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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