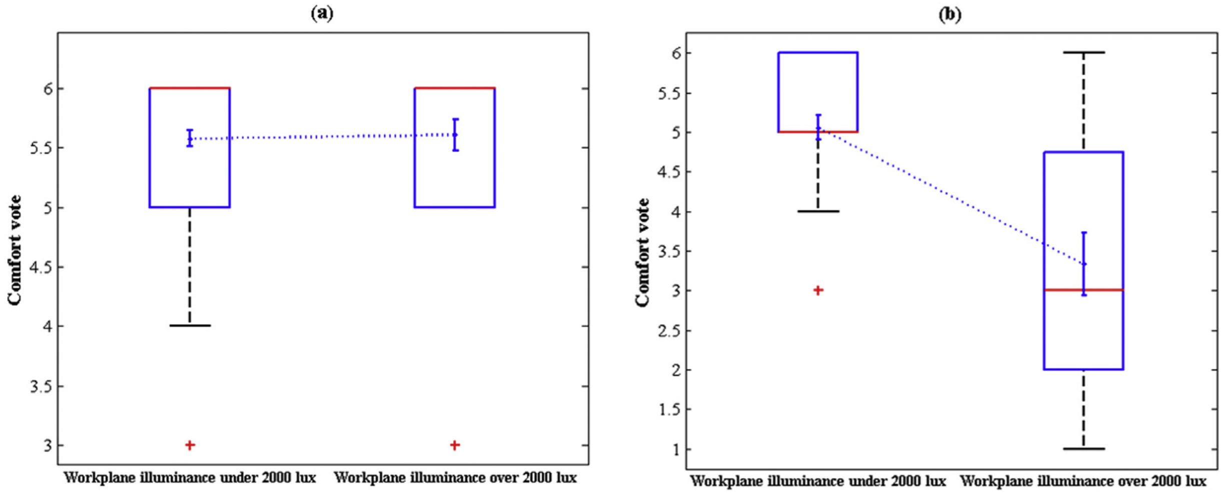

Fig. 21. Comfort with amount of light for setup 1 (a) and setup 3 (b).

fully automatic. Occupants could move shades to intermediate positions and select intermediate light dimming levels using manual (wall switches, remote controllers) or web interfaces. The modular web interface was specially designed to (i) enable interactions with shading and electric lighting (ii) capture comfort levels when the actions occur and (iii) consider non-physical variables. In addition to extending the current knowledge of human-building interactions to different and more advanced systems, this study provides new insights that support the development of new modeling representations and personalized controls.

The main findings of the study are summarized as follows:

- The dynamics of human interactions with motorized roller shades and dimmable electric lights are different from those found in studies without these advanced control options. The results indicate the need for developing predictive models of occupant interactions with these systems. The importance of non-physical variables (e.g., outside view, privacy, etc.) in shading and electric lighting interactions was demonstrated along with the need to incorporate such variables in modeling frameworks, in addition to the consideration of occupational dynamics.
- Window shades and electric lights were found to be operated interdependently, with increased electric light levels more frequently selected with lower shade positions (and vice versa), and resulting implications on daylight utilization of the space. This interdependency needs to be checked and accounted for when deriving predictive models to describe human interactions with shading and electric lighting systems, whether modeling their operation states directly or occupant actions on the systems.
- Different dynamics in occupant interactions with different control interfaces (wall switches and web-interfaces) pronounce the need to incorporate the "ease of access" to building systems when constructing models of human-building interactions. These dynamics result in similar lighting preferences in both setups but have different energy impacts. Higher daylight utilization in offices with easy-to-access controls was observed, which implies less frequent use of electric lights and less energy consumption accordingly. This finding shows advantages in providing office users with higher level of accessibility to environmental controls.
- Differences in occupant responses, in terms of comfort with the amount of light and visual conditions, between offices with different accessibility to shading/lighting control, reveal a strong preference for customized indoor climate along with a relationship between occupant perception of control and acceptability of a wider range of visual conditions. Under the same physical conditions, participants showed different levels of comfort with different control setups. Therefore, the access to control is an important parameter when evaluating occupant visual comfort and should be further investigated.

It should be noted that findings reported in this paper are based on a field study with solar paths between April 1st and June 15th 2015. Occupant interactions with shading and lighting systems may differ under low sun conditions or different occupant seating positions (i.e. facing the window) and related findings will be reported in forthcoming publications by the authors. In addition, future experiments will further investigate the impact of test duration in terms of the number of days that human test-subjects stay in an office environment, considering a large number of participants. In the future, the results of this study and the datasets can be used to develop human interaction models with motorized shading and dimmable lighting systems, considering all factors mentioned above. Similar field studies are needed in different locations around the world for a larger database and investigation of interactions with different building systems. The developed web interface is a first step towards standard methods for studying human interactions with building systems in a consistent and reliable way.

Acknowledgments

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Appendix A. Outdoor illuminance conditions during the course of field study

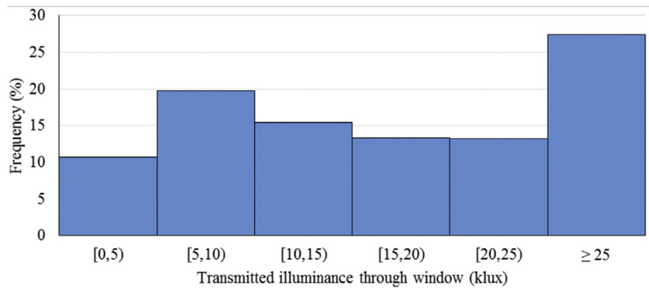

Fig. A1. Frequency distribution of measured transmitted illuminance through the window during the field study.

Appendix B. Camera response curve and camera illuminance reading validation

Cameras were calibrated using a Konica LS-100 luminance spot meter and a Macbeth Color Chart, extracting the response curve. As the cameras were located close to the subject's head, it was of the essence to create the least possible distraction, a goal that affected both the number of LDR photographs consisting each HDR image, decided to be 5, and the period between each shooting sequence, decided to be 15 min. For that reason, Magic Lantern firmware [68] was used in the cameras to automate the shooting sequence. The LDR photographs were merged into HDR images using the response curve of Fig. B1 along with the HDRgen UNIX command line tool and an automation script to handle the high number of measuring instances throughout the whole experiment. As wider apertures are responsible for more controlled light penetration in the sensor, leading to less apparent vignetting distortions [76], an aperture of F11 was used for all the photographs. Authors assumed that with a wide aperture of F11 and by applying the generic correction included in the firmware of the camera, vignetting errors would be negligible, an assumption which was confirmed by evaluating the extent of vignetting as suggested by Inanici and Galvin [76]. Validation of the calibration performed with the luminance spot meter could be case sensitive, depending on the target chosen. For that reason, a side-by-side comparison of vertical illuminance values was performed, using the values extracted by the HDR images through Evalglare and the values recorded by either the photometers or Konica T10 illuminance sensors, attached on the top of the lens and having the same measuring span as the camera. The results showed a good calibration fit, including some outliers that are always present in HDR approaches (Fig. B2).

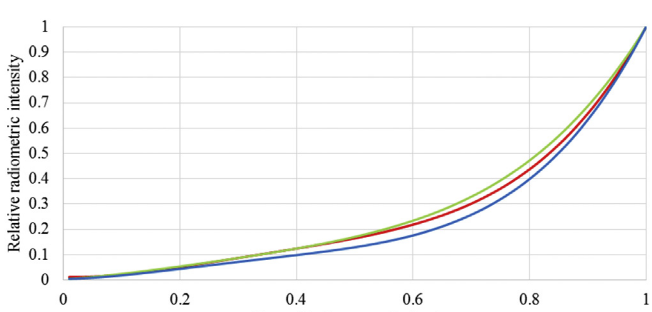

Fig. B1. Extracted response function for the combination of camera and lens.

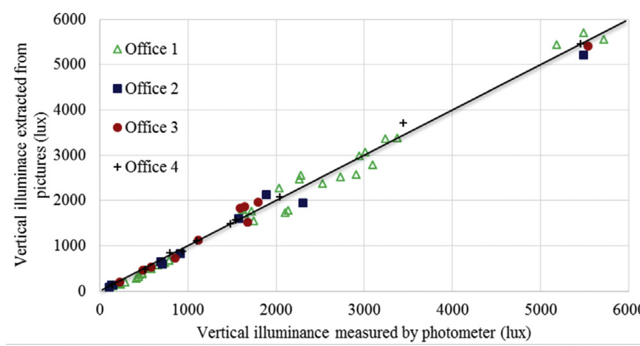

Fig. B2. Validation of illuminance readings from the camera.

Appendix C. Consistency in human-building interactions

Initial tests were conducted to ensure that occupant interactions with building systems would be consistent when human test-subjects stayed more than one day in the office. For this purpose, human test subjects attended the same office with the same control setup for three consecutive days and their interactions were monitored. Consistent behaviors were observed for all participants during this test. Representative results (Fig. C1 and C2) show the work plane illuminance along with the selected shade position by a human test-subject for three consecutive days in control setup 2.

For example, it is clear from Fig. C1 that this participant preferred a slightly dark lighting condition at his/her workspace and interacted with building systems accordingly on all three days. The average value of work plane illuminance remained in the same range between the days. The occupant's preference towards dark conditions was also reflected by the answer to a question in the online survey asked at the end of day three (In general, how would you prefer the lighting conditions at your workspace? 1. Very dark … 7. Very bright). Similarly, as shown in Fig. C2, the participant preferred moderately bright conditions on all three days.

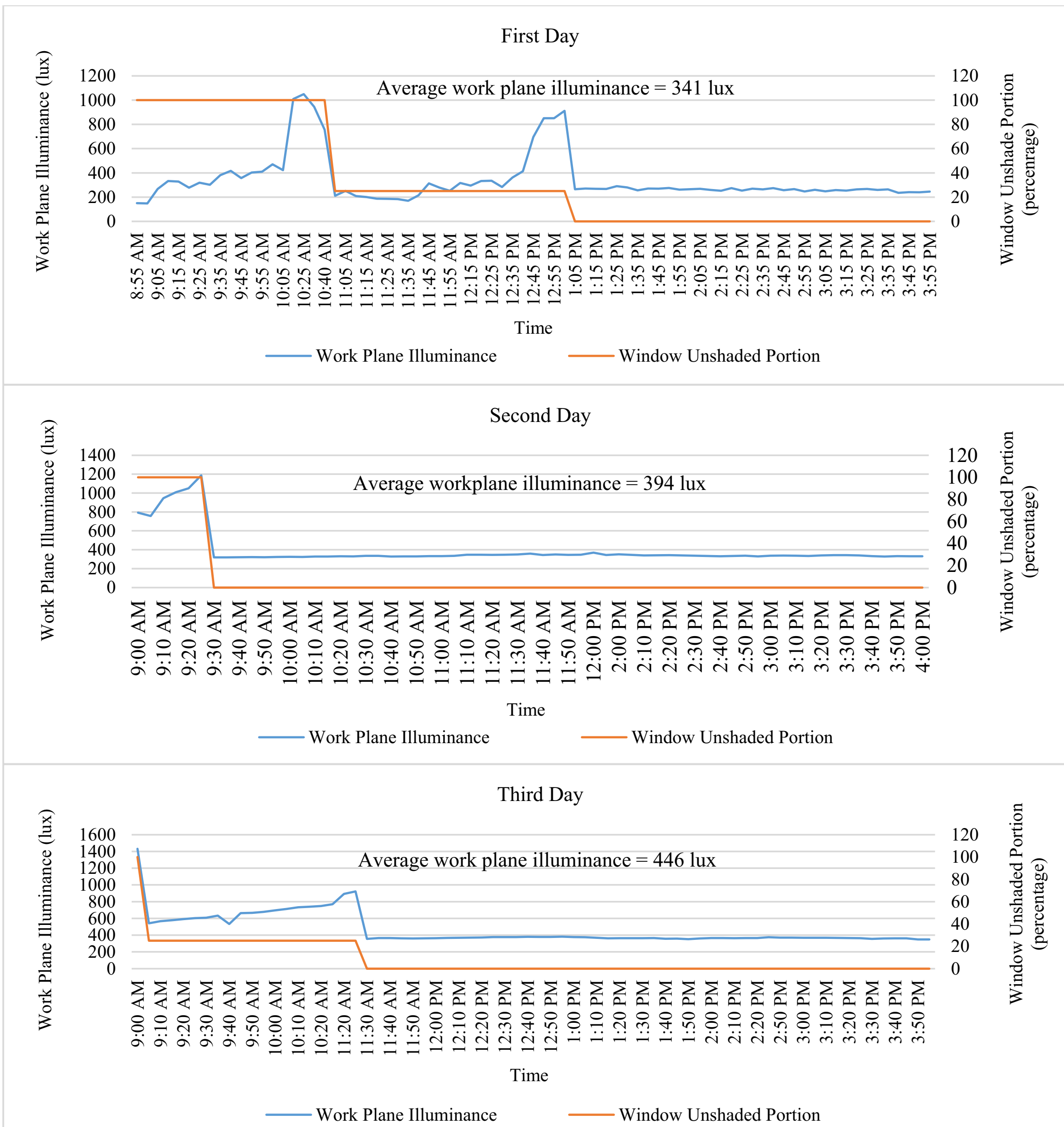

Fig. C1. Investigating the consistency in human-building interactions in control setup 2 (lighting preference: slightly dark).

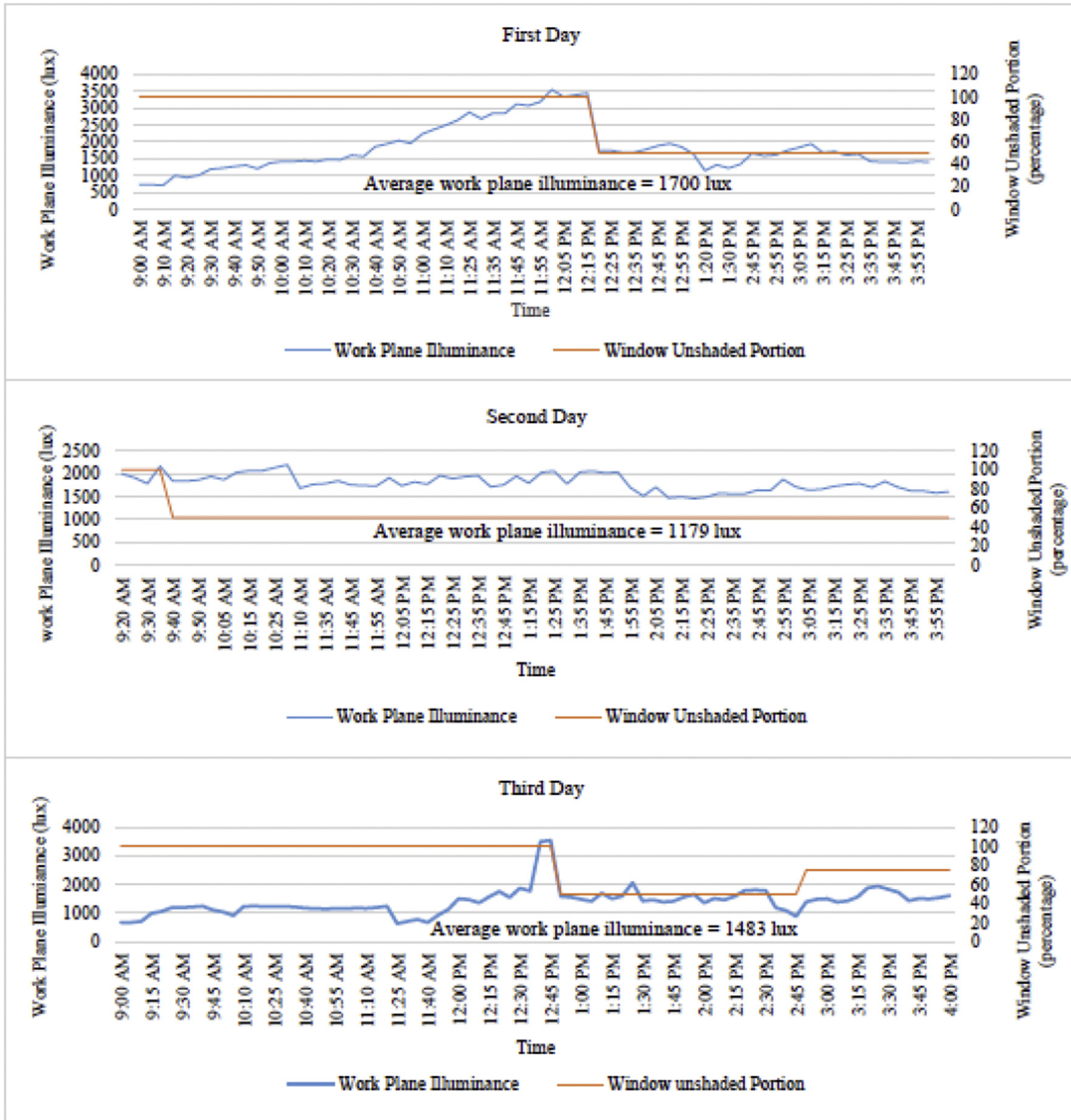

Fig. C2. Investigating the consistency in human-building interactions in control setup 2 (lighting preference: moderately bright).

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