Use of Immersive Virtual Environments to Understand Human-Building Interactions and Improve Building Design

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Abstract. Previous research has shown occupants' behavior and interactions with building systems and components have a significant impact on the total energy consumption of buildings. Incorporating occupant requirements to the design process could result in better operations, and therefore, improve the total energy consumption of buildings. Currently, buildings are primarily designed based on several common assumptions about occupant requirements, which in many cases are incorrect and result in inefficiencies during the buildings' operation phase. With the recent improvements in the fields of virtual and augmented reality, designers now have the opportunity to accurately collect and analyze occupants' behavioral information. In this research, through the use of immersive virtual environments, the influence of different design features on end-user behavior (preferences and patterns) and performances are examined. A case study is presented, in which the authors measure the end-users' lighting preferences to better understand the impact of preferences on end-users' performances and lighting-related energy consumption.

Keywords: Immersive virtual environments · Human building interaction · Design features · Design process

1 Introduction

Building energy use accounts for roughly 41 % of the energy consumption in the United States, 37 % in the European Union, and 39 % in the United Kingdom [1, 2]. Studies have shown that occupant behavior has a significant impact on a building's overall performance and energy consumption. To better understand how human behavior and interaction affects the total energy consumption in buildings, previous research has examined occupants' interactions with building systems and components for a variety of different purposes (e.g., lighting and blinds control, temperature adjustments, noise levels and etc.). Yet, such studies have been done in actual office spaces, where many different factors and "experimental noise" could affect the studies'

C. Stephanidis (Ed.): HCII 2015 Posters, Part I, CCIS 528, pp. 180–184, 2015.
DOI: 10.1007/978-3-319-21380-4_32

results (e.g. difference in interior designs, outside noise levels, weather conditions). In the past two decades, the advent of virtual reality and augmented reality has provided better opportunities for researchers and practitioners to collect occupants' behavioral information. Immersive Virtual Environments (IVEs) provide a sense of presence similar to that found in physical environments, such that the user can get the feeling of the environment as if they were physically immersed in it. Such environments allow the researchers to manipulate their variables of interest while keeping design features (e.g., lighting system, interior design, etc.) constant, resulting in reduced experimental noise. 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 this research, the authors present a novel approach, where they use IVEs to collect information about end-users behavior and performance within a virtual office space to better understand how building design could be improved in order to meet occupant preferences while decreasing the buildings' energy consumption. In this paper, the authors present an experimental study that investigates the impact of preference on end-users' performance and lighting-related energy consumption in an office space through the use of IVEs.

2 Understanding End-user Behavior Through IVEs

In the past two decades, the architecture, engineering, and construction (AEC) industry has adopted new technological advancements from different fields in order to improve (cost and time) the design, construction, and operation phases of buildings. One of the adopted technologies is building information modeling (BIM) where 3D models of a building along with its geometric and semantic information can be developed and communicated among different parties. BIM has significantly improved the design process by becoming an important tool to communicate between different parties involved in a project and allowing the end-users to get a better understanding of final designs of buildings. Although BIM provides 3D models and the necessary geometric and semantic information, research has shown these models lack the spatial feeling and presence that end-users need to better understand the designed environment and provide the necessary feedback.

Various studies have shown that IVEs not only have the same advantages and capabilities as BIM models, but they also increase interactivity and immersivity for the users, providing them with a more accurate feeling of the physical environment and a sense of presence (which BIM models currently lack). To evaluate whether IVEs are adequate tools to study different design features, the authors designed an experimental study, in which they compared participants' performance, perception, and sense of presence between a physical office space and a designed office space in an IVE. By analyzing data collected from 112 participants, the authors concluded that participants perform similarly in an IVE setting as they do in the benchmarked physical environment. They also concluded that participants felt a strong sense of presence within the IVE. A detailed discussion of this study can be found in [3].

Additionally, after discovering the benefits of IVE, in their previous research, the authors used IVEs in order to explore how different design features can affect behavior. For example, the authors investigated the influence of manual and semi-automatic lighting control options in an office environment by analyzing participants' interactions in a virtual office environment. Through this study, the authors concluded that end-users are significantly more likely to use natural light if there is only a semi-automatic control system located next to their desk to open the blinds instead of having no semi-automatic control system to open the blinds or a semi-automatic control system to both open the blinds and turn the artificial lights on. A detailed discussion of this study can be found in [4].

Building off of their previous research, the authors use IVE in order to understand more about how different design features affect energy consumption and performance. More specifically, the authors aimed to better understand (1) which lighting profiles are the most preferred ones by users, (2) in which lighting profiles do users perform the best on office-related activities, and (3) how much electricity is used by implementing each lighting profile. With this data, the authors can discover which lighting profiles maximize comfort and performance and minimize building energy consumption with the end goal to incorporate this information to the design process for achieving efficient and sustainable design.

3 End-user Lighting Preferences – Experimental Study

Previous research has identified lighting as one of the major factors to affect occupants' behavior and performance in indoor environments [5]. To better evaluate the impact of different lighting settings (luminance and illuminance) and develop end-users lighting profiles, the authors collected and analyzed end-users' lighting preferences within an IVE. The parameters measured in this experiment were based on the choices the participants made to adjust the lighting levels and their corresponding performances in those lighting setting.

Prior to running the experiments, each model with different light settings (e.g. 2 blinds open and 3 light bulbs on, all blinds open with no light bulb) was simulated using simulation software (grasshopper + honeybee + ladybug), where a light map along with different lux values across the room were calculated. Once the participants selected their most preferred light setting, the corresponding simulated model (light map + lux values) was identified to better understand the participants' preferred settings' lighting-related electricity consumption.

3.1 Data Acquisition and Experimental Procedure

An office space was designed based on similar dimensions and lighting features of a physical office environment. The models with different lighting setting were designed and rendered in Revit© 2015, 3ds Max©, and Unity 3D. In order to provide a better feeling of immersion to the participants, an Oculus Rift DK2 along with a positional tracker and an Xbox controller were connected to Unity 3D.

The participants were initially placed in a dark room with all the lights turned off and all the blinds closed. They were asked to adjust the lighting levels of the room to their most preferred lighting setting in order to perform a set of office-related activities (e.g., reading, writing, watching a video). Once the participants felt comfortable with their chosen lighting level, they were asked to read a short passage and answer a few comprehension questions based on what they read. Upon completion of the provided task, they were asked to answer a set of survey questions related to how they determined their most preferred lighting setting and if there were specific features that impacted their decisions. They were also asked to fill out a survey to assess how environmentally friendly there were.

3.2 Results

40 participants were recruited for this study, in which 40 % were females and 60 % were males (average age = 26 years old). 96 % of the participants preferred to have at least one of the three blinds open and 72 % of those preferred to have all three blinds open. A sample of participants' lighting preferences profile is provided in Fig. 1 in which the participant's reading speed and comprehension (number of correctly answered questions based on the given passage) measures are shown. As shown in Fig. 1, the participant's preferred lighting setting is matched to the previously generated heat map of the lux values in the room.

4 Discussion and Future Work

The presented research in this paper anticipates and utilizes IVE as a tool to collect and incorporate human behaviors and needs during the design phase. IVEs have been adopted for practical reasons to enable more expansive and cost effective data capture and experimentation but equally as a means to develop realistic environmental settings representing a physical environment to allow for more accurate design feedback from the end-users. As part of the authors' ongoing and future work, they collect more lighting preferences data and create end-users profiles to better understand the preference types on a larger sample of the population. The authors are also in the process of collecting personality types along with lighting preferences, hypothesizing that there is a relationship between end-user personality types and their lighting preference profiles. The authors will use the collected lighting profiles as a rule set into a multi-agent system

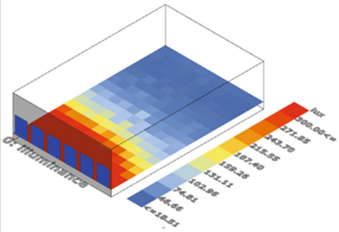
Participant	A
Comprehension (%)	75
Reading Speed (word/s)	2.5
Preferred Light Setting	All Blinds Open 0 Light Bulb on Each Fixture
Avg. Lux Value (natural + Artificial)	160
	

Fig. 1. Participant "A" lighting preference profile. The heat map represents the preferred lighting-setting's lux values distribute around the room and the rendered image is what the participant would see in IVE.

that will design building components with the objective to account for the end-user behavior and performance data. The authors will also explore the impact of other design features such as, wall openings and window types and sizes, on end-users' behavior.

Acknowledgments. This project is part of the National Science Foundation funding under the contract 1231001. Any discussion, procedure, results, and conclusions discussed in this paper are the authors' views and do not reflect the views of National Science Foundation. Special thanks to all the participants and people that contributed to this project, specifically Saba Khashe and Joao Carneiro for their contribution on helping with preparing and running the experiments.

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