Evaluation of a new user-centric sensor-based lighting control approach for circulation areas

Ö Karaman Madan 1,2 and MK Pekeriçi1

1Department of Architecture, Middle East Technical University, Ankara, Turkey

2Building Lighting Group, Building Physics and Services Unit, Department of the Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands

o.karaman.madan@tue.nl

Abstract. Suitable lighting control strategies are essential for energy efficiency in buildings. Occupancy sensors are highly promoted by the building codes as one of the most cost-effective solutions in the sector. However, widespread use of these systems is still limited due to lack of user satisfaction. In this study, it is hypothesized that the “conventional use” of occupancy sensors (where user steps inside a dark area, and only afterwards the area becomes lit) is the reason behind the dissatisfaction. To overcome this problem, a new user-centric sensor-based lighting control approach is proposed in this study where users walk into an already lit area. An experiment was carried out in the circulation areas of a university building to test the feasibility of the proposed scenarios along with a conventional occupancy sensor scenario and the existing “no sensor” scenario. The main results revealed that the conventional use of occupancy sensors was not favoured by the participants in circulation areas while use of the proposed user-centric approach was as favourable as the existing constantly lit situation. It is the claim of this study that both energy efficiency and user satisfaction can be provided by the use of user-centric control systems.

1. Introduction

Occupancy sensors are the most cost-effective solutions in the market to reduce lighting energy use in buildings, especially where the occupancy patterns are not steady. However, widespread use of these systems is still limited due to a lack of consideration of user satisfaction [1], [2], [3]. While occupancy sensors are accepted in small-scale spaces, they are not fully accepted in more complex areas [2]. In the literature, there are a lot of studies in terms of energy efficiency gains of occupancy sensors, but there are only few studies on user satisfaction. Ref. [1] also pointed out this problem in their state-of-art review and addressed the lack of research in the literature and lack of recommendations in guidelines and standards on user-centric lighting control. Today many buildings are subject to 24-hour operation per day. Special emphasis has been given to dark hours, where these buildings' occupancy patterns in circulation areas may be subjected to huge variations. In that case, occupancy sensors are suggested to increase energy efficiency. However, the use of occupancy sensors may cause dissatisfaction among the occupants. Late triggering of the sensor, false on and off, or inappropriate delay times may be the reason. These problems can be overcome by better quality products or better commissioning. There are several
studies in the literature focusing on user satisfaction of sensor based lighting control systems in terms of effects of optimizing the lighting settings by dimming speeds [4], dimming levels [5], different illumination levels on task, surrounding and background areas [6], adaptation of control parameters by personalized set-points [3], different time delay settings [7] [8] [9], and optimal placement methods for sensors [10].

As researchers observed and it was also pointed out in the literature [2], conventional usage of occupancy sensors (user steps inside of an area, only after occupancy sensor detects occupancy and energizes the luminaires in that area) may be another reason of dissatisfaction for the occupants in circulation areas, especially during night use. There are only few studies focused on that problem. Ref. [11] proposed an intelligent system using multiple sensors (light sensors and occupancy sensors) and wireless communication technology to control illumination intensity by user movement and brightness in the area. When the occupancy is detected the light intensity increases to a maximum pre-defined value; if no movement is detected, the light intensity decreases to a minimum pre-defined value. The authors tested the system but they did not reveal feedback from the users. Following that study, Ref. [2] proposed a sensor-based lighting control system which dims the light down without turning it off completely. They tested it in a corridor type space. Results of the study show that significant energy savings are achieved, and a survey revealed that almost 80% of the occupants did not feel uncomfortable. This research makes a major contribution to the lack of literature on the issue. However, it is still not giving insight on users’ perspective and criteria behind their satisfaction. Researchers also observed that facing dark spots in the sight of view might be another reason of dissatisfaction during night use.

To overcome these problems, a new approach is proposed in this study where lighting in an area is controlled by the occupancy sensors placed in the adjacent areas to enable users to walk into an already lit environment. Two lighting control scenarios are generated by this approach and tested in this study along with a conventional occupancy sensor scenario and a constantly lit no-sensor scenario. The aim of this study is to propose a new user-centric sensor-based lighting control approach, to test and compare it with the conventional system in a real environment and to present a user evaluation. Rather than the proposed approach, the contribution of this study is a user evaluation study in terms of sensor-based lighting control for circulation areas in off-operation hours.

2. Method

2.1. Experimental setting

The chosen experiment area is the entrance and the following corridors of a university building (METU Faculty of Architecture), which was found to be problematic for night use by the building occupants. The experiment area was divided into 3 zones to group and control the luminaires. This zoning was decided by the researchers in terms of spatial characteristics of the area (Figure 1a).

![Figure 1. (a) Partial plan denoting the location of zones, luminaires and sensors. (b) Procedure of the experiment.](image-url)
2.2. Procedure
As also shown schematically in Figure 1b, after an informative session, participants perform a task, evaluate and go back to start point for four times to experience and evaluate each scenario. The task was to walk from the start point to finish point: climbing the entrance stairs, getting inside of the building to Zone 1, walking towards Zone 3, entering Zone 3, going down the stairs and stopping at the finish point.

2.3. Experimental lighting control scenarios

Table 1. Lighting control principles shown schematically for each scenario.

| Finish - Entering the Zone 3 | Entering to Zone 1 | Start - climbing the stairs |
|------------------------------|--------------------|-----------------------------|
| (No-OS)                      |                    |                             |
| (Conv-OS)                    |                    |                             |
| (UC1-OS)                     |                    |                             |
| (UC2-OS)                     |                    |                             |

Table 1 schematically shows the lighting control principles of the experimental scenarios according to different positions of the participants. These positions are chosen to describe scenarios easier as they show the positions where the sensors are triggered. The no-sensor constantly lit scenario (No-OS) was the existing lighting control approach in the area. In the conventional occupancy sensor control scenario (Conv-OS) lighting in the area was controlled by the sensor inside the same zone. Zone 1 is controlled by S2 and Zone 3 is controlled by S3. In the first proposed user-centric occupancy sensor scenario (UC1-OS), the idea was to give occupants an impression of being in a constantly lit environment when they experience this scenario. The occupant enters an already lit area (lighting controlled by the occupancy sensor placed in the adjacent area) and the occupancy sensor inside that area also controls the lighting of the adjacent area. Zone 1 is controlled by S1, Zone 2 and Zone 3 is controlled by S2. In the second proposed user-centric occupancy sensor scenario (UC2-OS), the occupant enters an already dimly-lit area (controlled by the occupancy sensor in the adjacent area), the occupancy sensor inside of that area is triggered to fully light that area and to dimly light the adjacent area. Zone 1 is controlled by S1 and S2; Zone 2 is controlled by S2; Zone 3 is controlled by S2 and S3.
2.4. Study design
Four different lighting control scenarios are tested with a “within subjects repeated measures design” method where same participant experiences each of the four scenarios. 38 participants participated in the study from 6-7 April 2019. Since the focus was on night use, experiments were conducted in the dark hours. To create a baseline for the sensor-based scenarios, the first scenario was the current lighting control situation (No-OS) where all lights were on. The order of the three sensor-based scenarios (Conv-OS, UC1-OS, UC2-OS) was randomized for each participant to enhance credibility.

2.5. Evaluation criteria
The evaluation questionnaire consisted of 10 statements (7-point Likert scale). There were no previous validated scales in the literature based on the assessment of lighting control systems in circulation areas. So, the questionnaire was structured based on literature knowledge on lighting design for circulation areas and lighting quality. According to the IESNA Lighting Handbook 9th Edition [12], human needs served by lighting are: visibility; task performance; mood and atmosphere; visual comfort; aesthetic judgment; health, safety and well-being; and social communication. Among these criteria, visibility, mood, atmosphere, well-being, sense of security and visual comfort were associated with the lighting control while other criteria were mostly based on other features of the lighting design. Moreover, appraisal and acceptance were added as criteria for the evaluation measures to evaluate self-reported satisfaction levels, as they were also suggested in [6]. Considering the example of Ref. [13], after determining the evaluation criteria, statements were generated to evaluate them in a more solid way. To bring the evaluation statements to its final version, a focus group study (a semi structured discussion with members of the targeted population guided by a moderator) was advised in the literature to better associate evaluation criteria to questionnaire statements [14]. After the focus group study, the order of the statements (Table 2) were organized according to task (from the start point to finish point) to make evaluation easier for the participants.

| # | Statement                                                                 | Evaluation criteria       | 1 (Strongly Disagree) | 7 (Strongly Agree) |
|---|--------------------------------------------------------------------------|---------------------------|-----------------------|--------------------|
| 1 | The building entrance looked inviting.                                   | Atmosphere Outside        | 1 - 7                 |                    |
| 2 | I felt uneasy before entering the building.                              | Mood Outside              | 1 - 7                 |                    |
| 3 | I felt good after entering the building.                                 | Well-being                | 1 - 7                 |                    |
| 4 | As I moved through the corridor, I easily perceived the environment.    | Visual Comfort            | 1 - 7                 |                    |
| 5 | Places in my field of view made be nervous.                             | Mood inside               | 1 - 7                 |                    |
| 6 | The atmosphere made me feel comfortable.                                | Atmosphere Inside         | 1 - 7                 |                    |
| 7 | I noticed the stairs in time.                                           | Visibility                | 1 - 7                 |                    |
| 8 | In general, I was satisfied with this lighting control.                 | Appraisal                 | 1 - 7                 |                    |
| 9 | This lighting control was acceptable to me.                             | Acceptance                | 1 - 7                 |                    |
| 10| This lighting control was reassuring.                                    | Sense of security         | 1 - 7                 |                    |

2.6. Analysis
Friedman’s test was applied to answer the research questions with a following post hoc analysis. To reduce the Type I Error risk, a Bonferroni correction was applied. To create a single score from 10 dependent variables (DV), a summated scale (a data reduction method which creates a composite value by summing and averaging the original variables) was created [15]. This was accurate for the experimental nature of this study since there were multiple DVs which are different measures of the
same construct and measured in the same scale. These scores were calculated for each of the experimental scenarios to compare the overall satisfaction levels and will be named from now on ‘Overall Satisfaction Score’. IBM SPSS 23.0.0 was used for statistical analysis with a .05 level of statistical significance (p value).

3. Results and discussions

3.1. Overall satisfaction scores

According to statistical analysis, the only statistically significant difference in overall satisfaction scores was between Conv-OS and other scenarios. Figure 2a reports the median scores and the spread. Since non-parametric tests were conducted and data was ordinal, median scores were used to compare results. According to this result, only Conv-OS is in the dissatisfaction range (score<4) and it can be deduced that conventional use of occupancy sensors is not favoured by the participants in night use of circulation areas. On the other hand, the proposed user-centric scenarios were as favoured as a constantly lit no-sensor scenario. This points out that, to achieve better energy efficiency, sensor-based lighting control systems can be used in the circulation areas without sacrificing user satisfaction when occupancy sensors are used in a user-friendly way.

Figure 2. (a)Median and range of overall satisfaction scores on experimental lighting control scenarios (N=37). (b) Spider chart representing the evaluation criteria.

3.2. Evaluation criteria

All statistical results are presented in Figure 2b for each of the evaluation criteria with their median values. While in Criteria 1 (outside atmosphere), 7 (visibility), 8 (appraisal), 9 (acceptance), 10 (sense of security) there were obvious differences by their median scores, in Criteria 2 (outside mood), 3 (well-being), 4 (visual comfort), 5 (inside mood), 6 (inside atmosphere) the differences were not so definite. Thus it can be highlighted that measures of giving an inviting entrance, providing sufficient visibility and sense of security are the most important criteria in terms of user satisfaction in dark hours. Only in Conv-OS, participants confronted a dark entrance when they were climbing the stairs. Results show that the entrance was not inviting for the participants. In daytime use, this would be acceptable for the users, but in the night use confronting a dark area causes discomfort. Moreover, in Conv-OS, when participants walked through the corridor (Zone 1), the neighbouring zones (Zone 2 and 3) were dark. So, it can be stated that, even though the participants were inside a lit area, surrounding dark areas in their sight of view caused discomfort. In this regard, improved user-centric sensor-based scenarios were successful as they offered an already lit entrance and prevented dark spots in the sight of view. That provided better “sense of security” to the participants. On the other hand, the “visibility” criterion was not favourable in Conv-OS, even though participants perceived adjacent zones immediately. This shows that, in
interrelated circulation areas such as this experiment area, it is more satisfying for the users to perceive clearly the surrounding areas (areas in their sight of view). This should be considered when designing user-centric systems.

4. Conclusions
The main objective of this study was to test a new user-centric sensor-based lighting control approach in terms of user satisfaction by presenting a comparison with conventional approaches. Based on the evaluation criteria scores, Conv-OS was not favoured by the participants due to being not inviting and causing a lack of sense of security, visibility and well-being. Since there was no statistically significant difference in the overall satisfaction scores between other scenarios (No-OS, UC1-OS and UC2-OS) and they were all rated as favourable, it can be deduced that proposed user-centric control approach can be as reassuring as constantly illuminated manual control systems. The dissatisfaction and satisfaction differences mostly concerned the criteria outside atmosphere, visibility, appraisal, acceptance and sense of security. Scenarios were tested in a limited area to ensure control over user traffic and lighting conditions in the sight of view. Even though the experiment took place in an actual area in an actual building that is used in night hours, the limited experimental setting area and limited exposure time to experimental conditions may limit the wider applicability of the results. The experiments were carried out with a single occupancy scenario and only one way to test the conditions in the most extreme case; more research will therefore be conducted to confirm the findings of this study. To conclude, it is the claim of this study that both energy efficiency and user satisfaction can be provided in circulation areas by the use of user-centric sensor-based lighting control systems.

References
[1] de Bakker C Aries M Kort H and Rosemann A 2017 Occupancy-based lighting control in open-plan office spaces: A state-of-the-art review Build. Environ. 112 308–321
[2] Byun J and Shin T 2018 Design and Implementation of an Energy-Saving Lighting Control System Considering User Satisfaction IEEE Transactions on Consumer Electronics 64 61–68
[3] Park J Y Dougherty T Fritz H and Nagy Z 2019 LightLearn: An adaptive and occupant centered controller for lighting based on reinforcement learning Build. Environ. 147 397–414
[4] Chraibi S Creemers P Rosenkötter C van Loenen E J Aries M B C and Rosemann A L P 2018 Dimming strategies for open office lighting: User experience and acceptance Lighting Res. and Technol. 51 513-529
[5] Tan F Caicedo D Pandharipande A and Zuniga M 2018 Sensor-driven, human-in-the-loop lighting control Lighting Res. and Technol. 50 660–680
[6] de Bakker C Aarts M Kort H and Rosemann A 2018 The feasibility of highly granular lighting control in open-plan offices: Exploring the comfort and energy saving potential Build. Environ. 142 427–438
[7] Garg V and Bansal N K 2000 Smart occupancy sensors to reduce energy consumption Energy Build. 32 81–87
[8] Leephakpreeda T 2005 Adaptive occupancy-based lighting control via Grey prediction Build. Environ. 40 881–886
[9] Nagy Z Yong F Y Frei M and Schlueter A 2015 Occupant centered lighting control for comfort and energy efficient building operation Energy Build. 94 100–108
[10] Wagiman K R Abdullah M N Hassan M Y and Radzi N H M 2020 A new optimal light sensor placement method of an indoor lighting control system for improving energy performance and visual comfort Journal of Building Engineering 30 101295
[11] Byun J Hong I Lee B and Park S 2013 Intelligent household LED lighting system considering energy efficiency and user satisfaction IEEE Transactions on Consumer Electronics 59 70–76
[12] Rea M S IESNA Lighting Handbook, Reference & Application, 9th ed., 9th ed (New York: Illuminating Engineering Society of North America)
[13] Eklund N H and Boyce P 2013 The Development of a Reliable, Valid, and Simple Office Lighting Survey Journal of the Illuminating Engineering Society 25 25–40
[14] Krueger R A and Casey M A 2000 Focus groups: A practical guide for applied researchers, 3rd ed. (Thousand Oaks: Sage Publications)
[15] Hair J F Black W C Babin B J and Anderson R E 2014 Pearson New International Edition: Multivariate Data Analysis (New Jersey: Pearson Prentice Hall)