Towards Measuring the Impact of Personal Control on Energy Use through the Use of Immersive Virtual Environments

Arsalan Heydarian[a], Joao Carneiro[b], David Gerber[c] and Burcin Becerik-Gerber[d]

[a,b,c,d] Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, USA
E-mail: heydaria@usc.edu, jcarneiro@usc.edu, dgerber@usc.edu, becerik@usc.edu

Abstract -

Recent studies have focused on increasing energy efficiency in commercial buildings through technological means (e.g., efficient HVAC systems, sensors and sensing systems). However, most studies underestimate the impact of occupants' behavioural choices. Lighting systems account for approximately a fifth of the total electricity consumption in the US; commercial buildings account for 71 percent of such consumption. This paper focuses on human behaviour related energy consumption by investigating the impact of personal control on lighting use in office environments. To effectively examine human energy consumption behaviour, alternative 3D design models of an office are created using an immersive virtual environment to visualize different lighting control features. Participants are brought into these immersive virtual environments by wearing Head-Mounted Displays and are asked to interact within these environments and perform a defined task. Participants were then allowed to control and change the room's lighting settings based on their preferences in order to perform their assigned task. Unique to our experimental design is the use of immersive virtual environments, enabling measurement and control of a series of design feature isolations and combinations. The work presents the impact of decisions made both during design and operation of buildings on occupants' energy related behaviour. The experiment demonstrated that when participants are provided with personal controls for the blinds and the artificial light, there is no significant difference in their preferences between natural and artificial lighting; however participants are significantly more likely to open the blinds remotely if they are only provided with a personal control for the blinds.

Keywords –

Immersive virtual Environments; Energy-use behaviour; Parametric Design; Human Building Interaction

1 Introduction

Buildings consume roughly 44 percent of the energy produced in the United States [1]. Global energy consumption and CO_2 emissions have significantly increased in the recent years by 49 percent and 43 percent, respectively, and these figures are estimated to annually increase by 2 percent and 1.8 percent, respectively [11,20].

In order to reduce the energy consumption of commercial buildings and CO_2 emissions in general, many researchers are investigating ways to make buildings more sustainable, intelligent, and responsive to occupants, environment, and the societal needs [4,14]. One potential way to improve the performance of buildings is to increase the interaction between buildings and their occupants. For instance, by allowing users to have more control over the available natural lighting in their office, the daily lighting energy-use could possibly be reduced.

Buildings are designed based on standard set-points and assumptions about occupants' behaviours and comfort levels that are thought to provide satisfaction to occupants. However, research studies have shown that occupants are not always satisfied and such set-points do not guarantee occupant comfort [3,13-15]. One method to incorporate occupants' behaviour in to the buildings' systems is through simulating defined behaviour models [9,21]. Simulations are commonly used to estimate the occupant activities and needs. However, due to the complexity of human behaviour and the diversity among building occupants, simulations are usually not a realistic representation of all occupants in a building [14,25]. Therefore, an accurate measurement of occupant behaviour could be an influential factor in reducing the energy consumption in buildings [14,25].

Lighting systems account for 18 percent of the total electricity consumption in the United States, where 71 percent of this consumption is from the commercial buildings [12,20]. Previous research has indicated that a large amount of energy can be saved with incorporating well-designed lighting controls to the building systems and more importantly by understanding the occupant's lighting needs and preferences [7]. In order to gain information on occupant behaviour and resultantly better understand the occupants' energy-use behaviour, the authors examine the impact of end-user's control on the available lighting (adjusting lighting levels both artificial and natural lighting) in a single-occupancy office room. To effectively examine the end-user behaviour, the authors have used an immersive virtual environment (IVE) to create alternative design environments of the office room with various lighting settings and controls that the users can interact with in order to measure the impact of user control on energy use. The participants were put in a dark room and were asked to read a passage. They were given a set of manual and semi-automatic lighting control options to adjust the room's available lighting in order to be able to fully read the passage. This paper measures the impact of having personal control on energy use through the use of immersive virtual environments.

2 Background

Previous researchers have studied occupants' lighting preferences when they are provided with different options of natural lighting vs. artificial lighting [22,24]. For instance, [24] showed that employees strongly prefer natural lighting and an outdoor view in an office environment. Other researchers have studied the effect of windows sizes and occupants' preferences about window types [19]. Many researchers have explored the effect of lighting control systems and the reaction of occupants towards such control systems [10,16]. Such studies have suggested that occupant satisfaction is increased with semi-automatic and manual modes of operations [23]. For instance, in the fully automated systems, the researchers studied the effect of sensor-controlled settings, in which the sensors determined how much natural lighting and artificial lighting should be available based on the availability of the natural light through the windows and the time of the day. In the semi-automated systems, the users were given limited control to manually adjust the sensor-controlled available lighting (i.e., dimming down/up the artificial lighting) [6]. Prior studies do not investigate the impact of having personal controls, though which occupants can increase the illuminance level from where they are located (impact of convenience) when performing a task, such as reading a passage. They also do not consider the energy consumption behaviour of occupants.

With the advent of virtual reality, augmented reality, and computer science fields, such as artificial intelligence and human-computer interaction, in recent years, Architecture, Engineering, and Construction (AEC) professionals have also access to such technologies more than ever. Such technologies provide AEC professionals with opportunities such as evaluating alternative designs [18], interacting and improving 3D models, communicating among parties [17,18], and more importantly studying human behaviour and preferences. Understanding human behaviour and preferences during the design phase allows architects and engineers to develop designs that would fit the end-users' needs the best, resulting in a higher satisfaction and comfort. For instance, [5] brought healthcare organization end-users (e.g., doctors, nurses, etc.) to an IVE in order to present different designed environments and get their feedback to make the necessary changes and adjustments, resulting in a more improved design based on the end-users' needs.

In this paper, in order to evaluate the effect of different lighting control options on energy consumption, an IVE was used to create alternative models with different settings, controls, and lighting settings, while providing realistic representations of physical environments. In another study, the authors investigated how human performance, perception and behaviour differ in an immersive virtual environment compared to an actual physical environment [8] and found no noticeable difference in terms of human performances between the two environments. The use of IVEs gives the researchers an opportunity to create environments with various control settings and evaluate end-users' behaviour and preferences given different scenarios. This process might also significantly help the AEC professionals during the design phase of buildings to ensure their design not only meets the end-users' preferences but also is more energy efficient.

3 Methodology

This paper examines human energy consumption behaviour and the impact of personal control on using different light sources (artificial vs. natural) in an office environment.

To evaluate the participants' energy consumption behaviour, two parameters were measured: (1) participant preference (natural vs. artificial) and (2) the impact of availability of a personal control on preference. Parameters were measured based on the choices the participants made in choosing the source (manual light switch, personal light switch, manual window blinds, personal window blinds) to increase the brightness of the room along with responses to the set of questionnaires asked to the participants.

3.1 Experiment and Hypothesis

In this experiment, three possible lighting settings (no light, natural light, and artificial light) for an office were designed within an IVE to evaluate the participants' behaviour when they were given the option to increase the brightness (Figure **4**). The participants were randomly assigned to 1 of 3 experimental groups that varied the options available to increase the brightness in the office (Figure **1**). In group 1, participants only had the options of manually opening the blinds or manually turning on the light switch, requiring the participants to physically move within the IVE to either turn on the light switch or open the blinds (Group 1 in Figure **1**). In group 2, the participants had the options of manually opening the blinds or manually turning on the light switch but they also were provided with a "personal remote control" that automatically opens the blinds; this control was set on the desk where the participants had to perform an assigned task (Group 2 in Figure **1**). In group 3, the participants not only had the options to manually turn on the light switch and open the blinds, but they also were provided with two "personal remote controls" that could open the blinds or turn on the artificial light while they were sitting at their desk next to where they had to perform an assigned task (Group 3 in Figure **1**). Figure **2** shows the different control options that each participant had to make the room brighter.

	Artificial Lighting System	Natural Light / Blinds
Group 1	Manually turning the lights on	Manually opening the blinds
Group 2	Manually turning the lights on	Manually or remotely opening the blinds
Group 3	Manually or remotely turning the lights on	Manually or remotely open the blinds

Figure 1 - Experimental Groups

Four hypotheses were developed to compare 'within' group and 'cross' group behaviours:

H1: *There is no significant difference between participants' choice of manually turning on the light switch and opening the blinds in group 1.*

H2: *Participants choose natural lighting significantly more than the artificial lighting when they are provided with a personal control only for opening the blinds (group 2).*

H3: *There is no significant difference between participants remotely turning on the light or remotely opening the blinds (group 3).*

H4: *There is a significant difference between remotely increasing the room's brightness (both for artificial and natural) and manually doing so (group 3).*

3.2 Model and Apparatus

In order to create a realistic model of an office space, an actual office room at the University of Southern California's campus was selected and all dimensions of this office room were measured. At first, a base structure of the room was designed in Revit© 2013. The Revit model was then imported to Autodesk 3ds Max© to create a realistic rendering of the room by adding lighting, shadows, reflections, furniture, and materials. The 3ds Max© file was then imported to Architecture Interactive© (the IVE software), in which the participants were able to fully navigate and interact with the models and objects within the model. To make the models more realistic and interactive, animations for opening the blinds, clicking on the remote controls, and turning on the light switch were designed; this allowed the participants to have a more realistic interaction with the model.

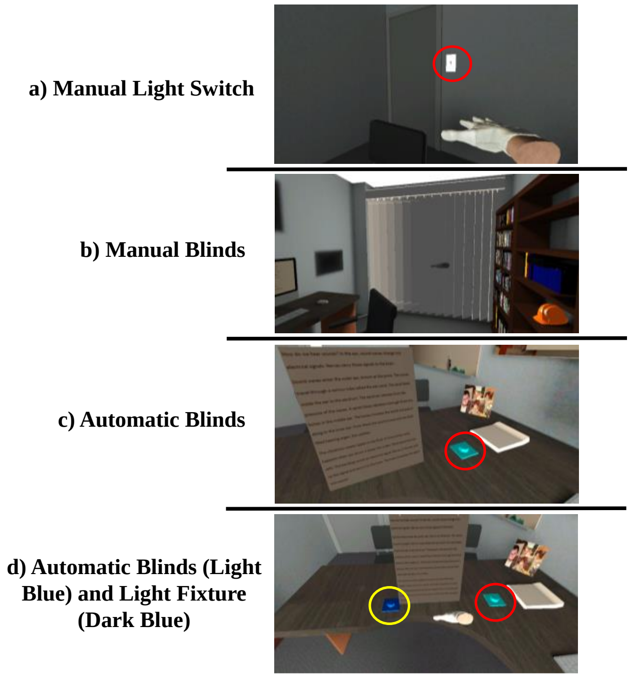

Figure 2 - Participants Lighting Control Options

The system configuration used for this experiment composed of a Microsoft© Xbox Kinect, an Oculus HMD, a tracker, a Microsoft© Windows graphics workstation with NVIDIA© 3000M graphics card. To increase the sense of presence and to allow participants to realistically interact with the IVE, a Kinect was used to track the body's displacement (3 Degrees-of-Freedom - DoF), a Head Mounted Display (HMD) was used to track the head rotation (3 DoF), and a tracker was used to navigate through the room, providing 4 DoF. Figure 3 shows the procedure for creating the models and the apparatus used for this experiment.

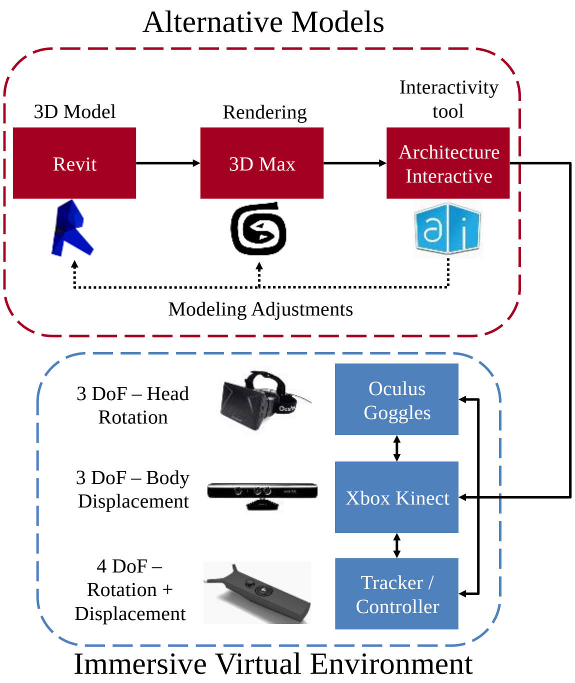

Figure 3 – Modeling procedure and apparatus

3.3 Procedure

In order to test the hypotheses, an experiment was conducted with 30 participants. The participants were undergraduate and graduate students at the University of Southern California between the ages of 18 to 36 years old. All participants completed a consent form. The participants had none or limited prior experience with IVEs. Since the participants were given the option to choose between the personal controls that were depicted in light and dark blue colours (Figure 2d), they were asked if they had normal or corrected visual acuity through a questionnaire for the purpose of this pilot experiment. Once the participants reviewed and agreed to the consent form, they were trained on how to navigate within an IVE, using a model different from the environment used in the actual experiment. During the training, they were instructed to find objects, navigate to different sides of the room using the tracker, and grab and move objects from one location to another. Once the participants felt comfortable with the IVE, they were instructed to remove the HMD and asked about their general feelings to ensure there was no motion sickness or headache caused by the IVE environment. Once the participants were ready, they were asked to put the HMD back on and were put in the experimental environment (the virtual office).

Figure 4 - Different Brightness Options Available in the Room. (a) Dark room with no available natural or artificial lighting, (b) bright room lit by natural light and (c) bright room lit by artificial light

In order to eliminate any order effect, participants were given a random number when they entered the office room that corresponded to one of the experimental groups (10 participants per each group – see Figure **1**). In each environment, the participants were instructed to navigate in the room and sit behind the desk and read a passage placed on the desk. At first the room was designed to be dark enough so the participants could not read the passage but were able to navigate and see the furniture in the room (Figure 4a). Then they were instructed on the possible choices they had in order to make the room brighter. For instance, if a participant was in group 2, he/she were instructed that he/she could (1) walk towards the door and manually turn the light switch on, (2) walk towards the window and manually open the blinds, or (3) click on the personal control right next to the passage to automatically open the blinds (Figure 2c).

Once he/she chose one of the options available in his/her group, he/she either turned on the artificial lights or opened the blinds (see Figure 4). The participants were then asked to read the passage on the desk to complete the experiment.

4 Results

To examine the impact of personal control on using different light sources (artificial vs. natural) and test the a priori hypotheses, 'within' group and 'cross' group comparisons were performed.

In Group 1, three participants chose to use the light switch manually and seven participants chose to open the blinds manually. In Group 2, nine participants chose to remotely open the blinds, one participant chose to manually open the blinds, and no participants turned on the light switch manually. In Group 3, two participants chose to remotely turn on the lights, six participants chose to remotely open the blinds, one participant chose to manually open the blinds, and one participant chose to manually turn on the light switch. Table 1 summarizes the details of the experimental data.

Table 1 – Cross-tabulation between the groups and conditions

Condition Crosstabulation							
			Room1				
			Remote Blind	Manual Blind	Remote Light	Manual Light	Total
Group	1	Count	N/A	7	N/A	3	10
		% within Condition	0.0%	70.0%	0.0%	30.0%	100.0%
	2	Count	9	1	N/A	0	10
		% within Condition	90.0%	10.0%	0.0%	0.0%	100.0%
	3	Count	6	1	2	1	10
		% within Condition	60.0%	10.0%	20.0%	10.0%	100.0%
Total		Count	15	9	2	4	30
		% within Condition	50.0%	30.0%	6.7%	13.3%	100.0%

4.1 Within Group Comparison

The 'within' group comparison examined the effects of different lighting control options within each group. The Null Hypothesis (H_0) for each group was that participants would choose each option equally at chance. If participants do not have a prior preference of the lighting options and/or are not influenced by the presence of personal controls, they are expected to choose the options randomly, leading to an approximately equal chance of choosing each option.

4.1.1 Group 1

The Null Hypothesis (H_0) specifically for this group was that 50 percent of the participants would choose to manually turn on the light switch while 50 percent would choose to manually open the blinds. To test the H_0, a Chi-square (χ^2) test confirmed that the percentage of participants that opened the blinds manually did not significantly differ from the percentage that manually turned on the light switch, χ^2 (1, N=10) = 0.21, $p > 0.05$. See Table 2 for more detail.

Table 2 - Group 1 χ2 Analysis

Group 1	
Manual Light vs. Manual Blinds	
Chi-Square	1.6
Degrees of Freedom	1
p-value	**0.20590321**
Yates' chi-square	0.9
Yates' p-value	0.34278171

4.1.2 Group 2

The (H_0) for group 2 was that 33.3 percent of the participants would choose to manually turn on the light switch, 33.3 percent would choose to manually open the blinds, and 33.3 percent would choose to remotely open the blinds. A Chi-square (χ^2) test confirmed that the percentage of participants who opened the blinds remotely significantly differed from the percentage that manually on turned the light switch, χ^2 (1, N=10) = 0.01, $p > 0.05$. See Table 3 for more detail.

Table 3 - Group 2 χ2 Analysis

Group 2	
Remote Blinds vs Manual Light	
Chi-Square	6.4
Degrees of Freedom	1
p-value	**0.01141204**
Yates' chi-square	4.9
Yates' p-value	0.0268567

4.1.3 Group 3

The Null Hypothesis (H_0) for this group was that 25 percent of the participants would choose to manually turn on the light switch, 25 percent would choose to manually open the blinds, 25 percent would choose to remotely open the blinds, and 25 percent would choose to remotely turn on the artificial light. Since the number of expected participants is less than 5 for each condition, Yates' correction is applied to the Chi-square (χ^2) test to make it a more conservative test. The first test compared the use of remote control for both blinds and artificial light. The Yates' chi-square test confirmed that the percentage of participants that opened the blinds remotely did not significantly differ from the percentage that remotely turned on the artificial lights, χ^2 (1, N=8) = 0.15, $p > 0.05$. See Table 4 for more detail.

Table 4 - Group 3 χ2 Analysis (Remote)

Group 3	
Remote Blind vs. Remote Light	
Chi-Square	2
Degrees of Freedom	1
p-value	**0.15729921**
Yates' chi-square	1.125
Yates' p-value	0.28884437

The second test compared the use of manual control (both for artificial lighting and blinds) vs. remote control (both for artificial lighting and blinds). This group comparison shows whether the participants were more likely to use the remote options more than the manual options. The chi-square test confirmed that participants used the remote options marginally significantly more than the manual options, χ^2 (1, N=10) = 0.057, $p \approx 0.05$. See Table 5 for more detail.

Table 5 - Group 3 χ2 Analysis (Grouped)

Group 3	
Manual vs. Remote (grouped)	
Chi-Square	3.6
Degrees of Freedom	1
p-value	**0.05777957**
Yates' chi-square	2.5
Yates' p-value	0.1138463

4.2 Cross Group Comparison

The within-group comparison in group 2 revealed that participants chose the personal control option for natural light significantly more than the manual control option artificial light. However, in group 3, when a remote control is added for artificial lighting, the participants did not choose the natural light personal control option significantly more than the artificial light personal control option. Therefore, comparing these two groups, having only a personal control for the blinds is far more effective than having a personal control for both the blinds and artificial lighting. This is indicated by the significant chi-square p-value for the remote blinds in group 2 (Table 3) and the non-significant chi-square p-value in group 3 (Table 4).

4.3 Questionnaires

Through a set of questionnaires, the authors examined the knowledge of the participants about green building features and their familiarity with IVE. On a scale of one to seven [2] (one being not environmentally friendly at all and seven being very environmentally friendly), participants rated their concern for the environment as 4.86 on average. Meanwhile, 13 people were familiar with the term LEED (Leadership in Energy and Environmental Design), the only word indicative of the participants' environmental knowledge in the series of words given to them. This indicates that the pool of participants could be slightly more knowledgeable about green buildings and energy efficient features than an average person.

The participants were also asked about how realistic they thought the IVE looked/felt and whether they thought the model was a good representation of an average office space, on a scale of one to seven (one indicating the model to be very unrealistic), they gave the modelling of the room a 5.22 on average. With regards to their familiarity with IVE, only three participants indicated that they have previous knowledge about the term; these participants indicated that they had an average amount of experience with virtual gaming.

5 Limitations and Future Work

Although served as a first step toward the research goals, this study had several limitations. There was a small sample size of 30 participants (10 for each group). In future studies, the number of participants will be increased. Also, most of the participants were engineering students, whom could be more environmentally friendly than the average population; in future studies a more diverse pool of participants will be used to reduce any bias in their decision making.

In future studies, a 'fourth' group will be added. This group will provide participants with the options of manually opening the blinds and manually turning on the light switch but also provide the artificial light personal control option without the natural light remote control option. We will then compare the effects of the remote control for artificial lighting on participants' energy consumption behaviour to investigate whether participants will choose to open the blinds manually or prefer to semi-automatically turn on the artificial lights.

Some of the features of the models could also be improved (shadows, reflections, objects in the room) that could provide the participants with more realistic view of the office environment. As part of the future work, the authors will further investigate the effects of different design choices on human energy-use behaviour using IVEs. The authors will also use IVEs to explore the integration of multi-agent systems to impact building design performance and occupant satisfaction.

6 Conclusion

Understanding occupant behaviour and their impact on the buildings' energy consumption is an important avenue of research in order to reduce building's electricity consumption. The authors aimed to explore the impact of personal control on lighting use in office environments using alternative 3D design models within immersive virtual environments. This paper demonstrated occupants are significantly more likely to use natural lighting if they are only given a personal control for blinds, but not more likely to use natural lighting if a personal control is available for both blinds and artificial light. Additionally follow-up questionnaires revealed that the participants chose the personal control feature for the blind, just because it was 'easier' and more convenient for them, which shows that such features could potentially not only be integrated to the existing operational buildings but more importantly could also be part of the design options for during the design phase of future commercial buildings. The use of IVE enables us to measure and control a series of design feature isolations and combinations to further understand what features are more effective compared to one another. This paper reveals an important application IVEs to increase the interaction between building design and construction and user behaviour and satisfaction.

7 Acknowledgment

This project is part of the National Science Foundation funding under the contract 1231001. Any discussion, procedure, results, and conclusion discussed in this paper are the authors' views and do not reflect the views of National Science Foundation. Special thanks to all of the participants and to the researchers that contributed to this project; specifically to Alex Coco and Samantha Kaplan for their contributions in preparing and running the experiments.

References

[1] B. Book, Building Energy Data Book, (2011).

[2] A.M. Colman, C.E. MORRIS, C.C. Preston, Comparing rating scales of different lengths: Equivalence of scores from 5-point and 7-point scales, Psychological Reports 80 (2) (1997) 355-362.

[3] S.P. Corgnati, M. Filippi, S. Viazzo, Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort, Building and Environment 42 (2) (2007) 951-959.

[4] T. Derek, J. Clements-Croome, What do we mean by intelligent buildings?, Automation in Construction 6 (5–6) (1997) 395-400.

[5] P.S. Dunston, L. Arns, J.D. Mcglothlin, G.C. Lasker, A.G. Kushner, An Immersive Virtual Reality Mock-Up for Design Review of Hospital Patient Rooms, 7th International Conference on Construction Applications of Virtual Reality (2011).

[6] S. Escuyer, M. Fontoynont, Lighting controls: a field study of office workers' reactions, Lighting Research and Technology 33 (2) (2001) 77-94.

[7] A.D. Galasiu, J.A. Veitch, Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review, Energy and Buildings 38 (7) (2006) 728-742.

[8] A. Heydarian, J.P. Carneiro, D. Gerber, B. Becerik-Gerber, T. Hayes, W. Wood, Immersive Virtual Environments: Experiments on Impacting Design and Human Building Interaction, Open Systems: Proceedings of the 19th International Conference of the Association of Comput-er-Aided Architectural Design Research in Asia CAADRIA (2014).

[9] P. Hoes, J.L.M. Hensen, M.G.L.C. Loomans, B. de Vries, D. Bourgeois, User behavior in whole building simulation, Energy and Buildings 41 (3) (2009) 295-302.

[10] D.R.G. Hunt, The use of artificial lighting in relation to daylight levels and occupancy, Building and Environment 14 (1) (1979) 21-33.

[11] IEA, Kew World Energy Statistics, International Energy Agency, 2013

[12] F. Jazizadeh, S. Ahmadi-Karvigh, B. Becerik-Gerber, L. Soibelman, Spatiotemporal lighting load disaggregation using light intensity signal, Energy and Buildings 69 (2014) 572-583.

[13] F. Jazizadeh, G. Kavulya, L. Klein, B. Becerik-Gerber, Continuous Sensing of Occupant Perception of Indoor Ambient Factors, Computing in Civil Engineering (2011), pp. 161-168.

[14] F. Jazizadeh, G. Kavulya, J. Kwak, B. Becerik-Gerber, M. Tambe, W. Wood, Human-Building Interaction for Energy Conservation in Office Buildings, Construction Research Congress 2012, pp. 1830-1839.

[15] J.-y. Kwak, P. Varakantham, M. Tambe, L. Klein, F. Jazizadeh, G. Kavulya, B.B. Gerber, D.J. Gerber, Towards optimal planning for distributed coordination under uncertainty in energy domains, Workshop on Agent

Technologies for Energy Systems (ATES) at AAMAS, Vol. 2011, 2011.
[16] J.A. Love, Manual switching patterns in private offices, Lighting Research and Technology 30 (1) (1998) 45-50.
[17] T. Majumdar, M.A. Fischer, Conceptual Design Review with a Virtual Reality Mock-up Model Building on IT: Joint International Conference on Computing and Decision Making in Civil and Building Engineering (2006).
[18] K.D. Maldovan, J.I. Messner, M. Faddoul, Framework for Reviewing Mock-ups in an Immersive Environment, 6th International Conference on Construction Applications of Virtual Reality (2006).
[19] E. Ne'Eman, R.G. Hopkinson, Critical minimum acceptable window size: a study of window design and provision of a view, Lighting Research and Technology 2 (1) (1970) 17-27.
[20] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy and Buildings 40 (3) (2008) 394-398.
[21] C.F. Reinhart, Lightswitch-2002: a model for manual and automated control of electric lighting and blinds, Solar Energy 77 (1) (2004) 15-28.
[22] J.A. Veitch, R. Gifford, Assessing Beliefs about Lighting Effects on Health, Performance, Mood, and Social Behavior, Environment and Behavior 28 (4) (1996) 446-470.
[23] E. Vine, E. Lee, R. Clear, D. DiBartolomeo, S. Selkowitz, Office worker response to an automated Venetian blind and electric lighting system: a pilot study, Energy and Buildings 28 (2) (1998) 205-218.
[24] B.W.P. Wells, Subjective responses to the lighting installation in a modern office building and their design implications, Building Science 1 (1) (1965) 57-68.
[25] Z. Yu, B.C.M. Fung, F. Haghighat, H. Yoshino, E. Morofsky, A systematic procedure to study the influence of occupant behavior on building energy consumption, Energy and Buildings 43 (6) (2011) 1409-1417.