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Development and implementation of an adaptive lighting and blinds control algorithm

H. Burak Gunay [a], William O'Brien [b, *], Ian Beausoleil-Morrison [c], Sara Gilani [b]

[a] National Research Council Canada, Construction Portfolio, Canada
[b] Department of Civil and Environmental Engineering, Carleton University, Canada
[c] Department of Mechanical and Aerospace Engineering, Carleton University, Canada

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ABSTRACT

In this paper, the light-switch and blinds use behaviours in ten private offices were analyzed with concurrent solar irradiance, ceiling illuminance, and occupancy data. Upon this analysis, an adaptive lighting and blinds control algorithm was formulated. The algorithm learns occupants' illuminance preferences from their light switch-on and blinds closing behaviours, and employs this information to determine the photosensor setpoints to switch off lighting and to open blinds. The algorithm was implemented inside controllers serving five private offices and a controls laboratory – a shared office space with a standalone controls network. Alternative control scenarios were analyzed through integrated daylighting and occupant behaviour simulations. The results indicate that the use of an adaptive lighting and blinds control algorithm developed in this paper can substantially reduce the lighting loads in office buildings – without adversely affecting the occupant comfort.

1. Introduction

Visual comfort depends on a large number of environmental and contextual factors. These factors include, but are not limited to, the luminance of the light source, occupants' position and orientation relative to the source, background luminance, contrast in the field of view, colour of the light source, reflectance of the furniture, individual preferences, types of activities undertaken (drafting vs. typing), age and health, and access to controls [1–6]. Despite the subtleness of the factors affecting visual comfort, it is impossible (or at least impractical) to foresee these factors, when the daylight-integrated lighting and blinds automation systems are being implemented.

When daylight-integrated lighting and blinds automation systems are designed, the indoor illuminance measurements are taken by sparse photosensors. The sensor's position also plays a crucial role on its readings. Even in a shallow perimeter office space, illuminance on the workplane can vary by a factor of ten or more [7]. For practical reasons, illuminance sensors are often positioned on the ceiling [8] or on the window frame measuring vertical illuminance on a view portion of the window surface [9]. However, the research on occupants' visual comfort, and lighting and blinds use behaviour has been mostly focused on workplane conditions [10]. Given the diversity in environmental and contextual factors and the variability of sensors' position, illuminance measurements associated with occupants' visual comfort conditions vary substantially from one office to another. An observational study involving 45 office occupants revealed that preferred workplane light levels ranged from 91 to 770 lux [11]. Similarly in another study, researchers observed that preferred workplane light levels ranged from 230 to 1000 lux [12]. An investigation conducted on occupants' blind use behaviour in 14 offices revealed that the workplane illuminance levels that trigger a blind closing action at arrival varied between 3 and 9 klux [13].

In an effort to address this variability during the implementation of the daylight-integrated blinds and lighting automation systems, it is commonplace to assume conservative photosensor setpoints – e.g., setting the automated blinds to close when the illuminance on the view portion of the window exceeds 2 klux [9] or 1.8 klux on the workplane [14]; setting lights to turn off above 500 lux on the workplane [15]. Regardless of these conservative setpoints, some occupants dislike their blinds opening automatically when it still feels bright. Some others dislike blinds closing before it feels glary because they may want to preserve their view

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* Corresponding author. Carleton University, Department of Civil and Environmental Engineering, 1125 Colonel by Drive, Ottawa, Ontario K1S 5B6, Canada.
E-mail address: Liam_OBrien@carleton.ca (W. O'Brien).

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and connection to outdoors [16]. Some dislike lights turning off automatically, when they think that it is still dark.

A simple solution to this problem stands out as the control of the lighting and blinds by the occupants. Previous research points out that there is a strong relationship between occupants' perception of control over their environment and productivity [17–19]. Automation systems that exclude occupants from the control-loop can infuriate the occupants [20]. Galasiu and Veitch [12] interpret this as the occupants' preference to have the capability to choose their environment rather than being obligated to accept the environment chosen for them. Two other studies [21,22] confirmed that the occupants' satisfaction with lighting systems improves with an increased ability to control the indoor illuminance levels. In line with this, in a different context (for thermostat use) Paciuk [23] reports that perception of control can increase comfort regardless of the physiological conditions.

Despite these benefits, manual control of lighting and blinds may cause inefficiencies in the use of daylight to replace electric lighting in the perimeter spaces [24]. Occupants promptly undertake light switch-on when it feels too dark or close their blinds when it feels too bright. However, beyond visual discomfort, light-switch off and blinds opening behaviours are affected by many contextual factors. Occupants' light-switch off behaviour in offices can be explained with environmental awareness or beliefs about the superiority of daylight against electric lighting [25,26]. Although occupants' blinds opening behaviour has been explained by the outdoor and indoor illuminance levels [13,27], one of the primary reasons for occupants to open their blinds is to increase their view and connection to outdoors [6]. In the presence of these non-physical motivating factors, if lights are switched on, occupants almost never switch them off during intermediate occupancy [28,29]. In fact, in a case study, Pigg et al. [30] observed that the probability that an occupant leaves the lights on upon taking an intermediate break shorter than 1 h is more than 0.75. This was about 0.50 for breaks between two to 4 h. Similar to the infrequent use of lighting, if blinds are closed, occupants rarely open them until the next time they arrive [13,31]. They almost never change their blind positions more than once a day [31,32]. However, the accessibility and control type (e.g., motorized or manual) of the blinds are also known to affect the frequency of blind use [5,13,27,33,34]. For example, Sutter et al. [33] reported that motorized blinds are used three times more frequently than manual blinds. According to Bordass et al. [35], occupants – especially in shared offices – position their blinds to mitigate worst-case visual conditions. In brief, occupants' goal is to avoid visual discomfort at minimum number of interactions with lighting and blinds – with little consideration to exploit daylight dynamically to offset electric lighting.

In building automation systems (BAS), the office occupants' interactions with their light-switches and motorized blinds are registered in real-time. In addition, commercial building BASs are either already equipped with or they can be easily upgraded to have sensors monitoring the occupancy and illuminance in individual offices. Concurrent analyses of the occupants' control actions with the sensory measurements provide invaluable information about their comfort preferences. Simply put, if we model an occupant's lighting and blinds use behaviour, we can predict the illuminance levels disliked by that occupant. And, if we undertake the occupant model development process recursively inside a building controller, we can deduce their preferences in real-time to adapt operating setpoints.

Occupants are not passive recipients of the indoor climates selected for them. They undertake adaptive behaviours to restore their comfort, when they feel uncomfortable [36]. These actions often involve adjusting their indoor environment through interactions with blinds, lighting, windows, and thermostats. The way these building components are used accounts for great uncertainty over a building's energy use and occupants' comfort [10,37]. Comfort affects the way occupants behave, and occupants' behaviours affect the energy use of the building.

Occupant models treat humans as a blackbox to seek statistically meaningful input-output relationships – instead of explicitly characterizing the human physiology [38]. By looking atleast one explanatory variable, they predict either the occupants' actions or the state of the building components with which occupants interact. For example, Reinhart [28]'s light-switch model predicts the likelihood of a light switch-on action as a function of the workplane illuminance. Similarly, Haldi and Robinson [13]'s blind use model predicts the likelihood of a blind closing action as a function of the workplane illuminance. In the last two decades, the researchers have instilled the basics of modelling occupant behaviour in office buildings [10,37,38]. However, the primary purpose of occupant modelling has been to better understand the occupants' influence on buildings' energy use. Only a few studies have attempted to exploit the potential of adaptive occupant behaviour models to retrieve unsolicited information about occupants' adaptive comfort [24,39–41]. Results of these studies indicate that the user specific comfort information derived upon occupants' behaviours render the potential to enhance buildings' operation significantly. In addition, because the occupant behaviour researchers have been focussing on developing adaptive behaviour models offline using batch data with access to established statistical tools and computational power, recursive formulation of a parsimonious algorithm to develop occupant models inside building controllers remained an open research question [10].

Another important gap in the reviewed literature is that the key findings of the occupant behaviour research on blinds and lighting use were not fully integrated during the design of the automation systems. Given that occupants are active in closing their blinds and turning on their lights upon feeling discomfort, there is no need to close their blinds or to turn on their lights automatically. Simply put, when needed, occupants can close their blinds or turn on their lights. Therefore, the blind closing and light switch-on actions should be exclusively left for the occupants. On the contrary, the researchers have been focussing on predicting the glare conditions to automatically close the blinds during occupancy [16,22,42,43]. In fact, occupants prefer to maintain their view and connection to outdoors [44]. In a case study, Reinhart and Voss [16] observed that occupants rejected 88% of the blinds closing decisions by the automation. Similarly, the default setting for some of the most common lighting controllers is to turn on the lights automatically with occupancy detection [45] – regardless of the daylight availability. In fact, two studies [24,46] demonstrated that automation systems that switch on lighting automatically with occupancy and daylight can use more electricity than simple manually controlled lighting systems in perimeter office spaces. Furthermore, in some cases, occupants can cover their occupancy sensors with the expectation of stopping their lights from turning on automatically [47]. Given the aforementioned tardiness of the occupants' light switch-off and blind opening behaviours, the automation systems should reopen blinds and turn off lighting after ensuring that doing so would not cause discomfort.

To address these gaps in the literature, this paper first presents the analyses of the light-switch and blind use data from ten West-facing private offices in Ottawa, Canada. Upon the analyses, an adaptive lighting and blind control algorithm was formulated. The algorithm was first tested inside a controls laboratory – a shared office space with a standalone control network. The algorithm was then implemented inside controllers serving five private offices.

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