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Impact of occupant autonomy on satisfaction and building energy efficiency

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ABSTRACT

The philosophy of building energy management is going through a paradigm change from traditional, often inefficient, user-controlled systems to one that is centrally automated with the aid of IoT-enabled technologies. In this context, occupants' perceived control and building automation may seem to be in conflict. The inquiry of this study is rooted in a proposition that while building automation and centralized control systems are assumed to provide indoor comfort and conserve energy use, limiting occupants' control over their work environment may result in dissatisfaction, and in turn decrease productivity. For assessing this hypothesis, data from the post-occupancy evaluation survey of a smart building in a university in Australia was used to analyze the relationships between perceived control, satisfaction, and perceived productivity. Using structural equation modeling, we have found a positive direct effect of occupants' perceived control on overall satisfaction with their working area. Meanwhile, perceived control exerts an influence on perceived productivity through satisfaction. Furthermore, a field experiment conducted in the same building revealed the potential impact that occupant controllability can have on energy saving. We changed the default light settings from automatic on-and-off to manual-on and automatic-off, letting occupants choose themselves whether to switch the light on or not. Interestingly, about half of the participants usually kept the lights off, preferring daylight in their rooms. This also resulted in a reduction in lighting electricity use by 17.8% without any upfront investment and major technical modification. These findings emphasize the important role of perceived control on occupant satisfaction and productivity, as well as on the energy-saving potential of the user-in-the-loop automation of buildings.

1. Introduction

Due to the high share of energy use in buildings, several attempts have been made to minimize building energy consumption. Occupants and their interaction with the building system have a significant impact on building energy performance [1]. As a result, more automated systems and less occupant control are often believed to reduce energy use for building operations [2]. One of the solutions is the use of automated building control systems, which aim to maintain the constant and predefined levels of comfort of occupants [3]. However, this solution may overlook occupants' preferences, and may not always be the most energy-efficient approach. Building automation and occupants' perceived control seem to be in conflict [2]. In fact, the relationship between occupant satisfaction and comfort is far beyond physical parameters [4]. Occupants are not only satisfied by comfort but also by other factors such as a sense of control over choosing the comfort level [5]. Several studies have confirmed the positive relationship between occupants' perceived control over their environment and satisfaction [3,6,7].

The key research question in this study is to understand the satisfyingly efficient ways of building energy management that satisfy multiple goals, particularly achieving reasonable energy efficiency as well as occupant satisfaction. The subsequent enquiry is whether a full automation strategy can enable these objectives or a compromise fuzzy approach, between 100% user-control and 100% automation, is more appropriate.

The impact of occupant control on their satisfaction needs more exploration [8], and studies on energy-saving potential of occupants' controllability are limited [6]. This paper aims to examine (1) the role of occupants' perceived control over building systems to determine whether and to what extent it influences satisfaction and perceived productivity, and (2) energy saving potential of giving occupants control over their environment. The innovation of this paper, from the research perspective, is that it relates occupants' satisfaction to their perceived control and shows that high levels of automation may weaken pro-environmental behaviors. We also show that the common expectation that automa-

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tion can always improve efficiency may be flawed and that automation should be used with care, taking into account such factors as human psychology when choosing the default settings. From the methodological perspective, the paper employs structural equation modeling to analyze a post-occupancy evaluation survey and test the influence of occupants' perceived control on satisfaction and productivity.

The paper continues as follows Section 2. focuses on literature review. In Section 3, methodology is described, followed by the field experiment in Section 4 Section 5. focuses on data analysis and results with further discussions in Section 6. Finally, the paper overviews its findings and points out the limitations.

2. Literature review

2.1. Indoor environmental quality, satisfaction, and productivity

A building is designed to provide comfort conditions for its occupants [9], and occupants' satisfaction with the building is associated with indoor environmental quality (IEQ) [10]. The main IEQ parameters include: thermal comfort, indoor air quality, visual comfort, and acoustic comfort [11,12]. Several studies confirmed the influence of IEQ factors on occupants' satisfaction [13,14]. Whereas poor IEQ can negatively affect occupants by causing discomfort and sick building syndrome [10]. In the context of the workplace, several studies confirmed that IEQ also plays a significant role in occupants' performance at work [9,13,15].

Besides, IEQ is also associated with the amount of energy consumption in buildings [12]. Thermal comfort is influenced by several environmental parameters, namely air temperature, air velocity, mean radiant temperature, and relative humidity [12]. Heating, ventilation, and air-conditioning systems (HVAC) are used to control these parameters in order to provide thermal comfort. As a result, HVAC accounts for a great share of energy use in non-residential buildings [16].

On the other hand, visual comfort is associated with the use of artificial lighting, shading devices, as well as the accessibility to daylight. Lighting is one of the major energy end-use in buildings and accounts for a quarter of the total electricity consumption in office buildings in Australia [17]. Several attempts have been made to reduce energy consumption for lighting. For example, there has been a huge improvement of the light bulb from 60-watt incandescent to 14-watt compact fluorescent, and recently 7-watt light-emitting diode or LED.

2.2. Perceived control

Over the past few years, there has been a growing number of automated control systems used in buildings, which aim not only to provide more comfort to the occupants but also to minimize building energy consumption [18]. Nevertheless, in the context of office buildings, the relationship between office energy efficiency and occupants' well-being and working performance is still unclear [19].

The automated control systems in buildings can drastically limit occupants' ability to exert control over their environment [20]. While some research reveals that a centralized control system can improve occupants' satisfaction and perceived productivity [14,21], other research shows that occupants working in green-rated office buildings have a lower level of satisfaction and perceived productivity compared to those working in conventional buildings [22].

From a psychological perspective, people need autonomy. Having a sense of control increases the feeling of comfort and occupants' satisfaction [23]. Similarly, the concept of homeostasis states that: *"if a change occurs such as producing discomfort, people react in a way to restore their comfort condition"* [24];. In fact, having a sense of control and having choices is closely related. People exercise control by making a choice in order to achieve their desired results or avoid undesirable ones [25]. McCunn et al [26]. found that perceived productivity has a positive association with perceived control. Similarly, Göçer et al [7]. found that personal control is a strong predictor contributing to occupants' perceived productivity in both high- and low-performance offices.

2.3. Default lighting settings and occupant behavior

One of the notions that appear to align with the concept of controllability is nudging. Nudging is a promising tool that can be used to change human behavior towards desirable outcomes. The core concept of nudging is not to limit people's freedom to choose but to improve the choice architecture instead [27]. Thaler and Sunstein [28], who introduced the concept of nudging, defined nudging as: *"any aspect of the choice architecture that alters people's behavior in a predictable way, without forbidding any options or significantly changing their economic incentives"*. The advantage of nudging is that it does not require a great amount of money to administer and implement, and can begin with the simple question: "*What's keeping someone from already doing the good things?"* [29].

One of the cognitive biases that have been effectively applied for nudging is status quo bias or the bias that makes people tend to stick to the default option [30,31]. The default option has been successful in several fields. For example, organ donations [32], financial savings [33], charitable giving [34], and food choices [31]. In energy-related applications, the default option has been applied to promote the domestic uptake of green energy [35,36].

In the context of building energy, lighting offers one of the greatest energy-saving potentials [37]. It is especially attractive when one takes into account: (1) the (small) effort required to turn off an unnecessary light in an office room; and (2) the number of such light bulb opportunities. In this context, the interaction between occupants and lighting controls gains much interest. For instance, Yun et al [38]. conducted a monitoring study in shared offices in a university in Korea. The findings revealed that the lighting usage behavior has a strong relationship with the occupancy pattern, while there was no statistical significance with the external illuminance. In other words, there was a strong tendency that occupants switch the light on when they first arrived at the offices in the morning and the light stayed on during working hours regardless of external illuminance level. Heydarian et al [39]. emphasized the importance of default lighting settings. Through an application of an immersive virtual environment, they found that people are more likely to stick with the default condition if the rooms had maximum simulated daylight available, no matter if the artificial lights are on or off. However, people also stick with the default condition if all the artificial lights are on. Furthermore, Gilani and O'Brien [18] examined the impact of lighting control systems on the energy use of private offices in an academic building in Canada, using both experimental and simulation techniques. The results indicated a reduction in lighting energy use by a factor of seven with a manual control system compared to an automated control system.

2.4. Conceptual diagram

Based on the above literature review, a conceptual diagram is shown in Fig. 1. The indoor environment influences occupant satisfaction. When occupants perceive dissatisfaction with the indoor environment, they interact with the energy using systems in the building, such as lights and air-conditioners. On the one hand, the energy using systems will adjust the indoor environment to meet occupants' preference. On the other hand, the energy demand for the systems will increase or decrease following the interaction of occupants and the systems.

3. Methodology

In this study, structural equation modeling (SEM) was used to explore the influence of occupants' perceived control on satisfaction and productivity. Schweiker et al [40]., recommended SEM to study indoor environmental perception and behavior studies as it allows us to understand the interdependent relationships. In this study, one particular

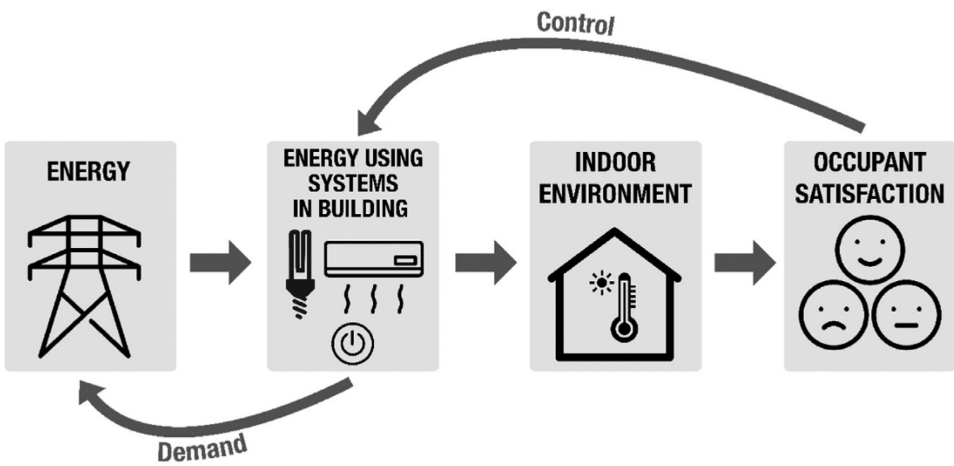

Fig. 1. Conceptual diagram of occupant interactions with energy using systems in building (For picture sources, see Appendix A in supplementary file).

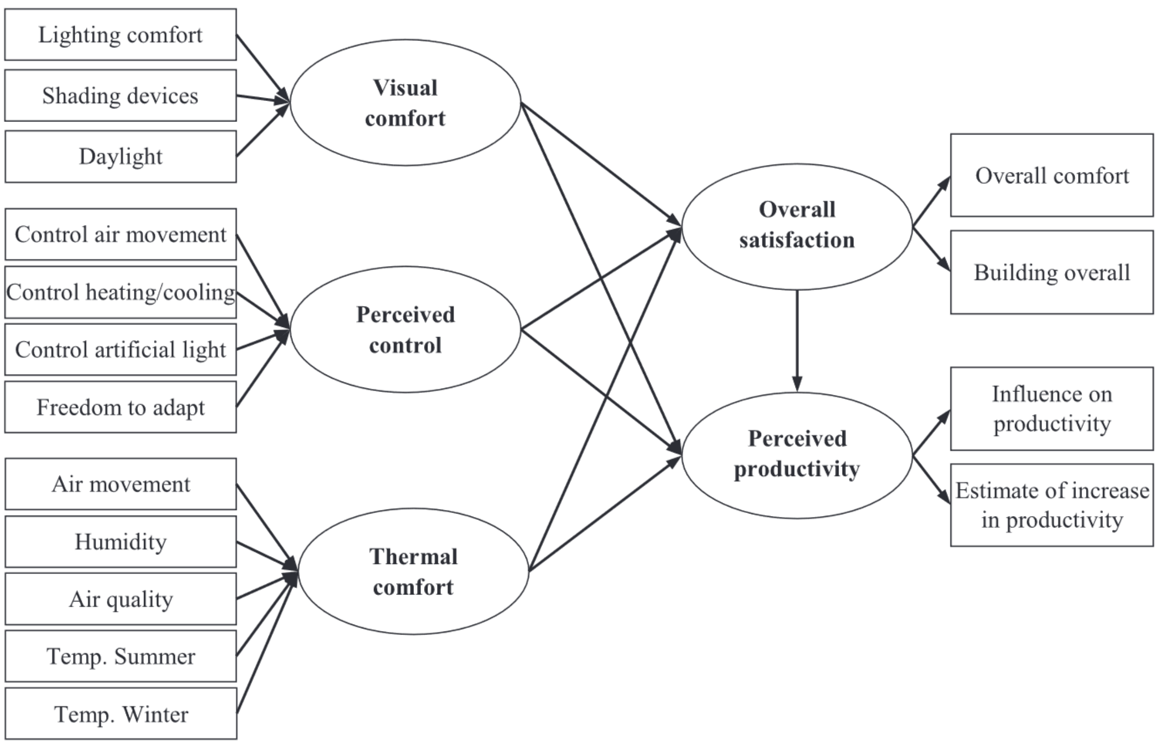

Fig. 2. The proposed model of occupants' satisfaction and perceived productivity.

variant of SEM, namely Partial Least Square (PLS) approach was used to estimate SEM parameters. The advantages of PLS are that the robust estimates are obtainable even with small sample sizes and it does not require multivariate normal distribution assumption [41,42]. The analysis was performed using the SmartPLS software version 3.3.3 [43].

3.1. Structural model

Based on the literature review, this study hypothesized that thermal comfort, visual comfort, and perceived control influence both occupants' overall satisfaction and occupants' perceived productivity. At the same time, satisfaction is hypothesized to influence perceived productivity. The proposed model is presented in Fig. 2.

Table 1 summarizes the model constructs and their underlying indicators. The means and standard deviations were calculated using RStudio [44]. It should be noted that the exogenous constructs, namely 'Thermal comfort', 'Visual comfort', and 'Perceived control' are evaluated by their underlying indicators formatively, as they influence the above latent variables. This is appropriate as these constructs are derived by the respective measures. Meanwhile, the endogenous constructs, namely 'Overall satisfaction', and 'Perceived productivity' are evaluated reflectively. This is appropriate as the constructs are influenced by the respective latent construct, correlated and are interchangeable.

3.2. Questionnaire

We used a subset of data from the post-occupancy evaluation survey called BOSSA [45], which originally aims to assess occupants' satisfaction with the IEQ performance of the building in a separate and independent research project. We therefore characterize this data as external and secondary to this study.

Participants are the occupants of a 13-story academic building located in Central Sydney, Australia. The building serves as both teaching spaces and staff offices. It is designed with sustainable features and has been awarded 5 Star Green Star Design & As-Built certified by the Green Building Council of Australia. The external wall of the building is made

Table 1
Model constructs and indicators.

Constructs	Indicators	Mean	SD
Thermal comfort	Air movement	4.342	1.960
	Overall humidity	4.973	1.617
	Overall air quality	4.824	1.805
	Temperature conditions in summer *(From uncomfortable to comfortable)*	4.947	1.679
	Temperature conditions in winter *(From uncomfortable to comfortable)*	4.813	1.762
Visual comfort	Lighting comfort	5.241	1.681
	Shading devices for controlling unwanted glare	4.668	1.852
	Access to daylight	4.877	2.132
Perceived control	Level of personal control over air movement *(From no control to full control)*	3.091	1.811
	Level of personal control over heating or cooling *(From no control to full control)*	3.086	1.880
	Level of personal control over artificial lighting *(From no control to full control)*	3.182	1.978
	Degree of freedom to adapt work area to meet preferences	3.406	1.903
Overall satisfaction	Overall comfort *(The overall ratings for work area comfort)*	4.492	1.710
	Building overall *(Satisfaction with the building)*	4.663	1.721
Perceived productivity	Influence on productivity *(From negatively to positively)*	4.321	1.780
	Estimate of increase in productivity *(From decrease by 30% to increase by 30%)*	3.963	1.801

of glass and covered with a semi-transparent façade. HVAC systems are centrally controlled from a facility plant and the local thermostats are set to be non-adjustable. Meanwhile, lighting systems are controlled by passive infrared (PIR) motion sensors to switch the light on and off.

Participants were asked to rate their satisfaction on a continuous seven-point scale where 1 is Unsatisfactory and 7 is Satisfactory unless specified otherwise. The survey was conducted between 23 July 2019 to 21 August 2019. It received 188 responses, for which one response was from a faculty staff working in another building. As a result, the final sample size for our analysis is 187.

The survey participants included professional staff (56%), administrative/technical/managerial staff (30%), and others (14%). Among these, 61% are males, 32% are female, and 7% prefer not to answer. The participants were distributed over 3 age groups: 30 years or under (14%), 31-50 years (53%), over 50 years (29%), and prefer not to answer. In addition, 45% work in private offices, 20% work in offices shared with other occupants, and the remaining 35% work in open-plan offices.

3.3. Model evaluation

3.3.1. Common method bias

Considering common method bias in survey research, Harman's one-factor test was performed. The test results indicate 41.58% of the variance is explained by the measurement items, less than the benchmark value of 50.0%. Thus, the common method bias should not be a concern in this study [44].

3.3.2. Measurement model assessment

This study consists of both formative and reflective constructs which require different assessment procedures [46]. The formative constructs in this study include 'Thermal comfort', 'Visual comfort', and 'Perceived control'. The measurement model results are reported in Appendix B. The formative items should be assessed for multicollinearity and their significance and weights. Variance inflation factor (VIF) is used to identify multicollinearity issues. VIF > 5 indicates a potential multicollinearity problem [46]. In this study, all items have satisfactory VIF, except the VIF of the item 'Control heating/cooling' was 5.0. This is probably because it is similar to the item 'Control air movement' because air movement and temperature can be controlled via thermostat. Thus, the item 'Control heating/cooling' was removed from the model. Regarding significance and weights of the items, item 'Temp. summer', 'Temp. winter', 'Control air movement' and 'Control artificial lighting' were not significant. However, their loadings are high (> 0.5), indicating the items are absolutely important and should be retained [46].

The reflective constructs in this study are 'Overall satisfaction', and 'Perceived productivity'. Three criteria should be examined, namely internal consistency reliability, convergent validity, and discriminant validity. Cronbach's alpha and composite reliability are used to identify internal consistency reliability. All Cronbach's alpha and composite reliability values of the constructs are larger than the threshold value of 0.6, indicating the reliability in the internal consistency among the constructs.

Next, convergent validity was tested based on factor loading and average variance extracted (AVE). The results of a bootstrapping procedure with 5,000 samples showed that factor loading of all items is significant and larger than the threshold value of 0.7 [46]. On the other hand, the AVE value of all constructs is greater than the recommended value of 0.5 [46]. Therefore, these examinations confirm the convergent validity of the measurement model.

Lastly, discriminant validity was examined based on cross-loadings and the Fornell-Larcker criterion. Discriminant validity is established when items load more on their intended constructs than on other constructs [47]. According to the Fornell-Larcker criterion, moreover, the square root of the AVE should be greater than the highest correlation with any other construct [46]. As shown in Appendix C, all the items load high on their own constructs. Also, the square root of the AVE of each construct is larger than the highest correlation with other constructs (Appendix D). Therefore, the discriminant validity of the measurement model meets the requirements.

3.3.3. Structural model assessment

The criteria to assess structural model are the coefficient of determination (R^2 value), the f^2 effect size, and the predictive relevance Q^2. The R^2 value represents a measure of in-sample predictive power. Meanwhile, the f^2 effect size indicates the relative impact of a predictor construct on a target construct. On the other hand, the Q^2 value is an indicator of the out-of-sample predictive power of the model. The structural model results are reported in Appendix E.

The R^2 values of the overall satisfaction and perceived productivity were 0.536, 0.624, respectively, indicating substantial level of predictive power of the model [46]. In terms of the f^2 effect size, the signifi-

cant relationships had f^2 ranging from 0.062 to 0.8162. The f^2 value of 0.02, 0.15, and 0.35 represent small, medium, and large effect, respectively [46]. It should be noted that, as suggested by Chin et al [48]., the small f^2 does not necessarily mean an unimportant effect. On the other hand, the predictive relevance Q^2 of all constructs were above zero, confirming that items are well reconstructed, and the model has predictive relevance [46,49].

4. The field experiments

4.1. The offices

An experiment was carried out in the staff's private offices and meeting rooms. The lights in these offices are similar to other typical automatic lighting systems. As soon as someone enters an office the lights go on and stay on while any motion is detected inside. Then they are switched off after a fixed time delay, 20 minutes in our case, after the last motion detected. However, occupants are unable to switch the lights off as they always go back on whenever motion is detected. As mentioned earlier, the external wall of the building is made of glass and covered with a semi-transparent façade. There is plenty of diffuse daylight coming into the building while eliminating glare. In other words, the external walls of the offices along the edge of the building are all glass from floor to ceiling. The external side of the offices in this study is facing south, and there are two high-rise buildings across the street.

4.2. Sydney's daylight

The Sydney metropolitan is located on the eastern coast of Australia at 34°S, 151°E [50]. Daylight saving is observed which begins at 2 am on the first Sunday in October and ends at 3 am on the first Sunday in April [51].

The sunshine duration in Sydney varies depending on the season. During the experimental period, November and December 2019, approximate sunrise and sunset time are 5:40 am and 7:50 pm, respectively [52]. Although there is visible sunshine immediately after sunrise and just before sunset, the average number of hours of bright sunshine each day, as reported by the Bureau of Meteorology, is 7.8 hours in November and 7.6 hours in December 2019. However, this period has the highest bright sunshine hour of the year.

4.3. Experiment design

Based on the literature review above, our experiment stems from three assumptions: (1) we are not going to limit the participants' freedom of choice (2) if participants are satisfied by the conditions provided by the default option, they would stick to those conditions, and (3) if participants perceive discomfort, they would try to restore their comfort, by switching the light on in this case.

The experiment was done by reconfiguring lighting controls in the rooms facing outside in the case study building, which included 27 private offices and 2 meeting rooms. The reconfiguration was implemented through existing software, and no physical modification was involved. We reconfigured the default lighting setting from automatic on and off to manual-on and vacancy-off with a 10 minute time delay. It is worth noting that we are aware of the false-off events that can happen even when the participants were present in their offices but had an inadequate movement for a period of time. Thus, to avoid disturbing participants while minimizing energy use, if any motion is detected within 1 minute after the lights have turned off, the light will switch back on without requiring the participant to press the wall switch. The changes that have been made to the settings are summarized in Table 2. It should be noted that the changes to the lighting controls were implemented after the post-occupancy evaluation survey was done. Thus, the experiment does not influence the survey results.

Table 2
Summary of detailed settings used in the experiment.

	Previous setting	New setting
Light ON	Automatic ON when motion detected by the sensor	Manually ON by pressing wall switch
Light OFF	Automatic OFF when no motion detected by sensor for 20 minutes	Manually OFF by pressing wall switch
		Automatic OFF when no motion detected by sensor for 10 minutes - If the motion is detected within 1 minute after the lights have turned OFF, turn the light back ON - If no motion is detected within 1 minute after the lights have turned OFF, keep the lights OFF and allow them to be turned back ON manually

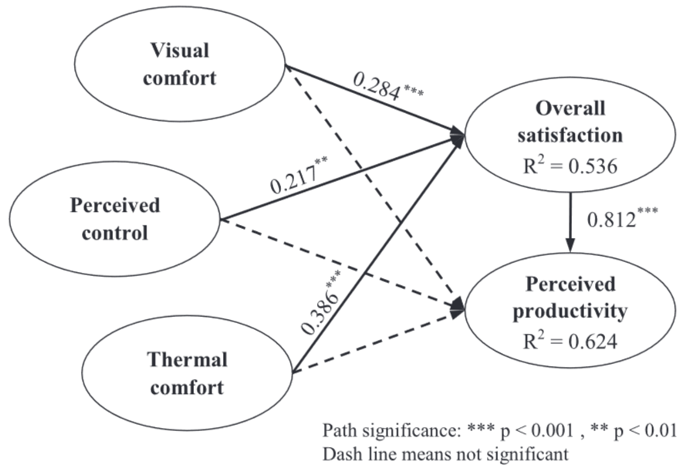

Fig. 3. Direct relationships between visual comfort, thermal comfort, perceived control with satisfaction and productivity.

4.4. Data collection

Data collection, including behavioral observation data and electricity consumption data, happened during weekdays in a four-week period, from 18 November to 13 December 2019. Inhabitant behavior was observed two times a day, at 10:30 am and 3:30 pm, by collecting the data on whether the rooms are occupied and whether the lights are on.

Electricity consumption data were obtained through the university's energy management system, which has sub-meters for measuring electricity consumption by lights in a particular area. However, the sub-meter is measuring electricity consumed by the lights in the whole school, which includes the inner-side rooms and research student workspaces that were not included in this experiment. A series of analysis of variance (ANOVA) is used to identify whether the reduction in electricity consumption is significant.

5. Results

5.1. The impact of perceived control on satisfaction and productivity

5.1.1. Direct relationships

Fig. 3 presents the direct relationships among the constructs. The results indicated that visual comfort, thermal comfort, and perceived control are the significant determinants of occupants' satisfaction, which 53.6% of the variance for occupants' satisfaction is explained by these constructs. Among the three constructs, the effect of thermal comfort is greatest (path coefficient = 0.386), followed by the effect of visual comfort (path coefficient = 0.284). Although perceived control has a smaller

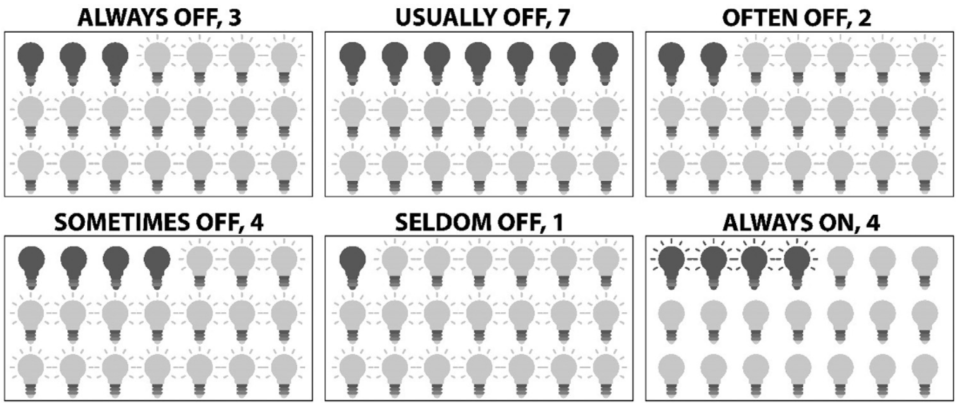

Fig. 4. Results of behavioral observation on the ratio of the lights were off to the number of times the offices were occupied (For picture sources, see Appendix A in supplementary file).

Table 3
Indirect relationships between each construct and perceived productivity.

Relationships	Path coefficient
Thermal comfort → Overall satisfaction → Perceived productivity	0.314***
Visual comfort → Overall satisfaction → Perceived productivity	0.230***
Perceived control → Overall satisfaction → Perceived productivity	0.176**

*** $p < 0.001$
** $p < 0.01$

effect than thermal comfort and visual comfort, it still emerges as a good predictor of occupants' overall satisfaction (path coefficient = 0.217).

However, the three constructs do not appear to influence occupants' perceived productivity significantly. According to the results, overall satisfaction is the only construct that significantly influences perceived productivity, which explained 62.4% of the variance. In addition, overall satisfaction also has a strong impact on perceived productivity (path coefficient = 0.812).

5.1.2. Indirect relationships

Since visual comfort, thermal comfort, and perceived control do not significantly influence perceived productivity, we further explore whether mediation relationships exist Table 3. presents the mediation relationships between the three constructs and perceived productivity. The results indicated that the three constructs significantly influence perceived productivity indirectly through overall satisfaction. In other words, it can be concluded that overall satisfaction plays a mediating role in the causal link between thermal comfort, visual comfort, perceived control, and perceived productivity. Similar to the direct relationships on overall satisfaction, the indirect effect of thermal comfort on perceived productivity is greater than the others (path coefficient = 0.314), followed by the effect of visual comfort (path coefficient = 0.230). On the other hand, perceived control also plays a significant role in indirectly influencing perceived productivity with the path coefficient of 0.176.

5.2. The impact of occupant control on energy consumption

5.2.1. Behavioral observation

From the observational data, the ratio of the number of times the lights were off to the number of times the offices were occupied was calculated. There were 21 offices frequently occupied during the observation period. Among these, the lights remained off in 10 offices for more than 80% of the time, with three of them the lights being always off. In contrast, there were four offices where the occupants always switched the lights on when they were in, while for the remaining seven offices, the lights were partially on, as shown in Fig. 4.

5.2.2. Electricity consumption reduction

Since it is not possible to isolate and measure the electricity consumption for the office rooms where the intervention was carried out, we report the electricity consumption for the whole area being monitored by the sub-meter. It should be emphasized that the corresponding sub-meter monitors electricity consumption for lighting only, electricity consumption for HVAC systems and plug loads are not included in this meter.

The electricity consumption during the period of the experiment is compared with the historical data of the same period in previous years since the commencement of the building in 2014 (Fig. 5). However, data for 2016 is missing, thus 2016 is excluded from our comparison. In addition, the average daily bright sunshine hours, which is the outdoor condition that potentially affects the need for indoor artificial lights, is also reported together with the electricity consumption.

Assuming similar academic activities for the same period in previous years, based on Fig. 5, the electricity consumption has shown a decrease in the year in which the experiment was carried out. Besides, it can be seen that the difference in bright sunshine hours does not reflect the difference in electricity consumption, which could be explained by the earlier automatic settings that switch the light on based on the presence of occupants.

To identify whether a reduction in electricity consumption is statistically significant, a series of analysis of variance (ANOVA) was conducted using IBM SPSS Statistics version 28.0. Before we ran ANOVA, the normality and homogeneity of variances assumption were tested. The results indicated the assumption held (Appendix F). The results of the ANOVA test show that there was a significant difference in electricity consumption between years (Appendix F). As a result, Tukey's HSD post-hoc tests were further performed to identify which year of comparisons the reduction was statistically significant.

Fig. 6 presents the results of Tukey's HSD post-hoc tests. The circles indicated the mean difference of average weekly electricity consumption of each pair of comparisons. The negative values mean the consumption between the pairs of comparison was decreased. However, if the interval contains zero, the corresponding means are not significantly different. Based on Fig. 6, the reduction in electricity consumption in 2019 is statistically significant when compared with the consumption in the previous years. Meanwhile, the reduction in electricity consumption from the commencement of the building to the year before the experiment was carried out is not statistically significant. The complete results of Tukey's HSD post-hoc tests are reported in Appendix G.

6. Discussion

This empirical study analyzed the role of occupants' perceived control over their thermal and visual comfort to determine whether and to what extent it influences satisfaction and perceived productivity, using data from post-occupancy evaluation survey for the case study build-

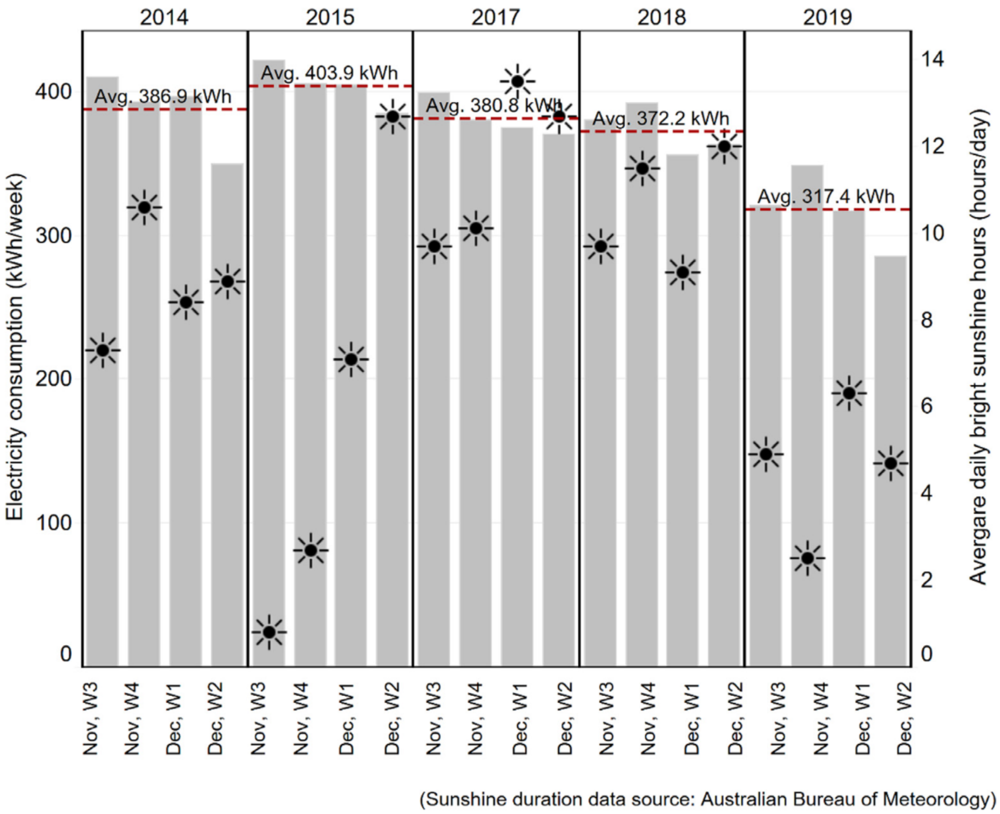

Fig. 5. Comparison of weekly electricity consumption and average daily bright sunshine hours (indicated by the sun symbol) during the period of study (Nov-Dec) in 2019 with the same periods in the preceding years.

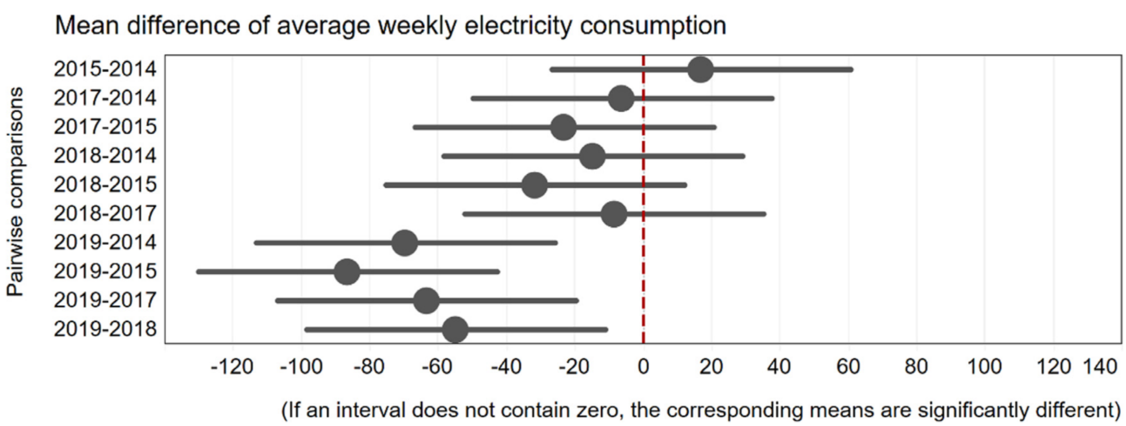

Fig. 6. Significant test results of electricity consumption reduction.

ing. The results of PLS-SEM revealed that perceived control has a positive influence on occupants' satisfaction. These findings are in line with the notion of controllability that having a sense of control increases the feeling of comfort and consequently makes occupants feel more satisfied [23,25]. At the same time, perceived control appears to indirectly influence occupants' perceived productivity through satisfaction. McCunn et al [26]. and Göçer et al [7]. also reported similar findings of the relationship between perceived productivity and perceived control.

Although the effect of perceived control on satisfaction and productivity is smaller than the effect of thermal and visual comfort themselves, it is still significant and should not be overlooked. In addition to the roles in improving satisfaction and productivity, our study also reveals energy-saving potential as a result of giving more control to the occupants.

In our experiment, we reconfigured the default setting of the lights from automatic to manual for switching the lights on but kept switching the lights off automatically when nobody was present. We also reduced the time delay before the lights go off when no motion is detected by sensors from 20 to 10 minutes. The experiment shows that about half of participants usually keep the lights off when they are in their offices, though they are free to switch them on. One-fourth of the participants do the same sometimes and only the remaining one-fourth always switch the lights on. It should also be noted that during the experiment period we also received some positive feedback; some occupants were telling us that they feel more comfortable without artificial lights in their offices and appreciated the new settings.

The modifications in the lighting system settings led to changes in occupant behavior and resulted in a 17.8% reduction in electricity consumption compared to the same period in previous years. These results are in line with Gilani and O'Brien [18] but contradict the simulation results of Zhang et al [53]., who found that automated lighting control strategy is more energy-efficient than manual control. However, the ma-

jor difference between the present study and the previous one may be in the specifics of the buildings analyzed. As the external wall of the building in our study is made of glass, there is more potential to take advantage of natural light and less reliance on artificial lighting as compared to other buildings with the non-transparent wall materials.

Based on our findings, occupants' comfort and satisfaction are not only influenced by physical parameters, such as temperature, humidity, and illuminance, but also influenced by psychological parameters, like perceived control over their environment. It should also be emphasized that humans are heterogeneous and comfort preferences are subjective. Thus, the operation of building systems should take this into consideration. Besides, it can be seen from our experiment results that rather than following the fully automatic control strategy for switching lights on, the availability of control choices not only improves occupant satisfaction but also reduces energy use. Therefore, instead of restricting choice, redesigning default choices in order to accomplish desirable results is another way for servicing system control strategy in buildings that does not require huge upfront investments, as well as major technical modifications. A combination of occupants' control and nudging can help to both provide comfort and conserve energy.

7. Conclusions

This study used data from a post-occupancy evaluation survey to analyze the impact of occupants' control on satisfaction and perceived productivity. We also conducted an experiment to explore occupant behavior in response to the new default light switch setting and the effect on lighting energy demands. The results of the secondary survey analysis confirmed the positive effects of occupants' perceived control on satisfaction, and in turn perceived productivity. The results of our experiment also revealed that people's comfort preferences are subjective. Our experiment does not limit people's freedom to switch the lights on and off. In fact, we gave them more control over the lights but changed the default option. We thought that the rather traditional and technocratic idea that lights should always be on is outdated and today we should be giving people more opportunities to save energy and avoid artificial lighting when natural light is in abundance. Our findings emphasize the significance of choice architecture provided in order to influence people to make desirable decisions. More importantly, they stress the importance of the interconnection between technologies and behavior in relation to energy use in buildings. While human behavior plays a significant role in the building's energy uses, it is obvious that human behavior is driven by what technologies in the building allow or do not allow them to do.

This study is subject to some limitations. First, the findings of this study are specific to our case study and may not be generalizable to other buildings. The effect of several influential factors may lead to different results, such as location, building design, functions, and materials. In our case, the external wall is entirely glass, providing much daylight. The buildings with different external wall materials and design may have different daylight availability, and in turn different levels of energy-saving potential.

Second, the effects of such characteristics of occupants, as age, have not been included in the experiment analysis. People in different age groups may have different requirements for illuminance and visual comfort, which may lead to different behaviors. Thirdly, characteristics of the work area have not been included in the survey analysis. The experiment in this study was done in private offices, while perceived productivity for people working in private or open plan offices may be defined by different factors. Also, behavioral change and energy saving may not be generalizable to shared offices or rooms with other purposes as distributed responsibility phenomenon may affect the efficiency of the process.

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.

CRediT authorship contribution statement

Wipa Loengbudnark: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Kaveh Khalilpour:** Conceptualization, Writing – review & editing. **Gnana Bharathy:** Methodology, Writing – review & editing. **Alexey Voinov:** Conceptualization, Writing – review & editing, Supervision. **Leena Thomas:** Investigation, Data curation.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbenv.2022.02.007.

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