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Immersive virtual environments, understanding the impact of design features and occupant choice upon lighting for building performance

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ABSTRACT

Studies have shown that occupant behavior has a significant impact on a building's overall performance and energy consumption. The objective of this study is to understand occupants' lighting-use behavior by investigating the influence of manual and semi-automatic control systems on lighting-use in a single-occupancy office space. 114 participants were randomly assigned to one of the four conditions that varied in available lighting control options in an immersive virtual environment. They were asked to adjust the room's lighting by choosing one of the following lighting control options: (1) manual control system for artificial lights and interior shades; (2) same options as condition 1 and a semi-automatic control system for the shades; (3) same options as condition 1 and a semi-automatic control system for the artificial lights; and (4) same options as condition 1 and semi-automatic control systems for both the artificial lights and shades. The results of the experiment demonstrate that the participants were significantly more likely to use natural light if there was only a semi-automatic control system to control the shades. However, they were not more likely to use natural light if they were given semi-automatic control options for both the artificial lights and shades.

1. Introduction

Building energy use accounts for roughly 41 percent of the energy consumption in the United States [1], 37 percent in the European Union, and 39 percent in the United Kingdom [2]. Prior research has studied occupants' behavior in an attempt to quantify and reduce their energy consumption. To do so, a number of studies have used behavioral models to simulate occupant behavior [3–6] in order to estimate the energy use consequences of occupants' activities, preferences, and needs. Due to the complexities of human behavior, these simulations do not usually provide realistic representations of occupant behavior and may result in underestimated or overestimated energy use predictions [7]. Thus, an accurate understanding of occupant behavior in buildings is needed to improve occupant-building interactions and encourage occupants to reduce their energy consumption [7–9].

To isolate occupant interactions with one of the many different building systems (e.g., heating and cooling systems, lighting systems, etc.) and to better understand occupants' decision making processes with regards to lighting use, this paper focuses on examining different control options that adjust the available lighting levels in a single occupancy office environment. In the United States, lighting systems are the second highest energy consumption source in commercial buildings (following HVAC systems), accounting for approximately 71 percent of the total electricity consumption [10]. Although, buildings and building systems are designed based on code-defined occupant comfort ranges to ensure satisfactory lighting conditions [11], they do not have any input about actual occupant behavior or comfort preferences [11–13]. Many times these standard ranges do not match occupant preferences [14] and lead to lack of comfort and satisfaction in buildings [15]. This mismatch between the set points and preferences may lead to a waste of energy since the standard set points might result in higher electricity use than what occupants' preferences might require. Additionally, a previous survey study suggests that up to 40 percent of lighting electricity could be saved by adopting a combination of modern control strategies such as, daylight harvesting, occupancy sensing, and scheduling and load shedding [16]. Therefore, the ability to improve occupant decision-making through the use of different lighting control options could

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potentially result in reducing the total energy consumption in buildings [17–19].

To effectively understand how personal control options affect occupants' lighting use, it is important to study such scenarios in actual (physical) office environments [9]. Although performing such experiments is possible in existing buildings, there are several factors that could affect the results (e.g., cloudy/sunny weather in different days, different window types, different interior space designs, and etc.). These factors, which in some cases are not possible to control, might cause experimental noise or impact the results. Therefore, in this paper, the authors have utilized immersive virtual environments (IVEs) as the experimental settings. IVEs allow the experimenter to control for most (if not all) potentially confounding variables and isolate the variables of interest (e.g., lighting conditions). IVEs allow for participants to be immersed in an experimental setting with constant lighting levels, interior set-up, noise and so on, which provides the researchers the opportunity to keep all variables constant while manipulating only the variable(s) of interest. Previous research has suggested not only that participants perform similarly within IVEs as they do in physical environments, but they also feel similar feelings of presence within such environments [20–23]. Another important advantage of IVEs is that the experimenter is less salient to the participant (as participants cannot see the experimenter), facilitating behavior that is more natural. In addition, when participants feel like the experimenter is watching and/or judging them in physical environments, they often try to act in a way that is "virtuous", in the way they expect the experimenter wants them to act, or in some cases in a more reserved way [24,25]. This problem is reduced in IVEs as the participants cannot see the experimenter.

Given the potential to reduce energy consumption through influencing occupant behavior, the authors aim to answer the following research question, "How can we influence end-users energy use behavior by changing the design features in a building?" This paper specifically explores the influence of different lighting control options on occupant behavior, ultimately aiming at electricity use reduction through empirically impacting design decisions and options left for the occupant. The authors study the effectiveness of this intervention in a single-occupancy virtual office environment. The study aims to contribute to the existing literature by (1) exploring how different combinations of lighting/shading control options can influence human behavior with a potential to reduce energy consumption and (2) demonstrating the benefits of using IVEs to study human behavior and decision-making.

The paper presents the research through a literature review and gap analysis of various lighting and shading control option studies, along with an overview of IVEs in studying human behavior. The paper then presents the research methodology, the IVE system for data acquisition, and detailed results, discussions and planned future works.

2. Lighting and shading control systems and user preferences

Prior research has examined occupants' lighting control preferences when provided with different options for natural light versus artificial light [18,26–29]. These studies have examined the effects of architectural features, such as windows sizing [30,31] and shading positioning and orientation [32,33] on occupants' behavior and use of natural light. For instance, previous research has identified that employees strongly preferred natural lighting and an outdoor view in an office environment if they were provided with the choice of having control over shadings or the available lighting in an office environment [18]. By surveying building occupants [26], concluded more than half of the participants believed that their best work was performed in a space lit by daylight.

Literature suggests that increasing the use of natural light reduces energy consumption in commercial buildings [34]. In some cases, this reduction can be as high as 50% of the total lighting electricity consumption [35]. Research has also shown that by providing occupants with more control options for the lighting levels in their environment, their energy consumption can possibly be reduced [36]. For instance [37], showed a reduction in energy consumption behavior when participants were given the option to manually control a dimmer without having any incentive to save energy. Although control over the available lighting can result in a reduction of the total energy consumption, studies have shown when participants are provided with options that are difficult to control (or are complex), they might not use the control option. In some cases, these control options might result in higher energy consumption due to lack of interest from the users [38]. These studies reveal the importance of including easy-to-use control options in the design of buildings.

Many studies have explored the effect of lighting control systems on occupants' behavior [14,36,39,40]. For instance a study has shown that most of the switching on events occur upon the occupants' arrival to an office [41]. Once the amount of lighting is set (natural, artificial or a combination of both), lighting levels remains unadjusted irrespective of daylight conditions [14]. In these studies, researchers have determined that the patterns varied based on two factors: (1) occupants (e.g., personality, mood, etc.) and (2) the amount of available natural light when the lighting adjustment happened [39]. In addition, occupant behavior has been investigated for manual switching and manual dimming controls. Occupants were found to use the dimmer more when it was located on their desk to adjust the available artificial light compared to a manual option [37].

It has also been demonstrated that occupant satisfaction increases when occupants are provided with controls to adjust the available lighting levels [42]. For instance [32], provided occupants with fully automatic, semi-automated, and manual options to control the available lighting levels in an office environment. The authors studied the effects of sensor-controlled settings, in which the sensors automatically determined the amount of natural lighting and artificial lighting needed based on the time of the day and available natural light through the windows. In the semi-automated option, the system would automatically regulate the ambient light and a participant was able to manually choose the illuminance level to manually adjust the sensor-controlled lighting by dimming down or increasing the artificial lighting in the room. The authors concluded that the occupants did not find the automatic option annoying, however the participants felt more satisfied with the manual and semi-manual options. Also the authors determined when the control options were too difficult to use, occupants preferred to manually set the lighting levels without having to make any adjustments throughout the day. Studies have shown occupants often override the automated lighting and shading controls systems, in some cases, the overriding could be as high as 88 percent of the time [41]. Research has divided occupants desire to override the automated controls into two categories [43]: (1) desire for control, where participants prefer to have the capability to control their environment rather than accept an environment to be chosen for them [18] and (2) desire for a customized indoor environment, where automated systems are usually based on defined conservative set points but in many cases the occupants have shown the tendency to control outdoor accessibility (view, available lighting, etc.) according to their feelings and preferences.

Similar to the lighting controls, studies have also investigated occupant behavior through the use of shading control systems