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Analyzing occupants' control over lighting systems in office settings using immersive virtual environments

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ABSTRACT

Research has identified occupant behavior as one of the key contributors to building energy performance gap. Thus, this study systematically analyzed the impact of having personal control over lighting system on occupants' lighting choices, lighting satisfaction, and task performance in a virtual office setting. For this purpose, 30 participants took part in a 3-phased experiment with immersive virtual environments (IVEs). Each phase of the experiment offered a different degree of control over the lighting. Personality traits were also studied in relation to lighting choices. Finally, a technology acceptance model (TAM) was employed to further investigate the participants' attitude towards the virtual reality (VR) technology.

The findings of this study showed that using an interactive lighting system, which was as satisfactory compared to a conventional lighting system, encouraged the participants to use more natural light. The interactive lighting system imposed the same amount of cognitive load on the participants for performing a reading task as a conventional lighting system, which was significantly lower than their cognitive load scores for performing the task with automated lighting system. Personality analyses demonstrated that the participants with a high score on openness had a wide range of lighting choices either with conventional or with interactive lighting. This study's results differed from the previous studies by highlighting that the participants considered VR as a better fit to an enjoyable experience rather than a useful tool for performing serious tasks.

1. Introduction

According to several studies, there is a significant inconsistency between the estimated and the actual energy consumption of buildings [1–6]. Research has shown that the energy consumption of buildings, in reality, can sometimes be up to 300% greater than the estimated amount [7]. Some of the main factors influencing energy consumption in buildings are thermophysical properties of different building components, quality of construction, climate, building envelope, building energy systems such as HVAC and lighting, and occupants' behavior [8,9]. Studies have discovered that occupant behavior has a major effect on building energy consumption and should not be underestimated [5, 10–18]. This effect is so significant that different studies have recognized occupant behavior as the key contributor to building energy performance gap [19–21]. Energy-related occupant behavior is defined as "observable actions or reactions of a person in response to external or internal stimuli, or actions or reactions of a person to adapt to ambient environmental conditions" (p.134) [22]. To pledge energy efficiency, technological advancement alone might not suffice; it requires optimization and regulation of occupant behavior and manner of interactions with building systems towards energy efficiency [23].

Reviewing the literature shows that there are three different terms about occupants' interactions with building systems. The first term is behavior, which entails a broad sense. Occupant behavior represents human interaction with building systems in interest of regulating the interior environment to suit their health, thermal, visual, and acoustic comfort [7]. The second term is preference. Occupants' preferences embody a sequence of frequent decisions from a wide range of options over a long period [24]. Lighting preferences are typically studied in relation to lighting parameters such as color temperature and illuminance levels [24]. Last term is choice. Choices are temporary decision restricted by a number of possible options in a certain scenario [24]. In

Abbreviations: BFI, big five inventory; EF, effort; FR, frustration level; IVE, immersive virtual environment; NASA TLX, Nasa task load index; IU, intention to use; PE, perceived enjoyment; PEU, perceived ease of use; PU, perceived usefulness; SD, standard deviation; TAM, technology acceptance model; TD, temporal demand; VR, Virtual reality; WWL, weighted work load.

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this respect, choices and preferences are not equivalent, but related in a way that preferences may influence choices while the opposite is not necessarily valid [24].

The reason that occupants interact with building systems is to make their environment meet their comfort level [25]. These interactions are in the form of different activities such as: operating building openings, adjusting lighting and shading systems, setting HVAC systems, or using hot water and electrical appliances [7]. Central systems and automated systems in buildings can reduce energy consumption and maintain the quality of indoor space close to standards [26,27]. However, studies have shown that office occupants, especially in individual offices, prefer to have personal control over the building systems [28–30]. Additionally, various studies have identified potential correlations between occupants' perceived control, satisfaction, and comfort [31,32].

Occupant control does not have an explicit definition in the field of built environment yet and usually is regarded to various contexts of individual and personal control [33]. Greenberger and Strasser [34] (p. 165), define personal control as an "individual's beliefs at a given point in time, in his or her ability to effect a change, in a desired direction on the environment". Yet, this explanation is not specific to the built environment [33]. In environmental studies, the phrase personal control or occupant control, mostly, comes alongside with occupants' comfort [33]. Nevertheless, various studies have addressed occupant control over the environment in two forms of adapting different qualities in workspace [35–38] and individualizing it [39].

Research has shown that having control over one feature of the environment contributes to perceived control over other features as well [36,38]. A perception of control over the work environment can be a result of having adjustable features such as lighting, temperature, and sound [40]. Galasiu and Veitch [41] in their review study about occupants' satisfaction and preferences concluded that occupants generally do not support entirely automated systems. Additionally, facility managers find these systems overly sophisticated and harder to maintain. Moreover, favorable indoor environmental qualities, such as lighting condition or thermal condition, are specific for each individual. Therefore, full automation or central control is less likely to respond to everyone's preference and can result in low satisfaction [42,43]. However, giving the occupants a sense of control over their environment can result in satisfaction, comfort, and more productivity [40]. Consequently, having any type of control in an environment is associated with psychological and physical well-being [44].

For occupants to accept an automated control systems having a perception of control is crucial and can lead to optimal operation of the systems [45]. The association between occupants and personal control is complicated; particularly, knowing that occupants' preferences, personal characteristics, and awareness can influence their choices [46–48]. The same way that occupants impact their environment, indoor environment and buildings systems, like lighting systems or HVAC systems, are capable of influencing occupant's' productivity, health, satisfaction, mood [27,49–52]. Occupants can make different choices for controlling building systems according to their usability, accessibility, and undesirable effects [53].

Although many studies have explored various lighting systems in terms of energy efficiency, control methods, and occupants' satisfaction, there is little literature available on how perceived control affects occupants with the technological development. The aim of this study is to understand how different control levels over lighting systems influence occupants' choices and performance in office settings. The ultimate purpose of the study is to pave the way for designing and providing lighting systems that are not only more supportive of occupants' satisfaction and performance, but also have the potential to reduce the lighting-related electricity consumption in buildings.

2. Background

2.1. Lighting in office settings

To foster energy efficiency in terms of lighting in office buildings, many energy efficient lighting devices and control strategies have been designed and put into work, such as: LEDs which have the potential to save energy [54], daylight responsive dimming systems [55], and occupancy-based lighting controls [56], which function based on the presence of occupants in an environment. Previous studies have indicated that integrated daylighting systems can reduce building energy consumption up to 30%–80% [57,58]. These systems regulate the artificial lighting level in regard to the available indoor daylight to retain the required lighting level for a work plane on a real-time basis [59]. These systems employ luminosity sensors to work in integration with occupancy sensors in order to actively make use of natural light in a system that turns artificial lights off when the indoor environment is provided with enough natural light [47,60].

Optimizing lighting condition in office environments has the potential to improve satisfaction and productivity of office occupants by providing an efficient ambient [55]. Research has shown that sufficient light levels and high-quality lighting can improve the health and the mood of office occupants [50,61]. Various studies show that when occupants consider a lighting level to be of high quality, the advantages are considerable [62]. These advantages could be beneficial in different contexts. First, in general, adjustable lighting control systems, as one of the foremost contributing features to the perceived lighting quality, consume 10% less energy than a fixed lighting level, resulting in environmental benefits [28,63]. The occupants benefit from higher quality of lighting because it gives them a better mood [64], more visual and physical comfort [65], and higher environmental and job satisfaction [64]. Finally, employers gain profit from staff that are more engaged in work [64], take less time off work, and are more committed to their jobs [66].

Considering the foremost role of buildings in satisfying the need of comfort and protection, providing acceptable lighting control strategies for occupants is crucial [56]. According to Boyce et al. [28], fixed illuminance levels fails to satisfy occupants. Generally, occupancy-centered automated systems can lead to energy waste and occupants' discomfort by ignoring occupants' preferences [67]. Failure in responding to occupants' need of comfort, however, can impact both their health and work productivity [68,69].

2.2. Occupants' interaction with lighting systems in office settings

Understanding and improving occupants' lighting choices by implementing various lighting control systems have the potential to enhance energy efficiency in buildings [41,70,71]. Fabi et al. [47] and Stazi et al. [48] in their literature reviews classified the factors that influence occupants' lighting choices in buildings into the seven following groups: (1) environmental factors such as illuminance levels, interior temperature, and acoustics, (2) time-related factors such as time of arrival and departure, (3) contextual factors such as orientation, size, and view of windows, lighting type, and lighting controls, (4) physiological factors such as age, gender, and health, (5) psychological factors such as environmental concerns and personality traits, (6) social factors such as interaction with co-workers, and (7) other random factors. For example, occupants can be less interested in artificial lighting when the exterior illuminance level is exceeding a particular amount [28]. Occupants typically interact with artificial lighting switches when they arrive at their offices [72]. Another study showed that occupants are less likely to change the light setting once it is set to a level [73]. Moreover, by studying the influence of default lighting settings on occupants' behavior, Heydarian et al. [68] showed that when occupants are provided with natural lighting, they tend to keep the lighting setting.

The role of personality traits, among the seven aforementioned factors, is also significant. Research on residential sector has shown that there is a substantial potential to minimize energy consumption by analyzing the occupants' responses' to promoting energy efficient behaviors based on personality traits [74]. Since personality is the main driver of occupants' judgements, values, and perspective, it is expected that differences in individuals' personality can impact their environmental behavior [75]. Research about the composition of personality traits proposes five main personality dimensions as a model called The Big Five Inventory (BFI) model [76–79]. The five personality dimensions are neuroticism, agreeableness, conscientiousness, openness to experience and extraversion [75]. For example, a study showed that extraverted individuals had higher environmental concerns, while conscientious individuals had lower environmental concerns [80]. This model is extensively used for analyzing the relationships between work environment behaviors and personality traits and consequences such as job satisfaction, working motives, and organizational commitment [81].

Former studies, have investigated the influence of design features on occupants' preference and use of natural light, such as the size of the windows [82,83], shader placements and building orientation [30,84]. Consequently, developing an efficient control system is only possible by investigating occupants' behavior, features of blinds and lighting systems, and building geometry to increase user satisfaction and improve energy consumption [72,85]. Previous research has also explored lighting control preference of the occupants when they are provided with different lighting options [30,41,86–89]. For example, Galasiu and Veitch [41] showed that if occupants have a degree of manual control over lighting and shading in an office environment, they prefer natural lighting and an outdoor view. Other studies have shown that occupants hardly interact with manual blinds and if they do it is mostly to avoid glare [90–92]. In case there is no inconvenience, blinds and lighting usually stay in the same state [93]. This condition commonly increases building energy consumption and obstructs the outdoor view [93].

2.3. Occupants' lighting satisfaction and comfort in office settings

Carter, Slater, and Moore [94], showed that occupants are more satisfied with conventional manually controllable lighting systems, which do not even fit into the lighting standards than fully automated daylight responsive systems. Likewise, occupants rather set the light level themselves than to adapt to a light level, even if it meets the standards [95]. Satisfaction with the lighting choices is not the only advantage of availability of personal control [96]. Previous research has shown that having control over the lighting of work plane can also impact environmental satisfaction [97–99], perceived lighting quality [65,100], concentration and motivation [61,65], and indirectly improve the productivity of occupants [65,101].

In a fieldwork, Tamas, Ouf, and O'Brien [102] studied the effect of perceived control on occupants' comfort and their position on building automation. The results of their study denoted a moderate positive correlation between occupants' comfort and the level of perceived control on building systems. In another study, occupants' manner of interaction with building systems, which offered different levels of accessibility and four different levels of control from fully manual to fully automated were analyzed [103]. This study found higher comfort rates with the semi-automated systems that allowed the occupants to override the automation compared to the full automated system. Moreover, the results of this study revealed a relationship between the level of perceived control and acceptability of a broader range of lighting conditions.

A recent study by Kwon et al. [33] explored occupants' satisfaction in relation to the degree of control over the building systems in office settings. The results revealed that granting more control over the lighting and thermal systems to the occupants, increased their environmental satisfaction. This study connected visual comfort and satisfaction of the occupants to direct individual control over the lighting and shading. Other findings of this study suggest that having no control over the building systems in general is more acceptable to the occupants than not being able to operate an available control system. However, for visual comfort, having no control over the lighting systems made them more dissatisfied than not being allowed to operate the available systems. Furthermore, authors asserted that the influence of personal control on satisfaction is low with optimized but automated systems.

Vischer and Wifi [40] derived a list of environmental factors from practicable comfort studies that can affect task performance. Illumination and daylighting are among the main factors of this list since if they are appropriately provided for each task, they can result in occupants' comfort. However, only office occupants themselves can judge the lighting level as professionals of each task. Therefore, to achieve comfort occupants need adaptable work environments in which adjustable lighting systems are essential [40]. Illuminance level on the work plane is one of the main factors associated with lighting satisfaction in an office setting [104]. The average recommended illuminance level for offices in North America and Europe is between 300 and 500 lx on the work plane [104]. However, building occupants have different lighting preferences [96]. In a study, Boyce et al. [65], by providing a fixed illuminance level in an office setting, indicated that any fixed value can only lie within 100 lx of 45% of occupants' preference at best.

2.4. IVEs as a tool for studying occupants' behavior

Observational and experimental studies that analyze occupants' behavior in buildings are extremely susceptible to experimental noises originating from inconsistent design and environmental features [68]. In this light, immersive virtual environments are advantageous tools in data collection about users' behavior. A study by Kuliga, Thrash, Dalton, and Holscher [105] suggests that virtual environments allow us to systematically manipulate the setting according to our desire. This is a feature that cannot be easily achieved in real-world settings. Virtual environments enable designing any type of environment and provide the opportunity to assess the influence of certain variables by keeping the others constant [68,87,106]. Moreover, they allow integrating different simulations into the designed immersive virtual environment [106].

Heydarian et al. [107] designed a benchmarking experiment in immersive virtual reality to explore occupants' daily behavior, particularly in relation to lighting-related preferences in a single occupancy office environment. The results of the comparison with real environment indicated that the participants had a strong sense of presence in virtual environment, and they behaved similarly in both environments. Consequently, they suggested that immersive virtual environments are useful instruments for acquiring information about users' preferences, behavior, and performance. This finding is also in accordance with the results from its previous studies that virtual environments are reliable representations of real-world settings [108–111]. Research in this area has discovered no significant difference between participants' performance, immersion, and sense of presence between immersive virtual environments and real-world environments [69]. Accordingly, in addition to providing more control over the variables, these environments can considerably lower the costs of the experiments and cover for experimental incompetency [112,113].

In lighting research, a study on perceptual accuracy for daylit spaces, found positive outcomes for adequacy of IVEs in providing a real environment experience [114]. The findings of this study are highly promising for employing IVEs in lighting design and research as a tool to experience and to assess luminous conditions in interior spaces. As IVEs are being validated and putting into work in wider range of fields day by day, various studies try to evaluate their usability and acceptance. Although IVEs, have been validated for behavioral studies, there is still a literature gap in subjects' attitude towards using IVEs in such studies.

Conducting research in actual office environments is essential for effectively understanding the influence of personal control options on occupants' lighting choices [115]. Yet, having full control over different variables during the experiment is challenging and sometimes not even possible [87]. Many factors such as weather condition and different design features can impact the results [87]. Accordingly, employing immersive virtual environments for such studies are advantageous. Using IVEs, gives the researchers the opportunity to better investigate the variable of interest by keeping other variables constant [106]. Moreover, technology advancement nowadays has made virtual environment devices more accessible and user-friendly, which works in favor of using IVEs for research purposes.

3. Research methodology

3.1. Experiment settings

An experiment was designed to replicate a single occupancy office in an IVE. The virtual office space was designed to be similar to an existing single occupancy educational office setting in Bilkent University, Turkey. The experiment represented three different lighting settings, which provided different degrees of control for lighting arrangement, for the same virtual office setting: (a) conventional ceiling fluorescent lamps with manual turn on switches and manually adjustable blinds, (b) automated integrated natural and artificial lighting setting, which regulates the illuminance level according to the available daylight, and (c) an interactive lighting setting, which allowed the occupants to make a choice about the lighting type but kept the illumination level at a certain amount for energy efficiency reasons. Table 1 shows the lighting system and the control level for each scenario. In this context, the following hypotheses are proposed:

H1. The lighting choices of the participants with the interactive lighting system is significantly different from their lighting choices with the conventional lighting system.

H2. There is a statistically significant association between the availability of a degree of control over the lighting system and participants' satisfaction.

H3. There is a statistically significant association between the availability of a degree of control over the lighting system and participants' performance.

H4. The participants' personality trait affects their lighting choices.

H5. Participants perceive immersive virtual environment technology as a useful tool for serious tasks.

The experiment only authorized changing the variables of interest, simulated daylighting and electrical lighting, to minimize any undesired effect on the results. The window in the virtual office setting was facing South the same as the physical office. To avoid any disturbance on account of the time of day, the virtual environment represented the location of the sun for March 1, 09:00 a.m. in Ankara, Turkey. Also, the experiments were conducted consistently between 09:00 a.m. to 02:00 p.m. from July 2020 to August 2020 to avoid bias and preserve objectivity.

Additionally, to prevent participants from making choices under the influence of having a view, the view was replaced with a blue sky. Previous research has demonstrated that an outside view has a significant impact on the occupants' interactions with the shading systems [116–118]. Before starting the experimental procedure, participants were informed that there is no view outside the windows.

Table 1
Experiment scenarios.

Experiment:	Scenario I	Scenario II	Scenario III
Lighting system:	Conventional lighting (Control group)	Daylight responsive lighting	Interactive lighting
Control level:	Full control	No control Full automation	Semi-controlled
	No automation		Semi-automation

3.2. Experimental setup

The primary office model, composed of walls, floor, ceiling, and windows, was designed in Revit. It was then imported to 3ds Max to improve the space by adding furniture to the office room. Material textures were rendered by V-Ray Next in 3Ds Max environment. The final modifications for interior features and all lighting setup were applied using Unity. To measure the light levels and have more of a natural representation of light, Unity's High-Definition Render Pipeline was used. HDRP is the only available Unity renderer that uses physical light values. Fig. 1 shows the virtual office model.

The virtual model of the office setting was also imported into DIALux Evo to calculate the light level on the work plane to ensure that light levels in the IVE match the light values in a corresponding physical environment. First, the light level was calculated for natural light only at 09:00 a.m. for a clear sky. Then, artificial light levels were calculated for each condition. Finally, the average light levels for the work plane were set according to light values obtained from DIALux Evo.

3.3. Experimental procedure

The experiment took place in a virtual reality lab, equipped as an office setting in the same building as the original model of the virtual office. Before launching the main experiment, a pilot study was conducted to ensure that the setup worked as intended, and to detect any unforeseeable complications in collecting the participants' data. Accordingly, the virtual office setting, the user interface, and the questionnaires were modified. Prior to initiating the experiment, the research and the protocols were approved by Institutional Ethical Review Board.

3.4. Sample and setting

This study recruited a total number of 30 participants (18 females and 12 males). The participants were aged between 22 and 36 years old, with 63.3% of them aged between 25 and 28. Of all of the participants 36.7% were students in the Graduate School of Economics and Social Sciences, 56.7% were students in the Graduate School of Engineering and Science, and 6.7% were Graduate School of Education. Of these participants 66.7% of them were master's students and 33.3% were PhD students at Bilkent University.

The experiment consisted of three scenarios, each of which demonstrated one of the lighting systems. All the participants were asked to take part in all three scenarios. To minimize the learning effect, participants performed each scenario individually, with an interval of at least two days. Additionally, participants were assigned to attend the scenarios in a random order, which means they did not necessarily start

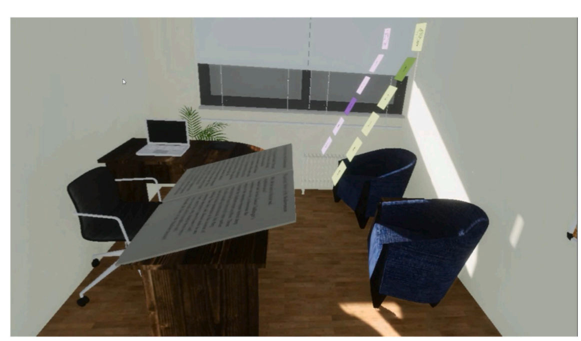

Fig. 1. The virtual office model. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the experiment with the first scenario, ending it with the third one.

All scenarios start in an initially dark condition. The scenarios I and III provided various lighting levels for the participants to choose from to meet their comfort to perform the reading task. In the scenario I, there were five modes for the blinds from 1 as fully closed to 5 as fully open, with three levels in between, and five modes for the artificial lights, from 1 as fully dim to 5 as fully bright with three dimming levels in between, making a total of 25 modes. This setting gave the participants complete authority to adjust the lighting level by either adjusting the blinds or choosing a level on artificial lights or selecting a combination of both. In scenarios II and III the system automatically opened the blinds halfway after 3 s. The lighting condition was completely unchangeable by the participants. However, in scenario III, there were also five modes for each of the natural and artificial lighting, making a total of 7 modes. However, the lighting setting interactively responded to the lighting choices of the occupants to save energy by restricting their choices. Fig. 2 illustrates the operation logic diagram of the interactive lighting system in scenario III. Table 2 shows the 25 average lux values on the work plane in each possible lighting arrangement. The highlighted cells represent the 7 average lux values in scenario III, and the value underlined in the first column, third row represents the average lux value in the automated condition. Fig. 3 shows the visual representation of the virtual office in each lighting mode.

3.5. Instruments and data collection

Prior to starting the experiment, the participants were briefed about it. Then, they performed a trial test to make sure they do not experience any motion sickness and to get familiar with the virtual environment. The duration of the experiment for each scenario was about 20 min. Those participants who wished to proceed after the test were asked to sign a consent form.

The experiment is comprised of three different lighting scenarios. In scenario I and III, the participants were asked to interact with the lighting system and adjust the lighting to the level that suits them best for performing a reading task. In scenario II, the lighting system automatically set the lighting and participants had no role in adjusting the light. Therefore, they could start with performing the reading task. The data collection involved an experiment and different questionnaires. The lighting choices of each participant in scenarios I and III were recorded. The participants were asked to answer a set of questionnaires after each scenario. Additionally, they assessed their cognitive load score with NASA Task Load Index (TLX). Fig. 4 shows the participants during the experiment with the IVE.

Table 2
Average lux values on the work plane in each possible lighting arrangement.

Artificial Natural	1	2	3	4	5
1	50 lx	320 lx	620 lx	900 lx	1200 lx
2	250 lx	530 lx	840 lx	1120 lx	1440 lx
3	500 lx	780 lx	1070 lx	1360 lx	1660 lx
4	850 lx	1150 lx	1440 lx	1730 lx	2050 lx
5	1300 lx	1580 lx	1900 lx	2140 lx	2460 lx

3.5.1. Experiment used for the virtual environment

The main equipment for conducting this study was a computer workstation and a complete set of virtual reality instruments. The computer used for launching the model and implementing the virtual environment was a Microsoft© Windows workstation with Radeon RX 580 graphics card. The virtual reality instruments included an HTC Vive Pro Head-Mounted Display, a Vive controller, and two SteamVR base stations. Fig. 5 shows the user interface for adjusting the lighting level within the IVE for performing the reading task.

3.5.2. Reading task

Previous research has shown that reading and comprehension tasks are significantly affected by illumination [119,120]. A reading task is not only a common obligation for an office environment, but it is also compatible with virtual environments. The participants were assigned to read a short passage in each experiment scenario. The passages were different in each scenario; however, they were about similar general topics. Topics were selected unrelated to the sample's academic background to avoid any prejudice. Each passage was a standard English text with approximately 185 words and average Flesch readability score of 45. This readability measure uses word length and sentence length to calculate a score between 0 and 100, such that higher scores indicate

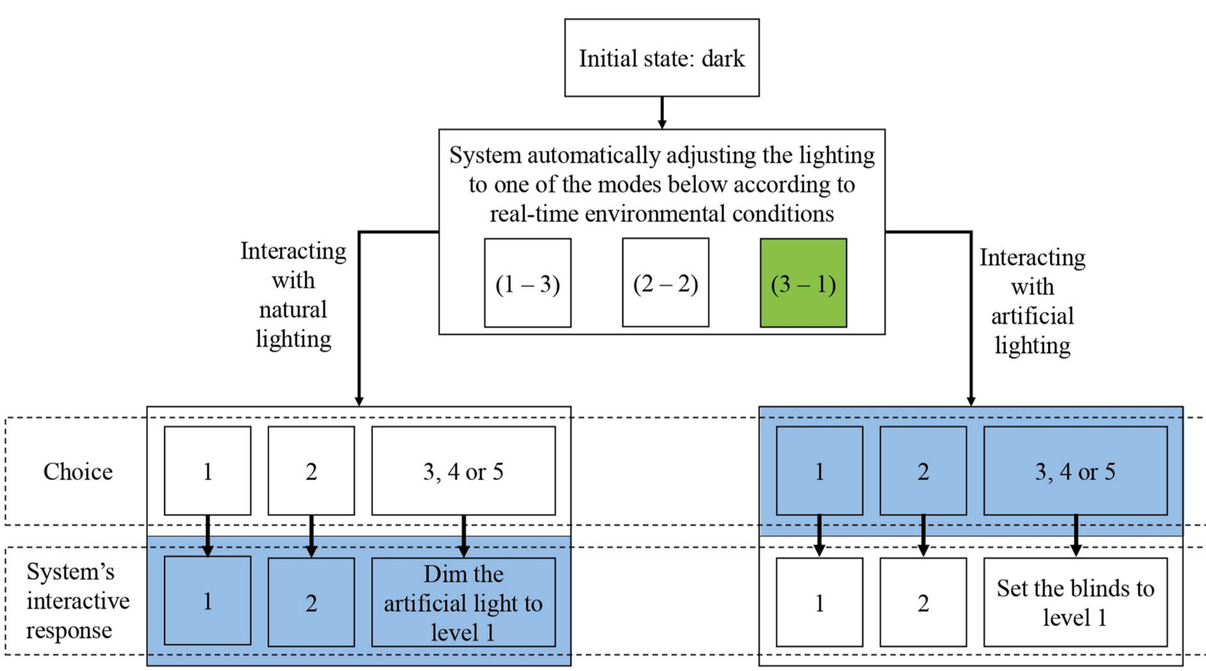

Fig. 2. The operation logic diagram of the interactive lighting system in scenario III. The green box represents the automatic lighting setup in the experiment. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

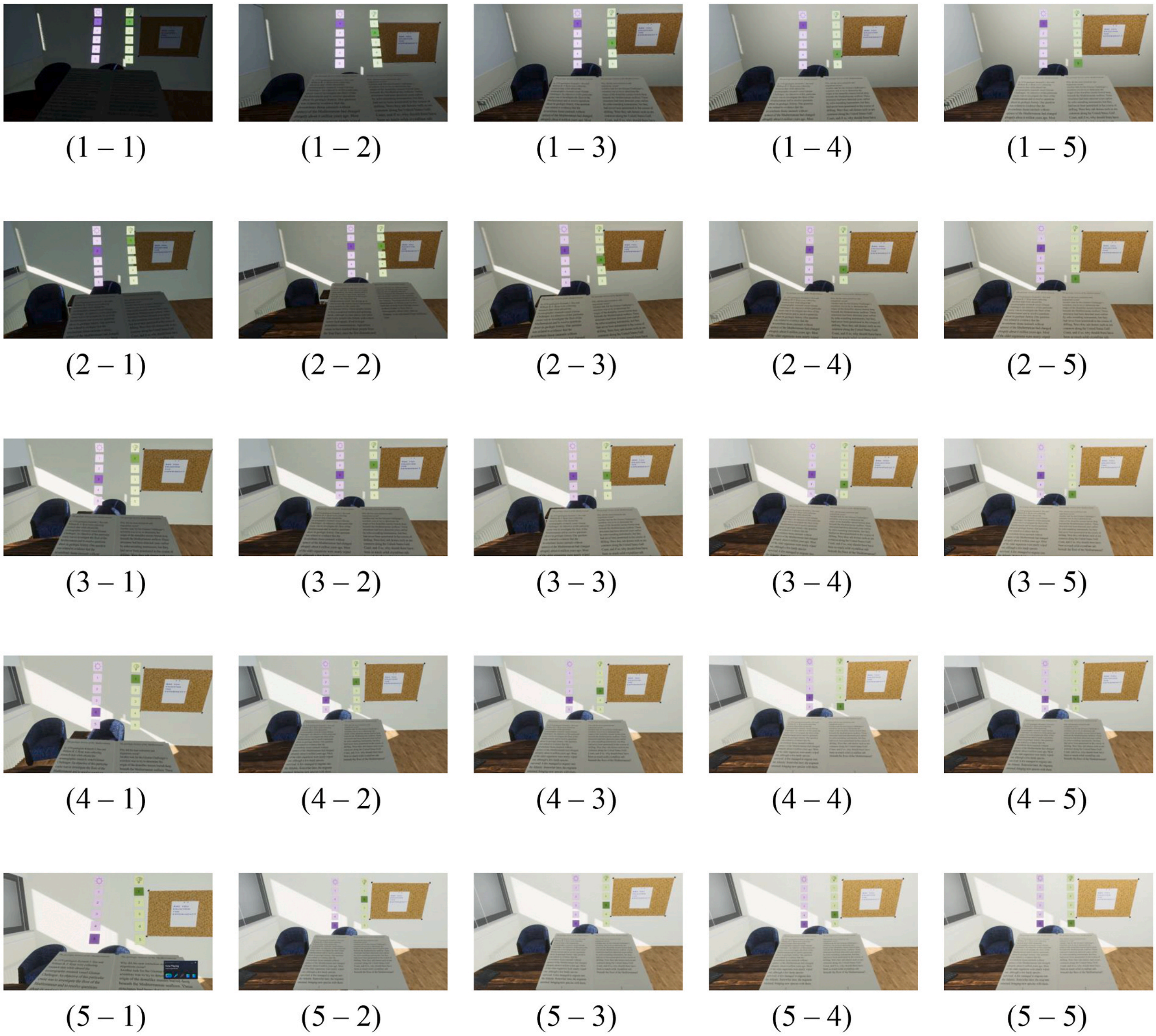

Fig. 3. The visual representation of the virtual office in each lighting mode. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

more ease of readability [121]. To assess the cognitive load in each scenario, the participants needed to read the text in 3 min and then answer a multiple-choice question about it.

3.5.3. *Cognitive load measurement*

Considering the type of task and the intention to analyze the effect of level of control over lighting and lighting quality on the cognitive load of the participants, NASA TLX [122] was used. NASA Task Load Index (TLX) is one of the most popular subjective measurements of cognitive load. NASA TLX has a multidimensional structure to present a comprehensive workload score, which relies on weighted average values on six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level [122]. A previous research has validated a simulation workload measure, which for the most part has also adapted NASA TLX. This study uses 4 out of 6 subscales of NASA TLX in their measurement which are mental demand, physical demand, temporal demand, and frustration level along with other scales. In the present study, the participants were asked to complete an adapted version of NASA TLX after each scenario as a subjective measurement of weighted workload (WWL) for performing the task. NASA TLX was adapted for this study by eliminating two factors of mental and physical demand, which were unrelated to the experimental context, and focusing on the subscales that satisfied the aims of this study more.

3.5.4. *Questionnaires*

Before starting the experiment, participants answered questions about their personal information such as age, gender, and education. After taking part in each scenario, participants filled out an adapted version of the Office Lighting Survey (OLS) by Eklund and Boyce [123]. The adapted version of the questionnaire consists of 9 questions about visual comfort, general light distribution, and rating the lighting for the task scenario. The first 7 questions followed an agree-disagree format, question 8 had a 3-point Likert Scale, and the last question had a 6-point Likert Scale format. The Likert Scale is a set of statements proposed for a real or hypothetical situation under study, using which participants can demonstrate to what extent they agree with a given statement [124].

After completing the third part of the experiment, participants filled out two additional sets of questionnaires: a TAM questionnaire and the Big Five Inventory (BFI) [125,126] for assessing the personality traits. The aim of TAM introduced by Davis [127] in its initial version, is to clarify the key factors of acceptance for computing technologies while justifying end-user behaviors in an economic and well-founded way [128]. TAM describes the process through which the external properties of a system influence end-user's attitudes and perceptions causing the actual usage of the system according to the theory of reasoned action [129]. The version of TAM employed in this study has four components: perceived usefulness (PU), perceived ease of use (PEU), intention to use

Fig. 4. Participants during the experiment with the IVE. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 5. User interface for adjusting the lighting level within the IVE. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(IU), and perceived enjoyment (PE). The TAM questionnaire aimed to evaluate the perceived usefulness, ease of use, and enjoyment of the participants during the use of the IVE technology, in addition to their intention to use it again in the future. Moreover, the BFI was employed to seek for potential relations between the participants' personality traits and their attitude towards various lighting control systems and lighting choices in different scenarios. Accordingly, the original version of the questionnaire was used, which consists of 44 questions on a five-point Likert Scale from strongly disagree to strongly agree.

4. Results

4.1. Lighting control systems' scenarios

To explore the effect of having different levels of control on lighting system in the virtual office setting, various comparisons were made between scenarios. First, the participants' lighting choices in different scenarios were assessed. The first hypothesis (H1) was 'the lighting choices of the participants with the interactive lighting system is significantly different from their lighting choices with the conventional lighting system'. Since the data was not normally distributed, non-parametric analyses were implemented to find the results. To verify the sample size, a statistical power analysis was performed for Friedman test as the main analysis of the study, using G-Power software. The results determined that a sample of 28 participants would be sufficient with a statistical power equal to 0.95. The Friedman test, the counterpart of two-way ANOVA, is an approach to explore differences between group classifications caused by independent variable [130]. Following the hypothesis, a Friedman test showed that the participants' lighting choices were significantly different from one another in the three scenarios ($p < 0.001$). To determine the differences, a Wilcoxon signed-rank test was run with applying the Bonferroni correction ($\alpha = 0.017$). The Wilcoxon signed-rank test is a non-parametric one-sample test that in a matched pair context examines the equivalence of the probability distribution between samples [131]. Confirming the hypothesis (H1), the results showed that the lighting choices of the participants in scenario III (interactive lighting system) were significantly different from their lighting choices in scenario I (conventional lighting system) ($z = -3.748$, $p < 0.001$). Table 3 summarizes the participants' choices in scenarios I and III. As the table shows, more participants tend to use natural lighting when they had a degree of control over an optimized interactive lighting system. In scenario III, initially, all the participants attempted to change the default lighting setting. However, in the course of the experiment 16.7% of the participants ($n = 5$) chose the default setting as their final decision.

To evaluate H2, a Friedman test revealed that the participants' satisfaction with lighting conditions in all scenarios was significantly different from each other ($p < 0.001$). To identify the differences, a Wilcoxon signed-rank test was applied with the Bonferroni correction ($\alpha = 0.017$). The test results demonstrated that the participants' satisfaction with the lighting was significantly different in scenario II comparing

Table 3
Frequency of participants' lighting choices in scenarios I and III.

	Scenario I		Scenario III	
	Frequency	Percent	Frequency	Percent
Natural lighting	7	23.3	19	63.3
Artificial lighting	1	3.3	9	30
Combination of both	22	73.3	2	6.7
Total	30	100.0	30	100.0

to scenario I ($z = -4.077$, $p < 0.001$). Also, the participants' satisfaction with the lighting was significantly different in scenario II comparing and scenario III ($z = -2.988$, $p = 0.003$). Comparing the mean satisfaction scores, participants were less satisfied with the lighting condition in scenario II (Fig. 6). However, the Wilcoxon signed-rank test with the Bonferroni correction ($\alpha = 0.017$) showed no significant difference between the participants' satisfaction with lighting conditions in scenarios I and III ($z = -2.080$, $p = 0.038$). As a result, H2 stating that 'there is a statistically significant association between the availability of a degree of control over the lighting system and participants' satisfaction' was affirmed. To gain a more distinct understanding of participants' satisfaction in each scenario the descriptive statistic values (mean, standard deviation (SD), minimum, and maximum) of their satisfaction scores was obtained. Table 4 shows the information about the participants' satisfaction scores.

Finally, the participants' cognitive loads in performing the reading task in different scenarios were explored. The hypothesis (H3) was 'there is a statistically significant association between the availability of a degree of control over the lighting system and participants' cognitive performance'. A Friedman test demonstrated that the participants cognitive load in all 3 scenarios were significantly different from each other ($p < 0.001$). In investigating the differences, a Wilcoxon signed-rank test with the Bonferroni correction ($\alpha = 0.017$) confirmed that the participants' cognitive load in performing the task in scenario II was significantly different from their cognitive load in scenario I ($z = -3.117$, $p = 0.002$). Similarly, the participants' cognitive load in performing the task in scenario II was significantly different from their cognitive load in scenario III ($z = -2.733$, $p = 0.006$). Participants' cognitive load was higher in scenario II compared to both scenarios I and III. Additionally, a Wilcoxon signed-rank test with the Bonferroni correction ($\alpha = 0.017$) showed that there was no significant difference between the participants' cognitive load in scenario III comparing to scenario I ($z = -1.334$, $p = 0.182$). The results supported the hypothesis (H3). Table 5 summarizes the average cognitive load values in each scenario.

Table 4
Participants' satisfaction scores.

	Lighting condition satisfaction score			
	Mean	SD	Min	Max
Scenario I	9.33	1.03	6	10
Scenario II	6.97	2.14	4	10
Scenario III	8.73	1.41	5	10

Table 5
The average cognitive load values in each scenario.

Scenarios	WWL Scores	
	Mean	SD
Scenario I	4.20	1.81
Scenario II	5.60	1.79
Scenario III	4.57	1.85

4.2. Personality traits and lighting choices

The lighting choices of the participants in scenarios I and III were analyzed in relation to the big five personality traits of the participants. Since the sample was small and the data was not normally distributed and each variable had multiple levels, it was not possible to reach any significant results. Therefore, no specific correlation between the participants personality traits and their lighting choices was found. However, through recoding the data, a few conclusions were drawn using scatter plot graphs and crosstabulation (Figs. 7 and 8). It was shown that participants who were open to experiences had a wider range of choices in both scenarios I and III. Participants with extravert personality tended to choose a combination of both natural and artificial lighting in scenario I. They chose to have natural lighting in scenario III. Participants with conscientious personality, mostly, chose a combination of both natural and artificial lighting in scenario I. Finally, in scenario III participants with high scores at agreeableness and conscientiousness were inclined towards natural lighting. Although the results were not conclusive, it can be said that the hypothesis 'the participants' personality trait affects their lighting choices' (H4) is consistent. Tables 6 and 7 summarize the frequencies of choices by different personalities in each scenario.

4.3. Technology acceptance model (TAM)

To analyze the virtual reality technology acceptance questionnaire, first, the reliability of the gathered data for consistency was investigated. Nunnally [132] suggests that the attained Cronbach's alpha value should be higher than 0.7 to be an indicator of internal consistency. A

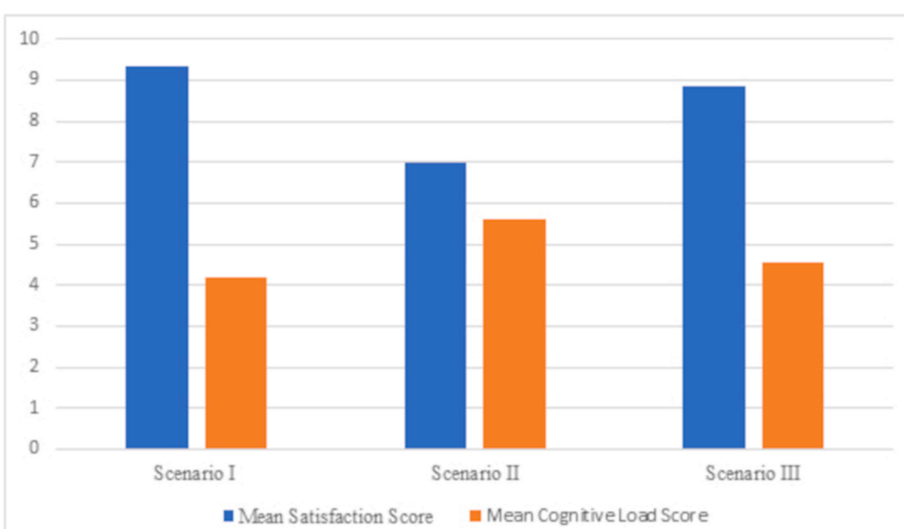

Fig. 6. Mean satisfaction scores and mean cognitive load scores in all 3 scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

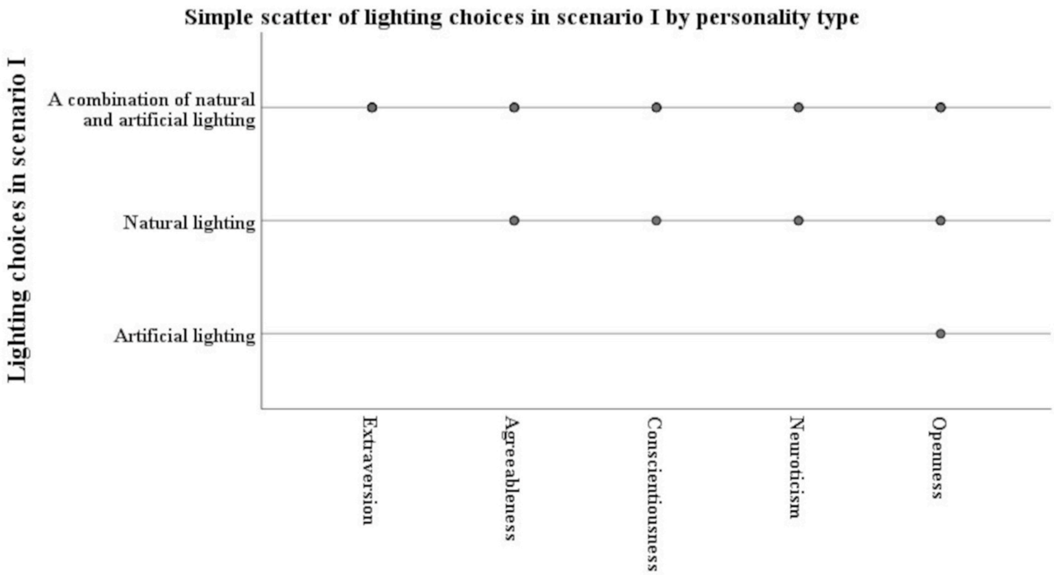

Fig. 7. Scatter plot of lighting choices in scenario I by personality type.

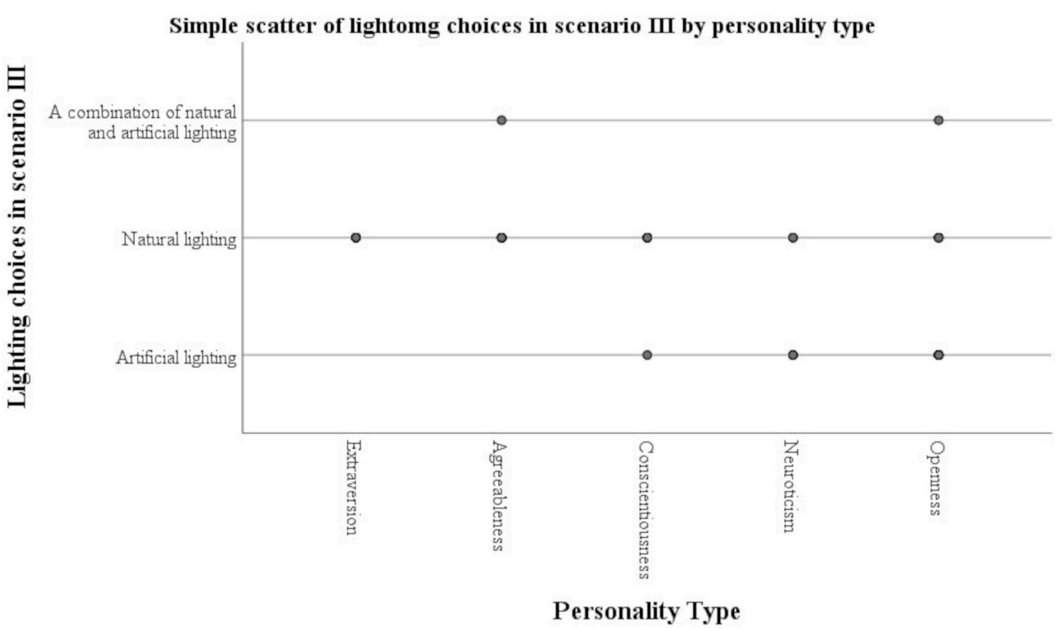

Fig. 8. Scatter plot of lighting choices in scenario III by personality type.

Table 6
Frequencies of choices by different personalities in scenario I.

	Personality type frequency					
	Extraversion	Agreeableness	Conscientiousness	Neuroticism	Openness	Total
Artificial lighting	0	0	0	0	1	1
Natural lighting	0	2	1	2	2	7
A combination of natural and artificial lighting	5	4	4	3	6	22
Total	5	6	5	5	9	30

Cronbach's alpha test was performed for each of the four categories to understand if the gathered data were reliable. Table 8 summarizes the Cronbach's alpha values for each category.

Then, hypothesis 5 (H5), 'participants perceive IVE technology as a useful tool for serious tasks', was tested. Comparing the mean values of the components of the TAM questionnaire shows that the participants enjoyed their experience with the virtual reality technology rather than considering it as a useful device they intend to employ for other

Table 7
Frequencies of choices by different personalities in scenario III.

	Personality type frequency					
	Extraversion	Agreeableness	Conscientiousness	Neuroticism	Openness	Total
Artificial lighting	0	0	1	3	5	9
Natural lighting	5	5	4	2	3	19
A combination of natural and artificial lighting	0	1	0	0	1	2
Total	5	6	5	5	9	30

Table 8
Cronbach's alpha values for each category.

TAM Categories	Cronbach's Alpha Values
PU	0.916
PEU	0.815
IU	0.786
PE	0.865

purposes. The lower mean scores for the PU (mean = 3.19) indicate that, overall, the participants potentially did not perceive the VR technology as a tool for performing serious tasks. Moreover, generally, the participants reviewed VR as a technology that is quite easy to use. Accordingly, hypothesis 5 (H5) was rejected. Table 9 summarizes the information of the rated values for each category of the TAM.

Four components of TAM were also analyzed for correlation. Since the data were not normally distributed, Spearman's Rho as a suitable non-parametric test for association was implemented. The results indicated that there was moderate positive correlation between 'perceived usefulness' and 'intention to use' of TAM components ($r = 0.627$, $p < 0.001$). 'Perceived usefulness' has also found to have a low positive correlation with 'perceived enjoyment' ($r = 0.357$, $p = 0.026$). Additionally, there was a low positive correlation between 'perceived ease of use' and 'intention to use' ($r = 0.332$, $p = 0.37$). Finally, the analyses revealed a moderate positive correlation between 'perceived enjoyment' and 'intention to use' ($r = 0.695$, $p < 0.001$). Fig. 9-12 illustrate the relationship between the correlated components.

5. Discussion, limitations and future work

The results indicated that the participants were more likely to choose to have natural lighting over artificial lighting when interacting with more energy efficient lighting systems, which gives them a perception of control. This state happened in a condition that participants maintained their satisfaction with the lighting system comparing to the circumstances where they had full control over a conventional lighting system and no significant increase in their WWL score was revealed. Additionally, the data gathered with OLS in three scenarios demonstrated that the participants were significantly less satisfied with fully automated lighting systems in contrast to manually controllable systems or semi-automated interactive lighting systems. These findings are aligned with the literature suggesting that having no control over the building systems fails to satisfy occupants [27,40,41,59]. Overall, the assessments suggested that the participants were equally satisfied with semi-automated lighting systems, which gave them a perception of control over the lighting comparing to conventional lighting systems, which provided them with full control. Comparing the participants' task performance through their WWL scores in different scenarios showed that the participants underwent a higher cognitive load when they performed a task with fully automated lighting system compared to the conditions where they had full control or a perception of control over the lighting system. This is in contrast with a previous research, which showed that having the option to control the lighting had no effect on task performance by participants [70]. However, the research stated that it made the tasks seem less difficult [70]. The justification behind the conflicting finding could be unavailability of natural light in the previous study, different ranges of lighting level in two studies. Natural lighting could have played a more significant role in this study considering that the participants chose natural lighting over artificial lighting in the interactive lighting scenario. Moreover, the participants expressed the same level of cognitive load for performing the tasks in both interactive lighting scenario and conventional lighting scenario.

Table 9
Mean scores of for each category of the TAM.

TAM Categories	Mean	SD
PU	3.19	0.95
PEU	3.68	0.80
IU	3.55	0.91
PE	4.25	0.68

Analyses of the personality traits showed that in both scenarios I and III the participants who scored high on openness had a wide range of lighting choices regardless of having different degrees of control over lighting. In case of having full control, participants with bold extraversion dimension mostly chose a combination of both natural and artificial lighting. In a study, Heydarian et al. [69] showed that extraverts are more inclined to have all shades and electric lights open simultaneously when they were given control over lighting. However, in this study, with interactive lighting system that limited they choices, they mostly preferred natural lighting. Conscientious participants chose to have a combination of natural and artificial lighting when they had full control over the lighting. On the other hand, in the interactive lighting system scenario, they mostly chose to have natural lighting. The rationale of more participants choosing natural lighting, could be because of their restricted lighting options. The limited options that the interactive lighting system offered the participants maintained their perception of control, while inducing them to choose natural lighting.

Finally, evaluating the technology acceptance by the participants showed that the participants had more of an enjoyable experience with VR in this study rather than considering virtual reality a useful tool for performing serious tasks. One reason could be that maybe the participants were still interested in conventional and tradition ways for performing their tasks. Furthermore, correlation analyses between the TAM components suggested that intention to use virtual reality technology by the participants was positively related with perceived enjoyment and perceived usefulness. Perceived enjoyment was mildly and positively associated with perceived usefulness. Analogously, a weak association showed increases in perceived ease of use values led to increases in intention to use the virtual reality technology. A part of the correlation findings also corresponded to former research about usability of virtual reality in design education that had discovered positive relationships between perceived usefulness with both perceived enjoyment and intention to use [133]. Furthermore, behavioral observations of the participants during the experiment signified that the participants had a strong perception of reality in the IVE. This is consistent with the previous research, which indicates that IVEs can provide an effective sense of presence and the participants show similar performance and behavior in IVEs as in physical environments [106,108,110,111]. Therefore, it can be noted that IVE was a valid instrument for assessing this study.

There were some limitations in conducting this study. First, the environmental factors and conditions were static and in favor of having

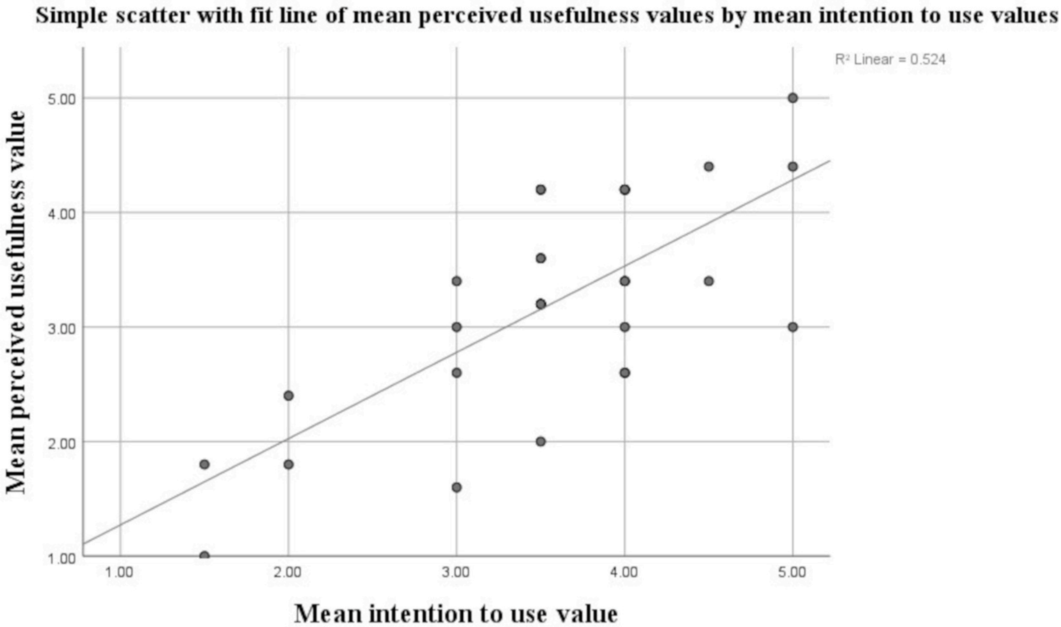

Fig. 9. Scatter plot of perceived usefulness values by intention to use values.

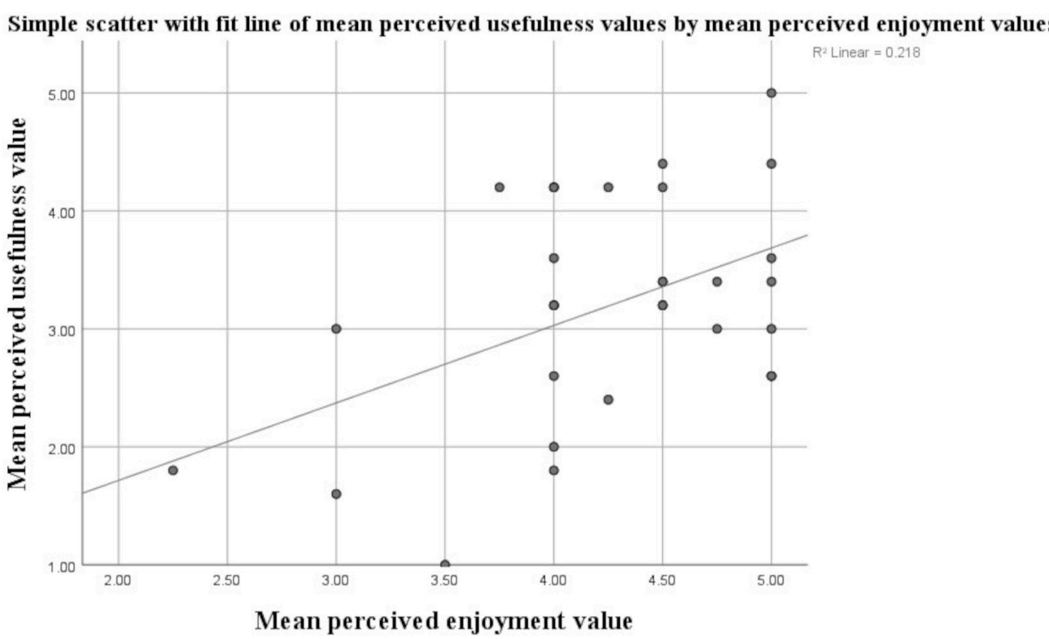

Fig. 10. Scatter plot of perceived usefulness values by perceived enjoyments values.

natural light throughout the experiment. Yet, in real environments, these factors can change and occupants' choices can alter accordingly. Occupants' attitudes and choices can also be different in different office types and during performing different types of tasks. Additionally, since this study was designed for virtual environments, the obtained average lux levels in the real work environments might result in different associations. Finally, due to the COVID-19 pandemic, the sample size was kept small, which resulted in constraints for data analysis. For example, the sample was not large enough to generate generalizable results about the effect of personality traits on lighting choices. Analyzing the effect of personality traits on lighting choices needs more comprehensive investigations in large sample sizes.

Future research could focus on implementing energy simulations to assess the energy performance of semi-automated systems. Further studies could also consider the mutual relationship between other visual comfort factors such as glare or thermal comfort factors, such as temperature, humidity, etc. Along lighting satisfaction.

6. Conclusion

This research attempted to understand the consequences of implementing automation or perception of control over lighting in occupants' aspect. The results of the research revealed that an energy efficient interactive lighting system that gave the participants a perception of control satisfied the participants in terms of lighting the same as a conventional lighting system that gave them full control. While performing a reading task with an interactive lighting system, participants reported a similar cognitive workload score as performing the same task

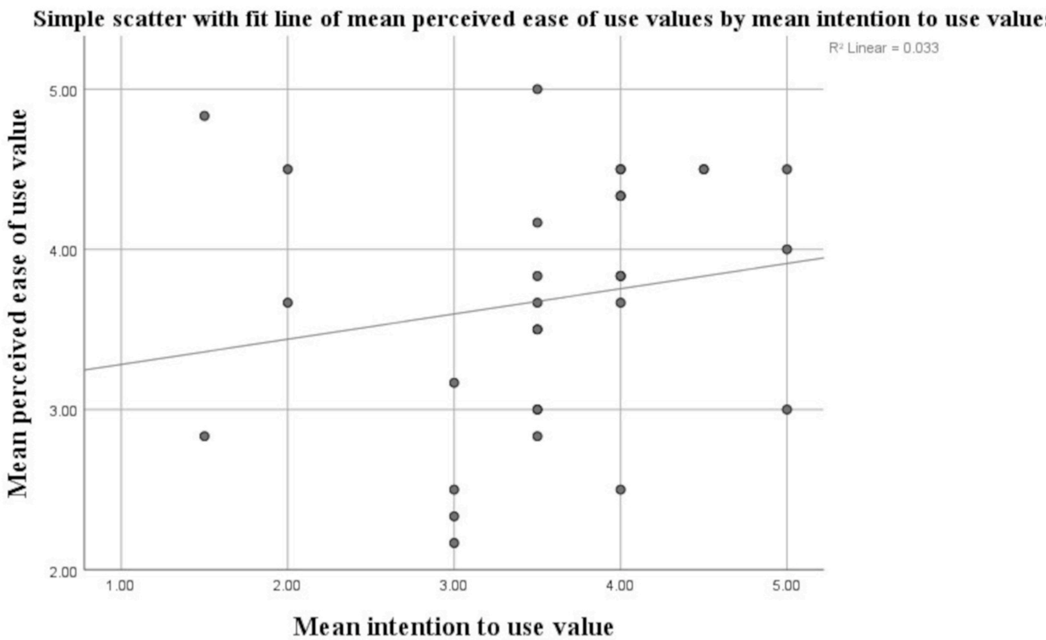

Fig. 11. Scatter plot of perceived ease of use values by perceived intention to use values.

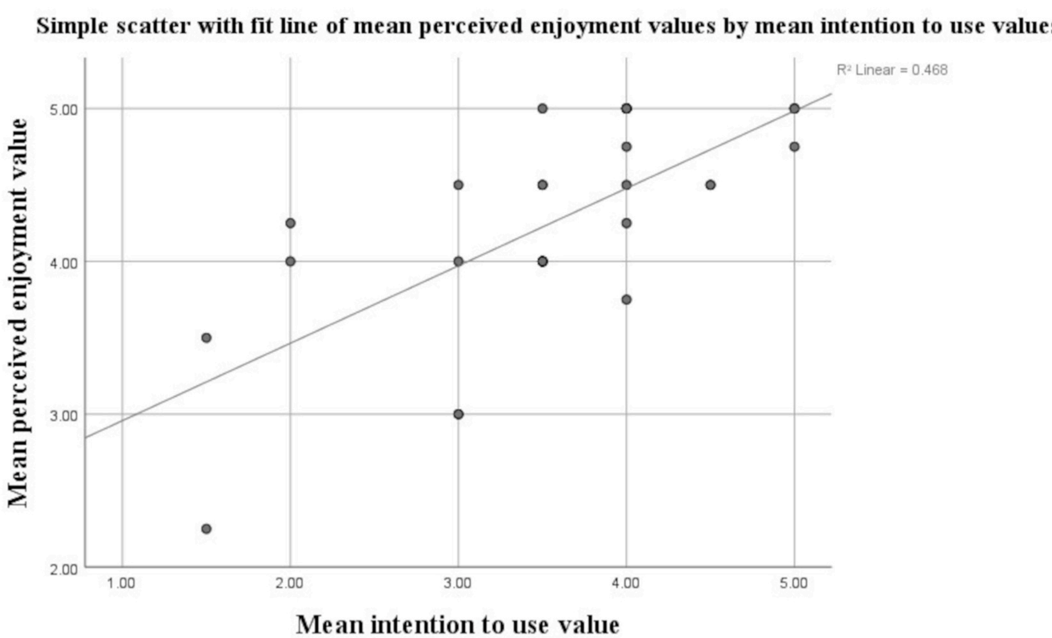

Fig. 12. Scatter plot of perceived enjoyment values by intention to use values.

with a conventional lighting system. Comparing these two systems in terms of lighting choices showed that the participants were more likely to choose to have natural lighting over artificial lighting when operating the interactive lighting system. However, findings suggested that the participants were significantly less satisfied with fully automated lighting system in contrast to conventional lighting system or interactive lighting system. Comparing the participants' cognitive loads in different scenarios indicated that the participants experienced a higher cognitive load when they performed a task with fully automated lighting system compared to the conditions where they had full control or a perception of control over the lighting system.

The findings of the personality analyses showed that the participants with a high score on openness had a wide range of lighting choices either with conventional or with interactive lighting. With conventional lighting, participants with bold extraversion dimension mostly chose a combination of both natural and artificial lighting. However, with interactive lighting system that limited they choices, they mostly preferred natural lighting. Conscientious participants chose to have a combination of natural and artificial lighting with conventional lighting system. On the other hand, with interactive lighting system, they mostly chose to have natural lighting. Obtaining the personality profiles of the occupants can be helpful for designing user-centered lighting systems that can meet the occupants' lighting preferences and detect the occupants who consume more energy [69].

Finally, this study showed that the participants considered VR a better fit to an enjoyable experience than a useful tool for performing serious tasks. Additionally, intention to use virtual reality technology by the participants was positively related with perceived enjoyment and perceived usefulness. Perceived enjoyment was found to be positively associated with perceived usefulness. Moreover, perceived ease of use was weakly yet positively associated with intention to use the virtual reality technology.

The significance of this study lies in demonstrating that satisfaction can be achieved by giving the occupants a perception of control over semi-automated energy-efficient building systems. This is in contrast with the previous studies suggesting that occupants are, generally, more satisfied with conventional manually controllable lighting systems [94]. Consequently, it may be critical to design building systems that allow the occupants to override their initial preferences and give them an adaptable level of energy-efficient control. The findings of this study, therefore, encourages researchers to further explore the psychological and physiological effects of control over the surrounding environment for developing new design regulations and improving user-centered design in the built environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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