Dynamic façades – An exploratory campaign to assess occupant multi-domain environmental satisfaction and façade interaction

Luna-Navarro, Alessandra; Hunt, Gary R.; Overend, Mauro

DOI
10.1016/j.buildenv.2021.108703

Publication date
2022

Document Version
Final published version

Published in
Building and Environment

Building and Environment 211 (2022) 108703

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Dynamic façades – An exploratory campaign to assess occupant multi-domain environmental satisfaction and façade interaction

Alessandra Luna-Navarro [a,*], Gary R. Hunt [a], Mauro Overend [b]

[a] *Department of Engineering, University of Cambridge, CB2 1PZ, UK*
[b] *Faculty of Architecture and Built Environment, TU Delft, the Netherlands*

ARTICLE INFO

Keywords:
Multi-domain environmental satisfaction
Human comfort
Adaptive façades
Dynamic façade
Occupant-centred automation
Occupant interaction

ABSTRACT

Building occupants interact frequently with façades. These interactions simultaneously affect several domains of the indoor environment (visual, thermal, air quality and acoustic) and occupant perception, as well as the energy performance of the façades. Yet this multi-domain relationship between façade and occupant is not well understood. This gap in knowledge is particularly problematic for dynamic façades, where automated controls endeavour to improve the energy efficiency and reduce occupant dissatisfaction. In particular, it is often unclear whether an integrated multi-domain approach is strictly required when evaluating occupant satisfaction with automated or manual dynamic façades. This research provides a "proof-of-principle" that such an approach is required. This conclusion was drawn after performing. small exploratory campaign conducted in a test chamber designed specifically for occupant-façade interaction in which several human volunteers were exposed to alternative façade typologies (a single-skin façade and a closed cavity façade) and different control strategies (manual control and automated control). As expected, the results show that the effects on the indoor environmental quality, occupant satisfaction and discomfort vary in space and time, and between the façade typologies investigated. It was also found that occupant satisfaction was not only affected by whether a certain thermal or visual condition had been reached, but also on how it had been achieved, e.g. whether the actuation was perceived as disruptive by the occupants. Finally, the results show that occupant satisfaction and the level of interaction in one domain may be affected by satisfaction in other domains.

1. Introduction

Automated dynamic façades can be programmed to respond in real time to changes in indoor and outdoor conditions. An effective responsive control of these technologies can reduce energy consumption [1] whilst improving occupant comfort and satisfaction with the indoor environment [2,3]. The effectiveness of façade automated controls depends, however, on occupant interaction and satisfaction with these controls [4–6]. If energy-efficient automated controls do not meet essential occupant requirements, occupants either switch off, or circumvent, the controls [5–7]. Occupants are often provided with some override controls; in these scenarios, occupant interaction and choices affect the pre-determined automated control performance and can undermine predicted energy savings and, thereby, result in a higher energy consumption [8]. Ultimately, the principal aim of automated controls in buildings is to save energy and resources for building operation, and simultaneously to enhance occupant satisfaction and well-being. Understanding how to design and operate automated dynamic façades in an occupant-centred manner is therefore essential for the success of these technologies and ultimately for achieving buildings that are occupant-centred and energy efficient.

Capturing occupant perception/interaction with automated dynamic façades is challenging for several reasons: (i) window and façades are the preferred means for environmental control by occupants, therefore interactions are frequent and driven by different reasons, such as adaptive behaviours to restore comfort [9] and, therefore, difficult to predict; (ii) façades have a multi-domain influence on occupant environmental perception [10], and often occupant environmental requirements are in conflict (e.g. glare mitigation *versus* daylight maximisation or vent opening for fresh air *versus* outdoor noise control); (iii) as in other human comfort problems, occupant requirements are highly individual [11], they change in time and vary with the distance between the occupant and the façade [12].

Occupant environmental satisfaction describes the state of mind

* Corresponding author.
E-mail address: al786@cam.ac.uk (A. Luna-Navarro).

https://doi.org/10.1016/j.buildenv.2021.108703
Received 21 August 2021; Received in revised form 30 November 2021; Accepted 20 December 2021
Available online 30 December 2021

whereby the occupant feels content with the quality of the indoor environment and usually with reference to a single environmental domain at a time, e.g. either (i) thermal, (ii) visual, (iii) acoustic, or (iv) indoor air quality. Multi-domain satisfaction refers to the state of mind whereby the occupant is content with all the four environmental domains simultaneously. Overall environmental satisfaction refers to a much broader domain where other factors, such as interaction, personal control, cleanliness or space layout, could affect the overall satisfaction of the occupant [13]. Previous work has extensively studied the effect of automated dynamic façades on energy, thermal or visual discomfort by using thermal or daylight simulations. However, in addition to building performance simulations, experimental research with human volunteers is essential to make progress in this field since it is the only means to simultaneously capture the multi-domain influence of façades on occupant environmental satisfaction and interaction. A few researchers have investigated the effect of automated or manual dynamic façades on occupant multi-domain environmental satisfaction by performing experiments with human volunteers. They have focussed on up to three environmental domains [14], or either on two environmental domains in combination with satisfaction with façade interaction [2,8,15]. To-date, only two studies have investigated the influence of façades on overall general satisfaction with the indoor environmental quality (IEQ), but neither includes satisfaction with personal control or interaction [16,17]. One study has investigated the influence of façades on all the four environmental domains and on the satisfaction with personal control and interaction, but without integrating the subjective data collection with a comprehensive objective environmental monitoring [18]. Integrating subjective data collection with objective environmental monitoring is necessary to relate façade characteristics to changes in IEQ and occupant environmental satisfaction.

The aim of this paper is to provide a proof-of-principle that an integrated multi-domain assessment of façade influence on occupant environmental satisfaction and interaction is required. The salient findings and omissions in previous research are discussed in section 2, leading to the objectives of this paper in section 3. Section 4 describes the methodology used in the present study, followed by the results obtained from an exploratory experimental campaign with automated and manual dynamic façades conducted in a bespoke test facility for occupant-façade interaction [19]. The conclusions are drawn in section 5 and some key recommendations are given for the efficient design and operation of façades.

2. Review of previous research on occupant-façade interaction and satisfaction

The salient findings for the practitioner/façade designer that may be gleaned from previous research with human volunteers on occupant environmental satisfaction and interaction with manual and automated dynamic façades may be summarised as follows:

- Provide personal control (overrides) of the façade alongside automated controls [3,20–22]. Occupants are more satisfied with the levels of daylight and lighting when they are able to override automated control strategies [3]. Moreover, occupants prefer manual control to automated controls if personal control is not available [6,23,24];
- Provide user-friendly occupant interfaces [3,5];
- Provide occupants with feedback on the rationale behind automated control actions as this improves user acceptance of automation [3,25];
- Deploy façade control strategies that maximise daylight but prevent discomfort from glare. Occupant acceptance of automated controls appears to be higher if blinds are raised or daylight and view are increased [5], and is usually lower when blinds are lowered [6,23]. However, the ability of automated controls to prevent glare is also valued by occupants and this is not always achieved by automated controls. For instance, glare prevention can be particularly challenging for roller blinds [14] and switchable glazing [10,15];
- Tailor the control strategies for specific façade technologies. The control strategy plays a key role for the effectiveness of a façade in mitigating discomfort. For instance, for glare, façades that are controlled according to the level of external solar radiation tend be obstructed for a longer time, while occupant-centred control parameters, e.g. vertical illuminance at eye level or daylight glare probability (DGP) from the occupant point of view, can improve the daylighting strategy and access to view [2], although potentially at the expenses of glare mitigation;
- Adopt short façade reaction times wherever possible in a manner that the façade promptly reacts to changes in outdoor and indoor conditions. The reaction time of the automated system is important for user satisfaction. For instance, switchable glazing that is too slow to react causes dissatisfaction [24,26,27];
- Provide automated control strategies that are not distractive by limiting the number of movements and the associated noise from the façade as these are perceived as a disturbance even when occupants realise this intervention is for their benefit [14]. If noise is limited, façade movements are deemed to be more acceptable [28];

Despite these useful findings, there is a lack of data and knowledge on the multi-domain influence of façades and on the weight that each environmental factor has on the overall individual occupant satisfaction. Occupants' requirements in terms of environmental satisfaction are often conflicting (e.g. daylight access *versus* glare prevention) [9] and occupants have different environmental preferences and rank orders of the importance that each environmental domain has for their individual environmental satisfaction. Even if the effect of façades is multi-domain, occupants are more aware of their visual effect and assign more importance to the visual satisfaction when choosing between different façade technologies [29]. For instance, Karlsen et al. [20] found that access to an outdoor view was one of the most important factors for occupant environmental satisfaction in relation to a façade, followed by visual comfort (i.e. daylight and glare mitigation). The importance of an outdoor view is also the reason why in previous studies, occupants preferred to control solar radiation with a "cut-off angle strategy", which is the angle that avoids direct illuminance in the occupied space, for venetian blinds rather than by fully-closing the blinds [20]. For the same reason, occupants preferred roller blind fabrics with a larger openness [22] and switchable glazing that does not stay in its darkest state for a long time, especially when electrochromic glass with an (undesirable) blue tint is installed. This was also confirmed by Inoue et al. [29], who reported that occupants preferred blinds to be left fully-raised for as long as possible.

There is also uncertainty concerning whether automated controls achieve better occupant environmental satisfaction than manual controls. This uncertainty is because imposing controls to prevent one type of discomfort can sometimes reduce comfort in other domains [28]. A few studies on automated controls have shown that occupants seemed more dissatisfied with the level of daylight [3,15,20], but more satisfied with glare prevention [3]. However, Meerbeek et al. [6] found that with automated controls of blinds, occupants had a higher environmental satisfaction, but a lower perceived control, than in the manual-control scenario. The reason for these seemingly contradictory findings is that the environmental satisfaction and overall satisfaction of occupants depend on the type of control strategy and façade technology, rather than on the façade being either manually or automatically controlled. When automated controls are programmed to restore the highest possible transparency while maintaining a low risk of glare, occupants are more satisfied with the automated provision of daylight [2]. Conversely, Konis [30] reported that occupants could remain satisfied with the visual environment even if blinds were often down for preventing glare and, therefore, the level of daylight was low. Maximising daylight can also increase the risk of overheating and occupants have often reported thermal dissatisfaction with automated controls [2,20]. In the case of openable vents, occupant acceptance of automated controls is higher if the controls are programmed to simultaneously meet thermal comfort and indoor air quality (IAQ) requirements, as reported by Stazi et al. [31].

There is also a considerable scatter of results from research on occupant interaction with automated dynamic façades. This scatter arises because the level of interaction and resulting satisfaction/dissatisfaction with personal control depends on the type of control strategy and the frequency of interaction, which both vary significantly from one automated façade to another. For example, Sadeghi et al. [5] found that occupants interacted more frequently with manually-controlled façades than with automated façades. Lee et al. [32] and Goovaerts et al. [33] also found that manual overrides were less prevalent in dynamic façades that maximise daylight levels when required. When façades are automated for preventing glare and overheating, occupant interaction is triggered predominantly by the desire to restore view or increase daylight [5,33,34], while for manually-controlled façades, most occupant interaction is for glare prevention [5]. However, if the façade control strategy is unable to prevent glare, occupant overrides will be driven by glare, as shown by Kelly-Waskett et al. [26]. Other important contextual factors when evaluating the effect of an automated or manual façade include the position and orientation of occupants in relation to the window, the position and number of sensing devices that trigger automated controls and the zoning of the controls [26].

The literature to-date therefore does not clarify whether an integrated multi-domain approach is necessary for evaluating occupant satisfaction with façade typologies or whether automated scenarios can outperform manual controls in providing occupant environmental satisfaction. The aim of the present work is to evaluate the indoor environmental quality, occupant integrated multi-domain environmental satisfaction and overall satisfaction associated with alternative façade typologies and control scenarios. In addition, previous works have mainly compared manual control with fully-automated control, without considering the effect of occupant interaction and overrides on the overall satisfaction and performance. Therefore, this work aims to capture the integrated multi-domain satisfaction and interaction of occupants with manual and automated dynamic façades to establish whether an integrated multi-domain approach has the potential to provide a more complete understanding of the influence of façade on occupant environmental satisfaction and interaction. This, in turn, is expected to lead to a more occupant-centred design and operation of façades.

3. Hypothesis and methodology

The experimental work presented in this paper aims to provide a "proof-of-principle" of the following hypothesis:

- o An integrated multi-domain approach is necessary in order to fully understand and compare the occupant satisfaction and interaction characteristics of alternative façade typologies.

A new methodology was presented in previous work by the authors [19], including the design and validation of the new experimental research facility developed specifically for this work. The methodology combines subjective and objective evaluation methods in order to evaluate the multi-domain occupant perception and interaction with façades. Firstly, the IEQ is evaluated by objective measures with environmental sensors while human volunteers occupy the space and interact with the façade. Secondly, occupant satisfaction and interaction with the façade were assessed by monitoring occupant control actions, questionnaires, and bespoke feedback interfaces. The IEQ was evaluated at three different distances (corresponding to three different occupant positions) from the façade; occupant satisfaction was assessed at the occupant position closest to the façade.

3.1. Experimental design

Experiments were conducted in a full-scale test chamber (5 × 6 × 2.5 m), named MATELab in Cambridge, UK [19]. The test chamber was designed specifically for occupant-façade interaction and perception studies. For this study, the test chamber was equipped with a glazed façade on the south orientation (Fig. 1).

Experiments were conducted from the August 28, 2020 to the November 6, 2020. Three scenarios were tested (A, B and C), each with three different control or façade typologies. The scenarios are summarised in Table 1. In the first two scenarios, the south façade was equipped with a single-skin façade (SSF) with internal venetian blinds. The blinds were made of fully rotatable 35 mm aluminium slats finished in matt grey. The glazing was a high-performance double-glazing unit (DGU) with a solar control coating. In the third scenario, the south façade was a closed cavity façade (CCF), which had a glazing with a higher visual transmittance. The venetian blind used in the first two scenarios was installed in the cavity of the CCF. Fig. 2.a and Fig. 2.b show a schematic section through each of the façade typologies tested.

In the first scenario, the internal blinds were manually controlled, while in the second and the third scenarios the blinds were automatically controlled according to the control strategy shown in the form of a flowchart in Fig. 2.c.

The control strategy is a rule-based algorithm, which uses real-time solar radiation measurements from the weather station on the roof of MATELab. This control was chosen on the basis that it is a well-established benchmark control algorithm commonly used for commercial buildings in London [35]. The external global solar radiation on the south-facing façade was chosen as the control parameter. The rationale behind the control algorithm is to prevent overheating by lowering the blinds when the vertical irradiance exceeds 250 W/m^2 and by rotating the slats to the "cut-off" angle. The blinds were also lowered and rotated to minimise glare when the sun is in the field of view, however the "cut-off" angle may still result in a strong secondary reflection that might affect visual comfort depending on view direction and profile angle [36]. Whenever the vertical irradiance is below the threshold of 250 W/m^2, the blinds are automatically raised to restore maximum levels of daylight. In order to avoid high-frequency blind movements (e.g. in response to highly variable sky conditions), the control condition must be achieved and maintained for at least 15 min before actuating the blinds. Since manual override is always allowed, the control system waits for 30 min before restarting the automated control following a user manual overriding of the control. Building services (i.e. cooling, ventilation and artificial lighting) were automated and no override was available to occupants. Details on the type of control and setpoints are reported in Table 2.

3.2. Experimental setup and procedure

The experimental setup, described in Luna-Navarro and Overend [19], shown in Fig. 3 and described in Table 3, consisted of an array of sensing devices at the occupant position (location 1 in Fig. 3.a and Fig. 3b), at two further distances (2.5 and 4.0 m) perpendicular to the façade bays (locations 2 and 3 in Fig. 3.a, respectively), on the façade (locations 4 and 5 in Fig. 3.a and Fig. 3c) and at the centre of the room (location 6 in Fig. 3a). In addition, two weather stations were installed on the roof of the MATELab (one of these is shown in Fig. 3.d as location 8) and a third weather station at ground level (location 7 in Fig. 3d). Further information on the sensor characteristics is provided in Appendix A, where the sensing devices accuracies are reported. Glare was monitored through the "glare unit" setup in Fig. 3.b. This unit was located behind the occupant in order to minimise the intrusiveness of the monitoring system but consequently suffered a loss in accuracy relative to a unit positioned as close as possible to the occupant's head. Information on the "glare unit" is reported in Appendix A. The other limitation was the lack of measuring devices that could monitor the

a) b)

Fig. 1. MATELab. a) Internal view; b) external view of south façade.

Table 1
Description of the experimental scenarios.

Scenario	Façade technology	Blind	Control strategy	Test dates
A	**SSF** DGU (6 mm glass with solar control coating 50/25–15 mm cavity – 8 mm laminated)	35 mm internal grey matt aluminium	Manual	Sept. 4th, 7th, 10th, 11th, 15th, 16th, 17th, 21st, 25th Oct. 1st
B	**SSF** DGU (6 mm glass with solar control coating 50/25–15 mm cavity – 8 mm laminated)	35 mm internal grey matt aluminium	Automated with manual override	Aug. 28th Sept. 2nd, 3rd, 8th, 9th, 14th, 18th, 20th 27th Oct. 2nd
C	**DSF - CCF** DGU (8 mm glass with solar coating 70/50 - 18 mm cavity – 8 mm laminated) + 100 mm cavity + 8 mm clear glass	35 mm, located in the CCF cavity, grey matt aluminium	Automated with manual override	Oct. 10th, 12th, 17th, 21st, 22nd, 23rd, 28th, 30th Nov. 4th, 6th

amount of direct solar radiation on the occupant's body, however the transmitted solar radiation was monitored by pyranometers mounted vertically on the façade, behind the blinds.

For this exploratory campaign, a total of ten volunteers agreed to participate in the experiment (6 females and 4 males, age 20–35 years old, 50% University of Cambridge students and 50% University of Cambridge staff). Prior to embarking on a larger-scale study with a significantly increased number of participants we wished to establish whether the methodology we put into place in this study is suitable and effective for gathering the quantity and type of data required for a definitive multi-domain assessment and that an integrated multi-domain approach to assess façade influence would reveal promising results. In other words, we wished to first establish that our approach justifies further investigation with the associated higher experimental effort and costs. However, if the results from the campaign are convincing, a larger number of volunteers may be required in subsequent research work.

Volunteers had no record of abuse of alcohol or drugs, had full colour vision, were generally healthy, a C2 level of English [37], and a body mass index in the range 18–25 kg/m^2. The volunteers were recruited by email invitation. The study was approved by the Ethics Committee of the Department of Engineering at the University of Cambridge, UK. Volunteers were invited to spend three working days (9:00–17:00 h) in MATELab, one day per scenario. 50% of the volunteers experienced scenario A as the first scenario, followed by scenarios B and C. The other 50% experienced scenario B as first scenario, followed by scenarios A and C. Therefore, the number of volunteers that first experienced scenario A and the number that instead first experienced scenario B were balanced, while scenario C was always conducted last since a completely different façade had to be installed.

Experiments to test the influence of the selected typologies and controls on occupant multi-domain environmental satisfaction and interaction were conducted only during days in which the sky was clear or low cast. Volunteers sat at the same position, 1.0 m from the façade and parallel to it (location 1 in Fig. 3a). Upon their arrival, volunteers were asked for consent to participate in the experiments, provided with the information sheet, and the purpose of the experiment was explained to them. Fig. 4 shows the schedule of the experiments. On the first day of experiments, volunteers were asked to complete an anonymous survey that was designed to collect general information, e.g. demographic information on the participants, etc., after which they received an identification code, which they were asked to use for logging in to the device (referred as the polling station) provided to record their level of satisfaction with the space throughout the day. Volunteers were informed that the experiments were designed to establish their general satisfaction with the office space, but they were not informed that the purpose of the experiments was to test the influence of the façade. They were requested to perform their daily desk-top work activities on their personal laptop and were provided with a chair and desk, including a fixed computer screen, keyboard and mouse. The view from their seated position was over a green space with trees (see Fig. 1a). A lunch break was permitted between 12:30 and 13:00, and bathroom breaks whenever they were required.

Occupants were requested to express their level of discomfort with the thermal, visual, air quality, acoustic and personal control by using the colour-coded buttons on their individual polling station. An image of the polling station is shown in Fig. 5 and its design is discussed in Ref. [19]. The same polling stations were also used to display questions to the volunteers for collating information on their satisfaction with the environment. Every hour, a reminder, in the form of a bright light, on the polling station would alert the participants to reply to the set of questions displayed on the polling station. The questions were formulated in order to solicit the participants' level of agreement with a sentence, which they indicated by using the slider on the polling station to give a vote from 1 to 5 (where 1 corresponded to the lowest and 5 the highest level of agreement with the sentence). The questions, listed in Appendix B, covered the following domains: thermal, visual (specifically enquiring about glare, daylight and view), air quality, acoustic and personal control. Appendix B also reports information on the validation of the questions by previous work. Questions on the volunteers' satisfaction with the office space, their level of concentration and perceived

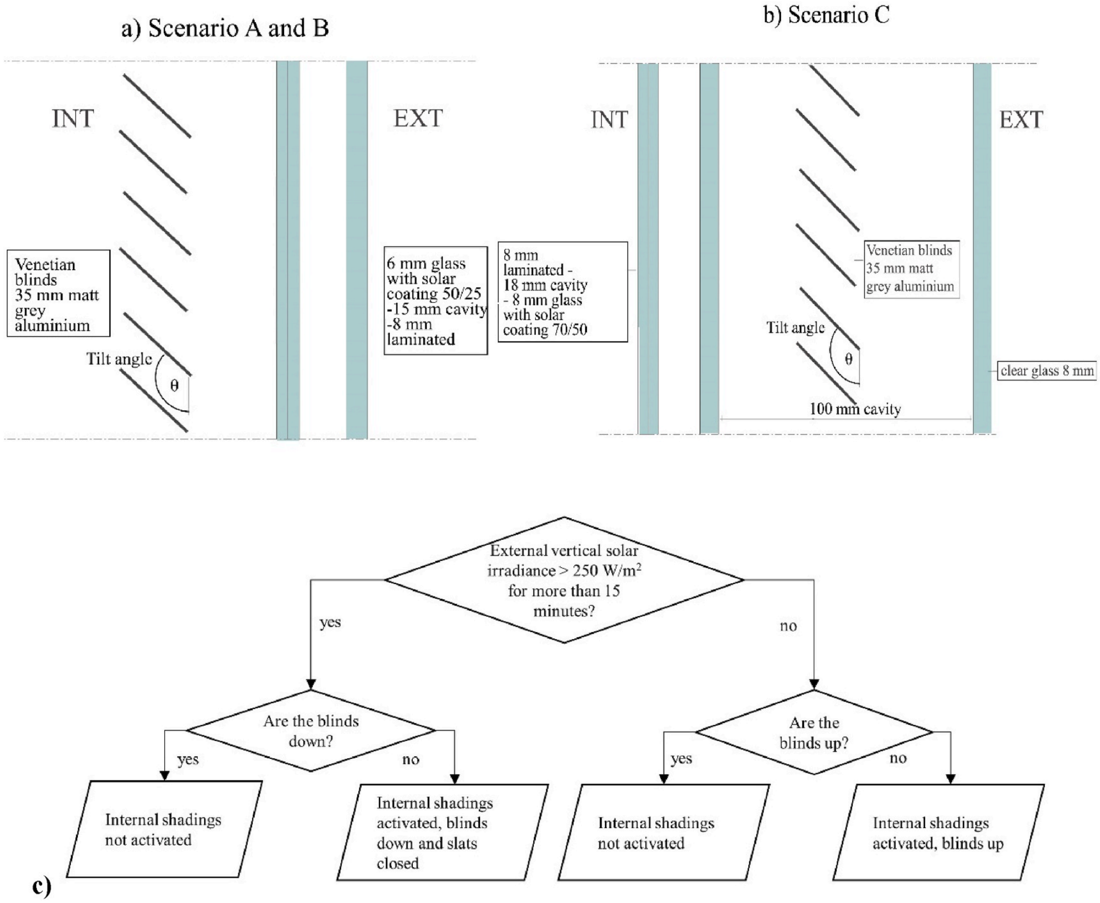

Fig. 2. Key features of the façades tested shown schematically: a) façade investigated in scenarios A and B: DGU with internal venetian blind; b) façade investigated in scenario C: CCF with venetian blind in the cavity. Full specifications are provided in Table 1. EXT and INT refer to the external and internal environment, respectively; c) control algorithm for the automated strategy.

Table 2
Information on the building services: set points, control strategy and occupant interaction.

Building service	Setpoints	Occupant override
Cooling	25 °C from 7 a.m. to 6 p.m.	Not permitted
Ventilation	50 l per second minimum	Not permitted
Lighting	Dimmable lights, controlled by a light sensor on the luminaire to provide 450 lx on desk when the room is occupied. Occupancy is assessed by a movement sensor.	Not permitted

productivity were also asked.

The same questions were also accessible through an app on their mobile phone. At the end of the three experimental days, the volunteers were also asked to complete a final questionnaire with specific questions on the different façade typologies they had experienced and the actual aim of the experiment was then revealed.

The polling station and the app were also used to measure other factors that could have potentially influenced occupant response (factors referred to as covariates in section 4.3). Since the experiments were conducted across several days and participants could have experienced different levels of habituation to the space, moods, stress levels, fitness condition, workload or rest, a number of general questions on these factors were also asked.

Every morning upon their arrival, the blinds were re-positioned with the bottom rail at its lowest position (at floor level) and with the slats in the horizontal position in order to provide identical initial conditions across the different scenarios. Since some knowledge on the rationale behind automated controls has been shown to improve user acceptance [25], volunteers were informed at the beginning of each experimental day that the automated control of the lighting, cooling, ventilation and façade blinds was driven by energy efficiency. Volunteers could control the blind position via wall-mounted switches (Fig. 5b), which were easily accessible from their sitting positions for the West bay, while they had to stand up to reach the East bay switches. Every time the volunteers wanted to interact with the façades, they were asked to record the reason for overriding using the app on their mobile phone.

3.3. Data processing and statistical analysis

The experiments were performed as repeated measures to assess the occupants' level of environmental satisfaction, perceived productivity, ease of concentration and contentment with the office space. In addition, the number of discomfort events and interactions of occupants with the façade across the scenarios were also monitored. Table 4 shows the independent, covariate and dependent variables considered in the experimental design. Covariates are independent variables that can influence the outcome of a dependent variable, but are not of direct interest. Potential covariates were considered, either by measuring and including them as variables in the experimental design, or by ensuring an equal number of scenarios for each value of the variable, balancing them across the experiment. Sky condition was not considered as a covariate since the experiments took place exclusively during clear or low cast days. The outdoor temperature and the sun elevation varied in the two-month experimental period and therefore were both considered as

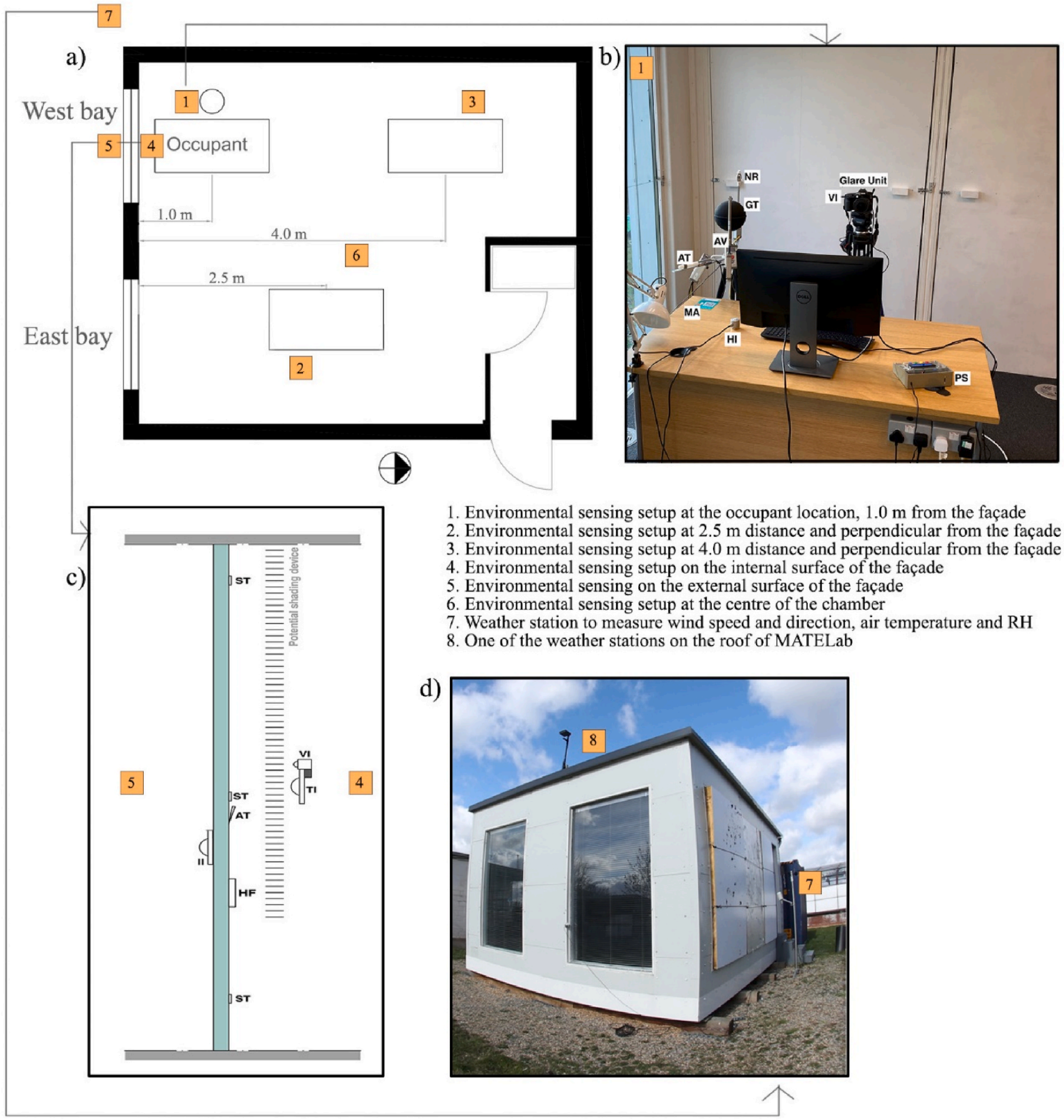

Fig. 3. Environmental sensing setup during the experiments (after [19]) (for label descriptions, see Table 3): a) plan view with location of the environmental sensing setups across the floor plan; b) view of the environmental sensing setup at the occupant desk location (1); c) section view of the environmental sensing setup on the internal (4) and external side (5) of the façade; d) view of two of the weather stations (7,8). The characteristics of the sensors are reported in Appendix A.

covariate variables. The effect of different outdoor temperature on the results is discussed in Appendix C. Sun elevation was dependent on time of the day, therefore it was excluded as a covariate. Time of the day and orientation of the façade are also potential covariates, but all the volunteers were exposed to the same orientation and for a whole day in all the scenarios. Therefore, orientation of the façade was excluded but time of the day included to account for the effect of different sun elevation angles and potential effects on occupant visual perception due to the time of the day.

The total number of "discomfort events" were measured by counting the number of times the volunteers pressed the corresponding colour-coded button. The difference in the number of discomfort events was used to compare the scenarios. The number of volunteer interactions with the blinds were also considered by counting the total number of interactions per day and logging the reason for interacting with the blinds.

4. Results

4.1. Occupant-blind interaction

Fig. 7 shows the blind position and slat angle during the three experimental scenarios A, B and C. Similar to the findings of previous work [10], the scenario with the façade A, which was the manually operated scenario, registered a very low number of interactions.

The blinds were left down (i.e. with the bottom rail at floor level) and with the slats horizontal for the whole day, since occupants very rarely interacted with the blinds. Table 5 shows the cumulative percentage of time that the blinds were left up or down. During scenario A, the blinds were fully down and with slats horizontal for more than the 90% of the occupied time. The façade was not occluded for the largest amount of time during scenario C (circa 50% of the time), followed by scenarios B and A. Scenario B recorded a much higher number of occupant interactions than scenario C.

As shown in Fig. 8a-b, occupants were equally satisfied with the automation strategy in scenario C when the blinds were being fully

Table 3
Environmental parameters monitored at the façade (locations 4 and 5 in Fig. 3a), centre of the test room (location 6 in Fig. 3a), occupant position (location 1 in Fig. 3a), at distances of 2.5 and 4.0 m from the façade (locations 2 and 3 in Fig. 3a) and outdoors (locations 7 and 8 in Fig. 3a).

Comfort domain	Sensor locations					
	Façade (4 and 5 in Fig. 3a)	Occupant position 1 (1 in Fig. 3a)	Building services	Occupant positions 2 & 3 (2 and 3 in Fig. 3a)	Centre of the test room (6 in Fig. 3a)	Outdoor (7 and 8 in Fig. 3a)
Thermal comfort	Surface temperature (**ST**) at multiple locations Air temperature (**AT**) Global transmitted vertical irradiance (**TI**)	Air temperature (**AT**) Globe temperature (**GT**) Air velocity (**AV**) Net radiation (only at the closest position to the façade) (**NR**) Surface temperature of walls closest to the occupant (**ST**)	Inlet air temperature before entering the plenum (**IAT**) Air flow rate before entering the plenum (**AFR**)	Air temperature (**AT**) Globe temperature (**GT**)	Air temperature (**AT**) Relative humidity (**RH**)	Solar beam radiation (**SB**) Horizontal global Irradiance (**HI**) Sun elevation and azimuth (**SEA**) Global incident vertical irradiance (II) Air temperature (**AT**) Relative humidity (**RH**) Wind speed and direction (**WSD**)
Visual comfort	Vertical illuminance transmitted (**VI**)	Horizontal illuminance on desk (**HI**) Vertical illuminance at eye level (**VI**) Luminance map of fixed view (**Glare unit**)	Illuminance at the luminaire (**IL**)	Horizontal illuminance on desk (**HI**) Vertical illuminance at eye level (**VI**) Luminance map of fixed view (**Glare unit**)		Outdoor illuminance (**OI**)
Air quality comfort			CO_2 level (**CO_2**)		CO_2 level (**CO_2**) VOC levels (**VOC**)	
Acoustic comfort					Noise Level (**NL**)	
Interaction	Façade state (**FS**), e.g. blind position and height, or glass					

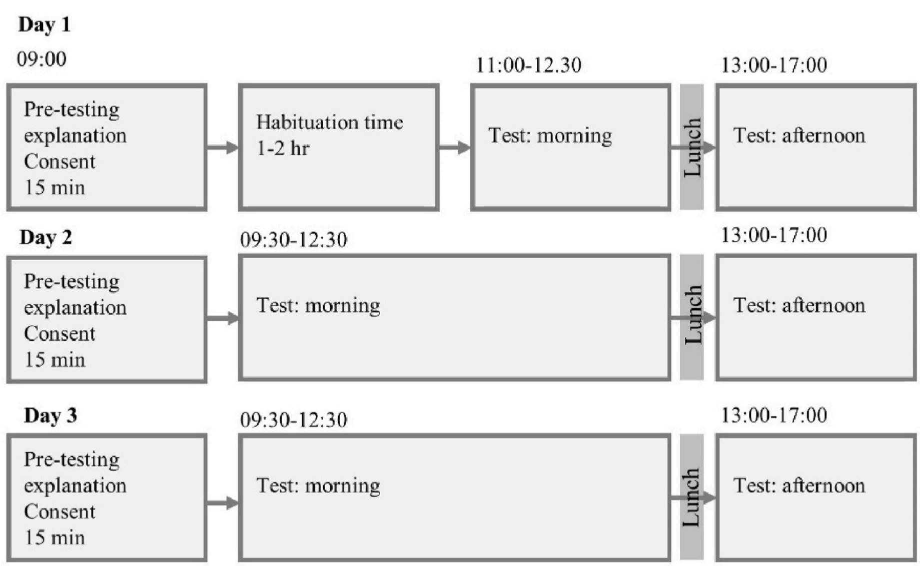

Fig. 4. Experimental procedure during the three experimental days.

lowered or raised automatically (note the similar position of the green boxes in subplots a) and b)). The analysis of the comments given by the occupants via the mobile-phone app indicated that they did not notice when the façade in scenario C was moving since the noise from the blind operation was very low. Conversely, for scenario B, the occupants were considerably more satisfied with the automation system when the blinds were being raised rather than lowered (note the different position of the blue boxes in subplots a) and b)). This is also confirmed by the largest number of overrides, which were performed in scenario B to raise the blinds and restore daylight or view. Differences in the number of interactions were also due to the lower frequency of occupant discomfort and differences in indoor environmental quality, depending on the façade technology as discussed in the sections that follow. Fig. 8.c shows the total number of interactions per façade and per reason of interaction. In scenario C, the automated control was overridden only nine times, either to increase the amount of view or daylight, or to mitigate glare, in contrast with scenario B where occupant interaction to restore daylight or view were more frequent (thirty-two in total). The façade bay on the east side was the bay furthest from the occupants and, therefore, it registered a slightly lower number of interactions than the west side. Overall, most occupant interactions were caused by visual discomfort, only on seven occasions in total, occupants interacted because of thermal discomfort with the environment. Other reasons for interacting were not selected.

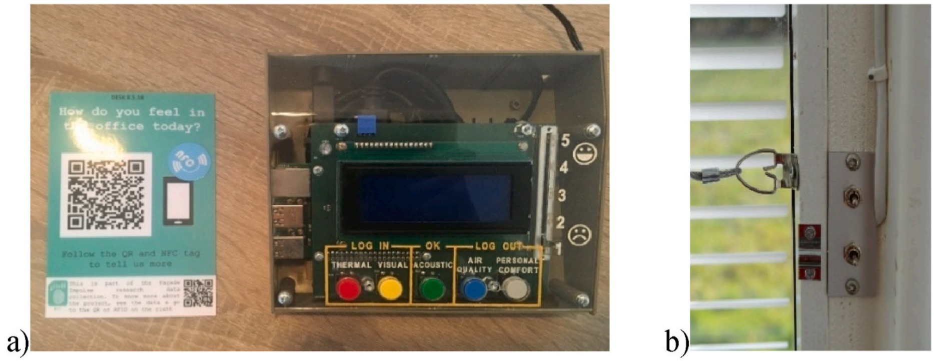

Fig. 5. Occupant interfaces used to solicit feedback. a) On the left, the quick response (QR) code and near-field communication (NFC) tag to open the app on the volunteers' mobile. On the right, the polling station used to gather feedback on discomfort and transient levels of environmental satisfaction, after [19]. b) The switches used by the volunteers to control the blinds.

Table 4
Variables considered in the experimental design.

Independent variables	Covariates (measured)	Covariates (balanced)	Dependent variable
Type of façade or control	Level of habituation	Gender	Thermal satisfaction
	Enjoyment of task	Order[a]	Visual satisfaction
	Level of happiness		Air quality satisfaction
	Level of workload		Acoustic satisfaction
	Level of rest		Personal control satisfaction
	Level of fitness		Level of perceived productivity
	Sun elevation		Level of concentration
	Time of the day		Number of interactions
	Outdoor temperature		Contentment with the office space
			Number of discomfort events

[a] Only between the scenario A and B, not the scenario C.

4.2. Environmental quality

4.2.1. Thermal quality

The operative temperature at three distances from the façade, namely, 1.0 m, 2.5 m and 4.0 m, was evaluated from the measurements of globe temperature, air temperature and air velocity described in Appendix A. The measurements were performed at a sampling rate of 1 s and averaged over 1 min. Fig. 9 shows the average operative temperature at each location and the thermal comfort range, which was computed from ASHRAE 55 [39] to be between 22.5 and 26.0 ± 0.15 °C, considering a metabolic rate of 1.1 met, 0.7 clo for the clothing level (long trousers and shirt sleeves). In order to compute the convection heat transfer coefficient, the air speed was measured at the occupant position by the anemometer reported in Table A1 in Appendix A, while for the occupant locations of 2.5 m and 4.0 m it was estimated to be less than 0.2 m/s since the underfloor air distribution system had low air flow velocities (below 0.2 m/s). The relative humidity was measured at the centre of the room and it had a daily average of 50% ± 1%. Across all the experimental scenarios, for the locations further from the façade (2.5 m and 4.0 m) the operative temperature was almost always within the comfort range during the occupied hours (09:00–17:00 h). However, this operative temperature did not take into account the effect of the direct solar radiation on comfort, which increases the occupants' exposure to radiant heat and therefore the perceived mean radiant temperature (MRT) [40].

Close to the façade, the operative temperature in the afternoon was above the comfort range for both scenario A and B, where a SSF with internal blind was tested. This façade technology is considered less effective in preventing overheating than the CCF tested in scenario C, since the blinds are internal rather than external and, therefore, admit solar heat gains even if the blinds are lowered. The operative temperatures alone (Fig. 9) are insufficient to confirm that scenario C was more successful in preventing thermal discomfort than scenarios A and B, because the outdoor temperature levels were different between scenarios A-B and C. However, the comparison of average glass surface temperature with the average net radiation in Fig. 10 shows that, despite the comparable levels of glass surface temperature between the scenarios, the net radiation at the occupant position was significantly lower for scenario C, thereby indicating that the internal blinds were reaching higher temperatures in scenarios A and B and emitting more long-wave radiation towards the occupant than in scenario C. This is particularly noticeable given that the average levels of transmitted solar radiation were higher for scenario C (Fig. 10c).

An analysis of the number of hours outside the comfort range (Fig. 10d) shows that, overall, the automated scenario with manual overrides (scenario B) was less comfortable than the manual scenario for the SSF with internal blinds (scenario A), while the automated CCF (scenario C) showed similar levels of thermal comfort to the manual scenario with SSF (scenario A).

4.2.2. Visual quality

Fig. 11a-c shows the average illuminance on the desk plane over the monitoring period and throughout the day at three distances from the façade. The levels of illuminance recorded at the occupant location 1.0 m from the façade differ significant between the three scenarios. Differences in horizontal illuminance between the scenarios were less noticeable at the larger distance from the façade considered (4.0 m from façade, Fig. 11c) since the daylight illuminance decreased with increasing distance from the façade. For all distances and scenarios considered, the illuminance levels were far above the minimum required level of 500 lx [41]. In scenario A, the blinds were often left fully down and at the horizontal position. As a consequence, daylight levels were lower than in the other scenarios, yet exceeded 1000 ± 30 lx on average. Fig. 11.d shows the distribution of horizontal illuminance for each experimental scenario. On average, the illuminance levels were rarely above the threshold of Useful Daylight Illuminance of 3000 lx, which is considered to be a proxy for excessive daylight levels [42].

At 2.5 m from the façade, the desk was aligned with the East bay, which was the façade bay further from the occupant and with which the occupant interacted the least. At the desk located 2.5 m from the façade, the levels of illuminance were higher in the automated scenarios (B and C) since in the manual scenario A the blinds of the left bay were often left fully lowered (as shown in Fig. 11b).

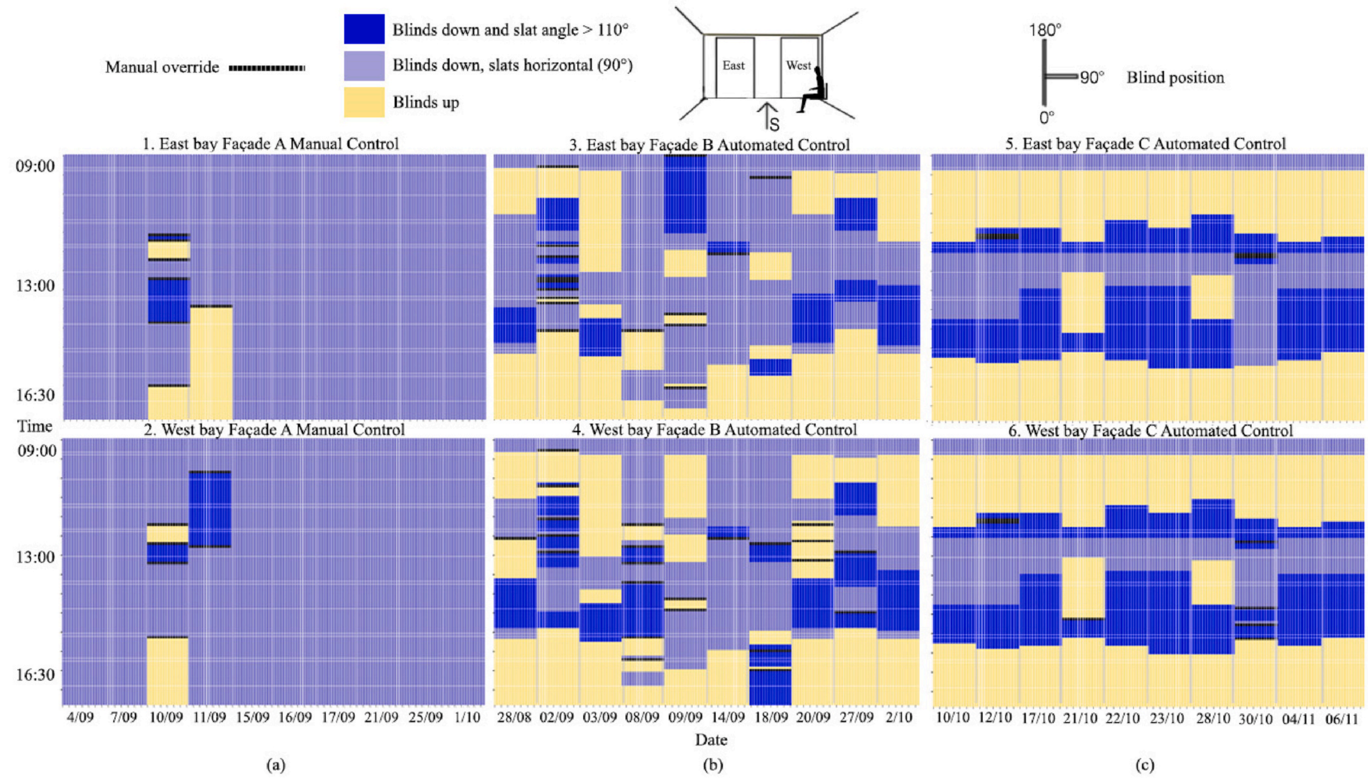

Fig. 7. Blind position and slat angle during the experimental scenarios A, B and C.

Table 5
Cumulative percentage of occupied time when blinds were in the fully lowered (starting position) or fully raised position for the different experimental scenario/façade typology.

Scenario	Fully lowered position and slat angle >110°	Fully lowered position and slat angle = 90°	Fully raised position
A	East: 4%; West: 2%	East: 93%; West: 92%	East: 3%; West: 6%
B	East: 18%; West: 23%	East: 49%; West: 40%	East: 33%; West: 37%
C	East: 28%; West: 28%	East: 22%; West: 22%	East: 50%; West: 50%

Fig. 12 shows the average vertical illuminance at the eye level and daylight glare probability (DGP) at the occupant position for the three scenarios. As described later in Section 5.2, in the manual scenario A, the blinds were almost always left fully lowered and horizontal and, therefore, the DGP levels were often lower than 0.35, which is considered to be the threshold for perceptible glare [43]. For scenarios B and C, blinds were often left fully raised, in particular this was always the case before noon, and therefore the DGP and vertical illuminance at the eye level were higher than in scenario A.

Although the automated control was identical between scenarios B and C, the level of vertical illuminance and the DGP were different because: i) occupant overrides were less frequent in façade scenario C; ii) façade C had a considerably lighter glass (70/50 *vs* 50/25, as shown in Table 1) and the sun elevation was slighter lower, as described in section 5.1, therefore potentially causing worse conditions for glare. Despite these limitations, the occupants were not overriding the façade so often in scenario C (CCF façade) but allowed the automated strategy to perform as programmed. This indicates that the automated CCF façade had a good glare mitigation performance. Overall, the DGP was rarely above the threshold value of 0.35, as shown in Fig. 11.e. In scenario C, DGP levels were occasionally very high, but in scenario B they were on average higher than in scenarios A and C. Since the automation strategy was a reactive strategy, wherein actuation is triggered when a pre-stablished threshold is reached, there was a time lag between the attaining of the control threshold and the activation of the blind. Therefore, during the time lag the vertical illuminance levels were

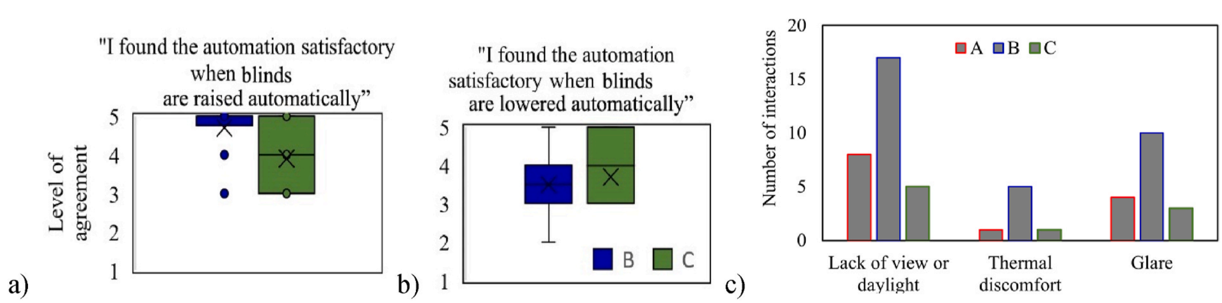

Fig. 8. a) Occupant's level of agreement with the statement "I found the automation satisfactory when blinds are raised automatically". The cross and the horizontal line indicate the average value and the median, respectively. The dots represent the outliers; b) occupant's level of agreement with the statement "I found the automation satisfactory when blinds are lowered automatically"; c) total number and reason for overriding façade blind position.

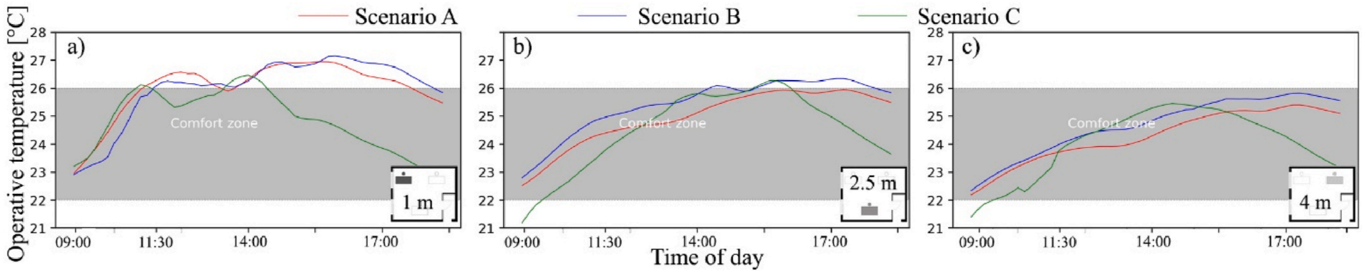

Fig. 9. Average operative temperature for the three scenarios at: a) 1.0 m; b) 2.5 m; c) 4.0 m from façade. The relevant desk location is shown in the inset floor plan.

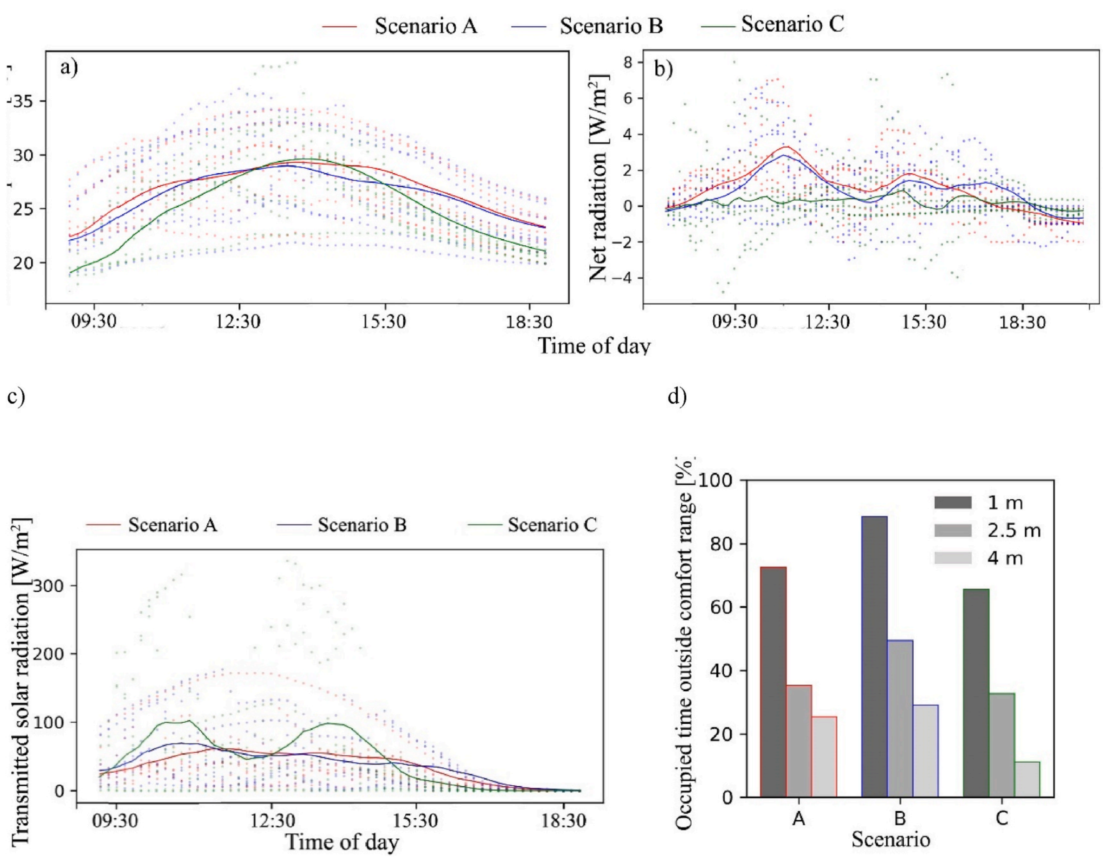

Fig. 10. Radiant heat gains from façade. a) Internal surface temperatures and average surface temperature of the glazing; b) net radiation and average net radiation at the occupant position towards the façade; c) transmitted solar radiation and average transmitted radiation for the three scenarios; d) percentage of occupied time when the operative temperature is above the comfort range (operative temperature >26 °C).

usually above the comfort threshold (on average around 11:30 a.m. when the sun entered the field of view).

4.2.3. *Acoustic and indoor air quality*

The measurement of sound pressure levels was performed with a sound level meter of accuracy class II [44] (details are reported in Table A1 of Appendix A) and measured as an equivalent continuous noise level with the frequency weighting curve "A" [45] (L_{Aeq}). Noise levels were recorded instantaneously and averaged over 1 min. As the heating, ventilation and air conditioning (HVAC) system was the only source of noise, the background noise level in the office was recorded to be 41 dB at the centre of the room, regardless of the scenario. Such low levels of background noise are explained by: 1) the absence of any noise source in the surroundings of the chamber given its isolated location; and 2) the low velocity of the air distribution system and, therefore, of the associated (low) noise level produced.

Fig. 13 shows the average equivalent continuous noise levels across the experimental days in each of the scenarios. The scenario with façade C was the least noisy, since the noise from the façade blind operation was very low in comparison to the noise produced by the blinds in scenarios A and B. The scenario with façade A was less noisy than scenario B since the façade blinds were operated less frequently.

In terms of indoor air quality, no significant difference in CO_2 or volatile organic compounds (VOCs) levels was found between the three scenarios - these results are reported in Appendix D. Details on the instrumentation used to monitor the indoor air quality are reported in Appendix A.

4.3. *Subjective assessment*

4.3.1. *Level of satisfaction*

The level of satisfaction with the office space, the thermal and acoustic environment, daylight, glare, view, air quality, personal control, level of perceived productivity, contentment with the office space

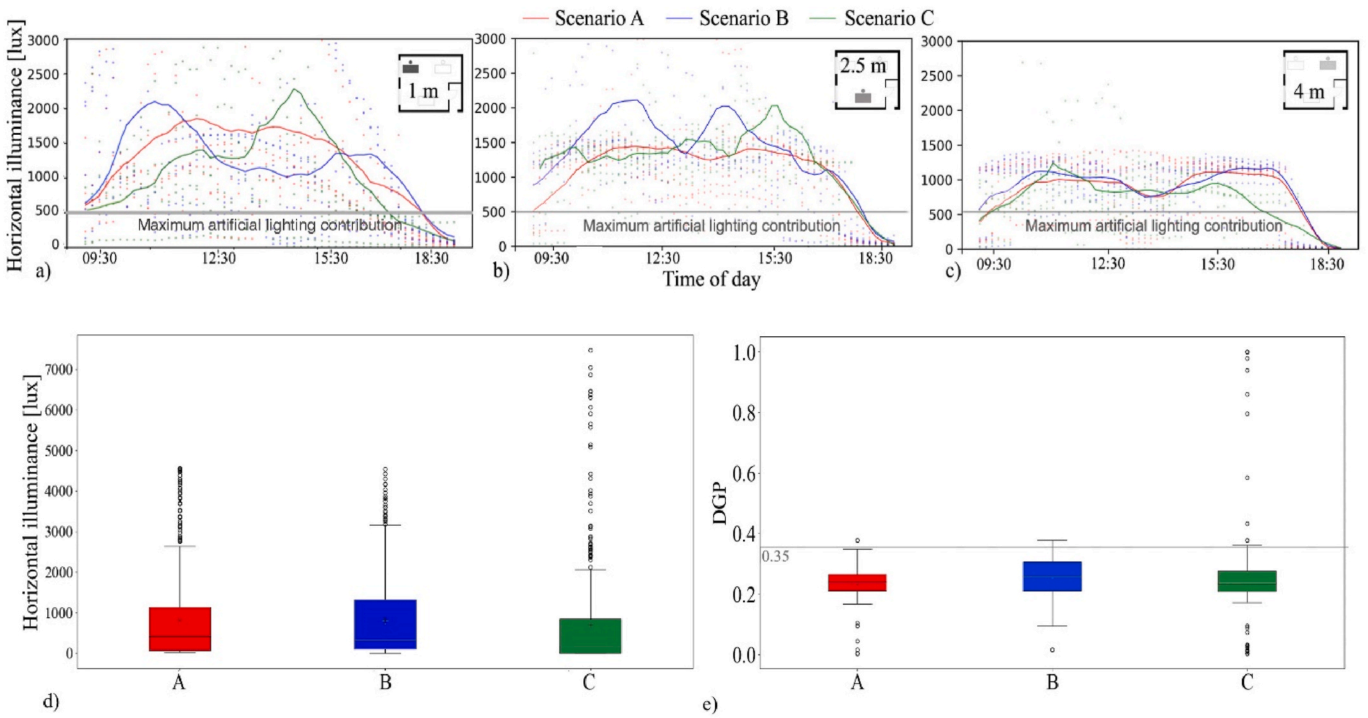

Fig. 11. Horizontal illuminance on the desk plane for (a) 1.0 m, (b) 2.4 m and (c) 4.0 m from the façade . d) horizontal illuminance on the workplace for scenarios A, B and C at occupant location 1.0 m from façade; e) DGP levels for scenarios A, B and C at occupant location 1.0 m from façade.

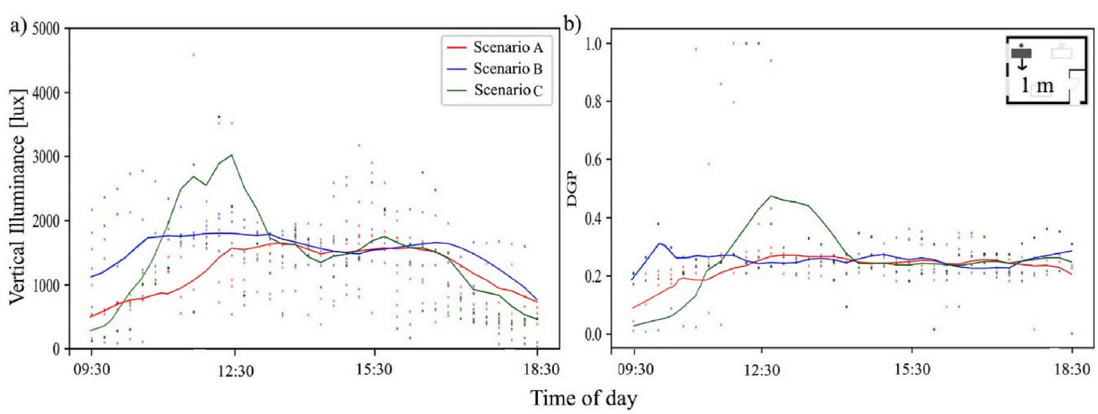

Fig. 12. a) Average vertical illuminance at the eye level and b) daylight glare probability (DGP) at 1.0 m from the façade on a typical day in September for façades A and B, and in October for façade C. The viewpoint was fixed and parallel with respect to the façade, the measurements were taken with a frequency of 15 min.

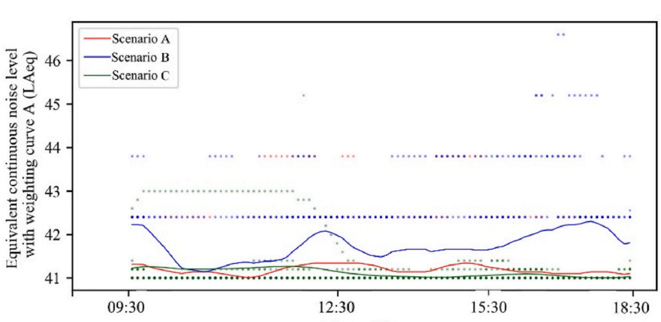

Fig. 13. Average equivalent continuous noise level frequency weighted with the curve A (L_{Aeq}) [45] across the scenarios.

and level of perceived concentration was recorded during the experiments Since the sample size was small, statistical significance was not computed. Nevertheless, the results here reported provide a preliminary assessment of the potential difference in occupant satisfaction that may be anticipated and confirmed by a larger sample size. The level of occupant satisfaction appears to be different when the results are analysed by the time of day, particularly during the afternoon when the sun was in the field of view, while the average level of satisfaction did not show large differences when averaged for the whole day (Appendix E). This trend was also shown in the indoor environmental quality data, shown in Section 4.2, where the main differences between the scenarios were reported when the sun was in the field of view.

In the afternoons, when the movements of the blinds were most frequent and the level of noise the highest, the average acoustic satisfaction was lower in scenario B than in scenarios A and C (Fig. 14c). The average thermal satisfaction in scenario B was also lower than in scenario C during the afternoons (Fig. 14a). A similar trend was shown for the satisfaction with the indoor air quality (Fig. 14b), although the air

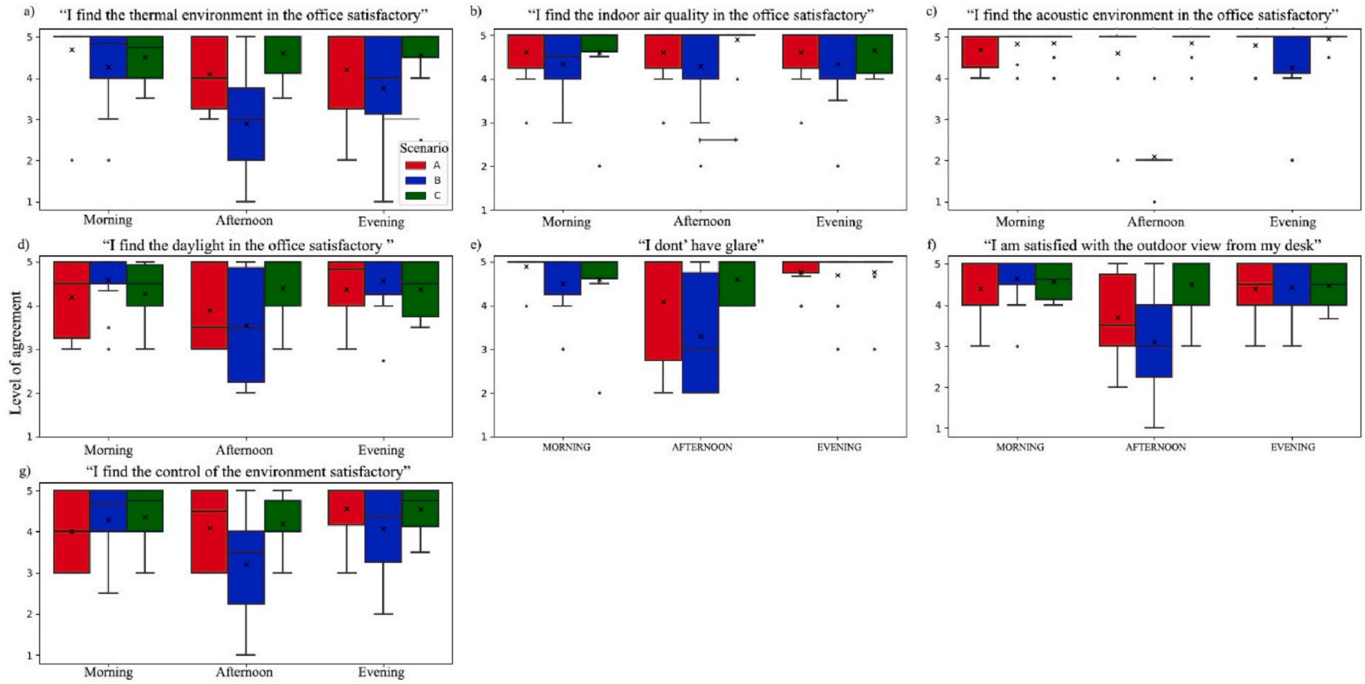

Fig. 14. Level of agreement with the statements above the subplots per time of the day.

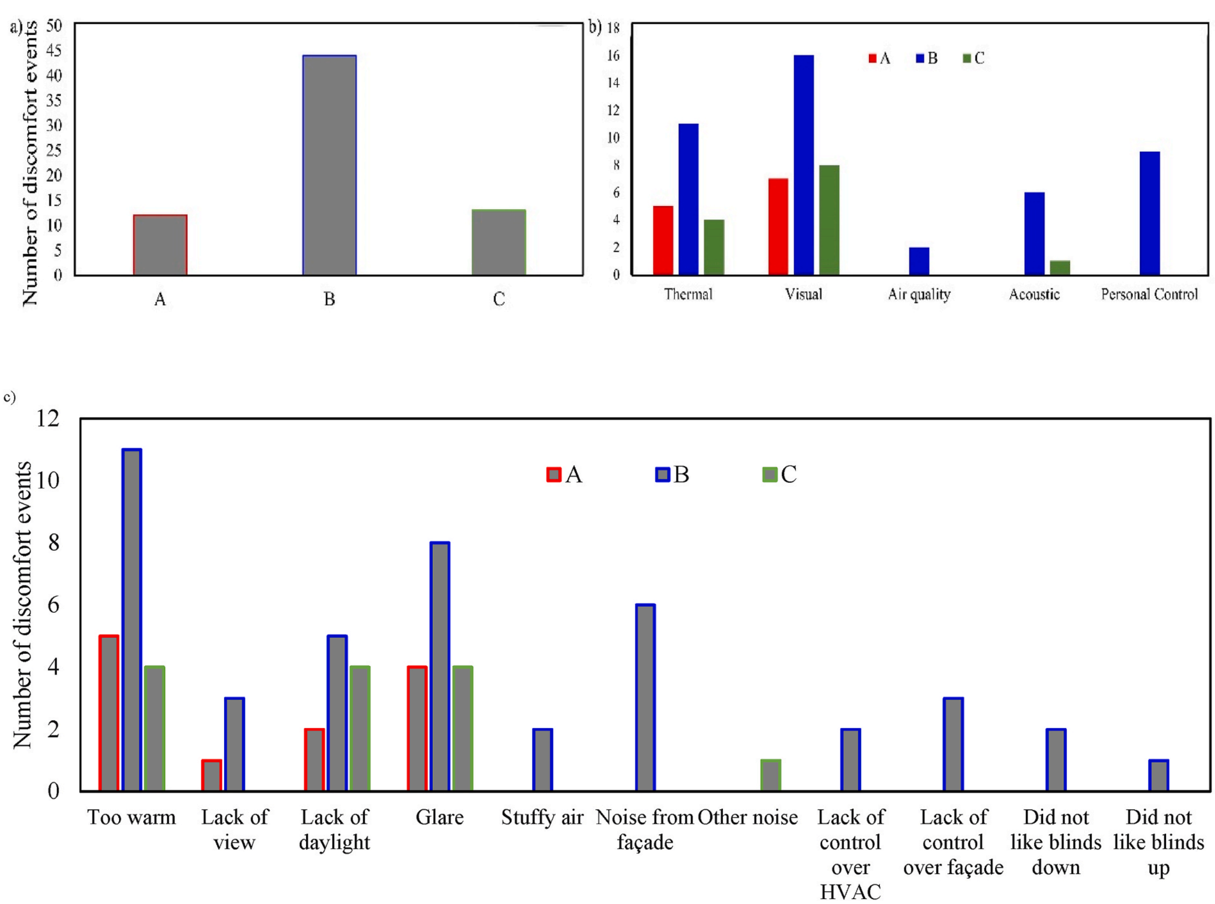

Fig. 15. a) Total number of discomfort events during the three experimental scenarios; b) discomfort events per scenario and comfort domain; c) number of discomfort events per motivation for pressing the discomfort buttons and per scenario.

quality monitoring did not show any differences between scenarios. This can be explained by the fact that occupants tend to confuse thermal perception with the perception of indoor air quality [46]. The satisfaction with the level of control was also lower for scenario B relative to scenarios A and C (Fig. 14g). This can be explained by the fact that occupants were more dissatisfied with the automated control during scenario B, thereby overriding the system more often and being more aware of their level of control, as also shown by the previous work of Stevens [22].

The satisfaction with the outdoor view (Fig. 14f) was lower in scenario A than in scenario C and this outcome was affected by the satisfaction with the level of rest. In scenario A, the venetian blinds were left fully lowered for a longer time and with the slats in the horizontal position, while in scenario C the blinds were, by comparison, deployed for significantly less time. The satisfaction with daylight followed a similar trend.

Even if glare was on average higher during scenario C, the satisfaction with glare was higher for scenario C than for scenarios A and B during the afternoon (Fig. 14e). The automated control prevented glare discomfort on several occasions while, in the manual scenario, blinds were lowered by occupants to mitigate glare only if they had already experienced discomfort glare with a consequential detrimental effect on occupant satisfaction with glare.

The automated control in scenario B was not appreciated by occupants who often chose to override it since they perceived it as disturbing. In scenario C, the control strategy was often left unchanged and therefore its performance was not disrupted by occupant interaction.

4.3.2. Discomfort events

As shown in Fig. 15.a, scenario B generated the largest number of discomfort events (measured by sum total the discomfort buttons were pressed). Scenarios A and C recorded a similar number of discomfort events. Discomfort was very often associated with the visual domain, followed by the thermal and the acoustic domains (Fig. 15b). Discomfort with IAQ and personal control was only recorded for scenario B. The largest number of discomfort events happened around mid-day. Fig. 15.c shows the number of discomfort events and the associated reasons. In terms of visual discomfort, this was often due to glare, followed by a lack of daylight and view. In terms of thermal discomfort, overheating was the main problem reported.

Discomfort with the noise from the façade was experienced by the volunteers during scenario B. In this scenario, volunteers were also the most uncomfortable with the level of personal control, either because they expressed dissatisfaction with the automated control actions, or because they felt their personal control of the façade was insufficient. This trend could have also been amplified by the fact that the highest number of environmental discomfort events were recorded for scenario B.

4.3.3. Overall occupant preference in scenarios and results summary

At the end of the three experimental days, occupants were asked to complete a final questionnaire with additional general questions on their overall experience of the scenarios. One of the questions was related to the preferred type of interaction strategy (Fig. 16a) and type of scenario (façade typology and interaction strategy) (Fig. 16b). Overall, occupants preferred a mixed control solution with automation and the option to override the controls. In terms of the preferred technology, despite a similar frequency of discomfort in scenarios A and C, as shown in Fig. 15.a, scenario C was preferred, with five out of ten volunteers reporting that they particularly liked the low noise levels and the "imperceptible" automated control of the façade. Two out of ten volunteers also reported that this was because the blinds were inside the façade cavity and therefore movements were less perceptible.

These results are also confirmed by comparison of the average levels of occupant satisfaction during the day and across the environmental domains, as shown in Fig. 16c-e. In these radar diagrams, each environmental domain is reported as being equally important, although the hierarchy of importance of each environmental domain is expected to be highly individual and to vary between occupants [47]. Scenario C showed the largest surface in the radar diagram. The success of scenario C relative to scenario B was due to the far less disruptive interaction strategy (lower noise and less perceived façade movements), which

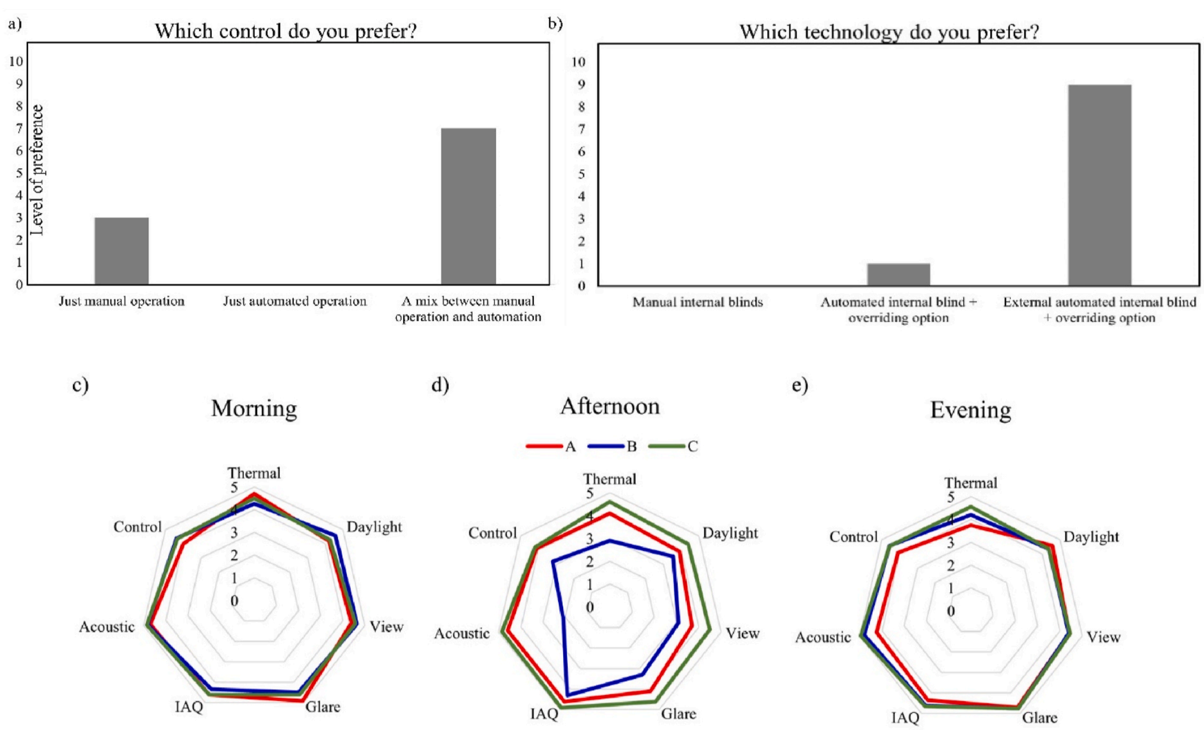

Fig. 16. Preference of occupants between: a) interaction strategies; b) façade typologies and interaction strategies. Averaged level of occupant satisfaction plotted as a radar diagram for the three scenarios A, B and C: (c) Morning (9:00–12:00); (d) Afternoon (12:00–15:00); and (e) Evening (15:00–18:00).

allowed the control strategy to perform at its best, preventing overheating and glare. The success of scenario C relative to A is due to a higher satisfaction with view and a lower discomfort with lack of view. Conversely, the levels of daylight and glare were better for façade A than for C, and the thermal satisfaction was marginally lower for A than for C, as also confirmed by the number of hours outside the thermal comfort range, which were comparable.

5. Discussion and conclusions

This paper presents the results of an experimental campaign on multi-domain environmental satisfaction with façades conducted in a test chamber designed specifically to monitor occupant-façade interaction that closely represents a real office environment. Alternative façade typologies (a SSF and a CCF) and interaction strategies (manual and automated control) were compared in terms of occupant interaction, environmental satisfaction and discomfort, and indoor environmental quality. Whilst our campaign involved a limited number of participants, whose perceptions were solicited over a relatively short period (circa 3 months) and, thus, our findings should not be generalised without the benefit of further data, the principal aim was to establish an initial proof-of-concept on whether an integrated multi-domain approach is required when comparing alternative façade typologies for occupant environmental satisfaction and interaction. We reason that expediting such a proof-of-concept by means of a smaller-scale campaign is both beneficial and necessary in order to be in a position to engender confidence in the outcomes and merits of a larger-scale study, particularly given the implications for cost and feasibility of the latter. Whilst we also acknowledge that there were marginally different outdoor conditions between scenarios A/B and C and in the order in which the occupants experienced these scenarios, the outcomes of our study undoubtedly provide new insights on the integrated multi-domain influence of façades on occupant interaction, satisfaction and discomfort, and may be used to guide larger-scale campaigns.

The results of the indoor environmental monitoring across the three scenarios showed that the effect of the façade on IEQ fluctuates in space and time, specifically it decreases with distance from the façade and varies with time of the day, being highest when the sun is in the field of view. Comparing the façades across the time of the day and at multiple occupant positions with respect to the façade is therefore essential to understand façade influence on the indoor environmental quality and occupant satisfaction. Results that are averaged over a whole day could lead to skewed conclusions, as shown in Appendix E.

The selected façade typologies and control strategies affected the thermal, visual and acoustic quality differently. Overall, the evidence pointed to scenario C (CCF with automated control and manual overrides) as providing improved thermal comfort conditions since the blinds were installed within the façade cavity and were therefore external to the indoor environment. Placing the blinds within the cavity resulted in a more effective control of the solar heat gains and a reduction of the long-wave heat transfer to the occupants - for scenarios A and B this transfer was higher than for scenario C because of the high surface temperature reached by the internal blinds, despite scenario C having a more transparent glazing. However, further work is required to confirm this since the outdoor boundary conditions were slightly different between scenarios A/B and C.

The performance of the façade was not only driven by the façade characteristics (e.g. type of glazing, position of the blinds, etc.) but also by occupant interaction with them. Occupant interaction with the façade varied significantly depending on: (i) whether the façade was manually controlled or automated and (ii) whether the automation control (if present) was accepted by the occupant or not. For instance, façades B and C had the same control strategy, however since the operation of scenario B was more disruptive to the occupants, the acceptance of the automated strategy was low and, as a consequence, occupants overrode the system more frequently than they did in scenario C. This evaluation was only possible since an integrated multi-domain perspective was adopted, which included the monitoring of indoor environmental quality and occupant perception/interaction with the four environmental domains and personal control.

In terms of visual quality, occupants found the automated controls in scenario C to be overall more acceptable and efficient in providing outdoor view, glare and overheating mitigation, whilst allowing daylight access. However, in terms of objective IEQ, other scenarios showed a better visual quality. For instance, in scenario A, daylight levels were higher than in scenario C, since the blinds were often left fully down but with the slats at the horizontal position while in scenario C, blinds were often fully-closed.

Occupants' preference for scenario C over the other scenarios appears to be driven by satisfaction with glare mitigation, view and acoustic quality. In terms of view, scenario B had access to an outdoor view (either blinds were fully raised or the slats were in the horizontal position) for a larger amount of time than for scenario A, but occupants seemed to be the least satisfied with access to an outdoor view during this scenario. This is because, even if the total amount of time with outdoor view access was similar or larger than for the other scenarios, the view was frequently disrupted by the automated control actions or occupant overrides. Conversely, in scenario C the blind control performed a lower number of actions and maintained an unobstructed view for longer. The better performance of scenario C in terms of outdoor view access was the main reason why occupants preferred scenario C to scenario A. Scenario C did record higher values of DGP as soon as the sun was in the field of view, since the glass was clearer and the blinds were fully raised in the first part of the morning due to the control threshold not being met until typically 11:30 h. However, the control in scenario C was able to respond efficiently to glare since the automated control actions were not overridden by the occupants, while in scenario B the average and the distribution of the DGP was higher than for the other scenarios because occupants often interacted with the system to restore daylight and view.

Based on our results we may assert that the success of a façade solution does not depend solely on the technology itself, or the type of control strategy, but also on the satisfaction of occupants with the interaction strategy. In other words, it is not sufficient to ensure that a certain thermal condition or light level is achieved, but it is essential to consider how it is achieved. In fact, the most successful façade solution was the one that fulfilled the requirements across all environmental domains and had the least disruptive interaction strategy. It is therefore essential for actuation and interaction strategies to be considered carefully in research, development and in the design of façades. Failing to do so may lead to a higher than predicted energy demand or a lower than predicted occupant satisfaction, or both.

Further research based on a greater number of participants is required in order to confirm the results from this exploratory campaign. A limitation potentially caused by the limited sample size is the lack of statistical significance in the difference of the agreement score between the scenarios. Moreover, the limited sample size did not allow an assessment of the cross-modal effects between different environmental domains. In order to compare the results from the proposed methodology with previous research work, the questionnaire we designed should be compared with established or traditional questionnaires in order to understand potential differences in occupant response.

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.

Acknowledgements

The authors would like to thank the Permasteelisa Group and ARUP for their financial and technical support during this research. The authors would also like to thank the EPSRC Doctoral Training Account and the Centre for Digital Built Britain (CDBB) for their financial support. GRH is grateful for the financial support of Innovate UK (grant no. 106163 Product Based Building Solutions - High Productivity Digital Integrated Assured DFMA for Lifecycle Performance) in collaboration with Laing O'Rourke and would like to extend his personal thanks to Prof. C. Middleton and the Laing O'Rourke Centre for Construction Engineering and Technology.

Appendix A. Indoor quality parameters monitored in this study

Table A1 reports information on the environmental sensing devices deployed in MATELab (after Luna-Navarro & Overend [19]). The DGP and the vertical illuminance were monitored behind the occupant using the equipment shown in Figure A1.

Table A1
Characteristics of the environmental sensing devices in MATELab.

Parameter	Technical characteristics of the sensor
Air and Surface Temperature (AT and ST)	4 wires Pt100 technology DIN A (Class A EN60751) Measurement range: 50 ÷ 70 °C Resolution: 0.01 °C Accuracy: 0.15 °C (at 0 °C)
Global transmitted an incident irradiance (TI and II)	Second class pyranometer ISO 9060 Spectral measurement range: 285 to 3000 × 10^{-9}m Rated operating temperature −40 to +80 °C Temperature response < ± 3% (−10 to +40 °C) Calibration uncertainty <1.8% (k = 2)
Heat flux metre	Heat flux plate Measurement range: +2000 to −2000 W/m^2 Sensitivity: 50 μV/Wm^2 Accuracy within +5/−5% on walls
Globe temperature sensor	Pt100 temperature sensor 150 mm diameter matte black globe Measurement range: 50 ÷ 70 °C Resolution: 0.01 °C Accuracy: 0.15 °C (at 0 °C)
Air velocity	Hot wire anemometer Measurement range: 0.01 ÷ 20 m/s Resolution: 0.01 m/s Accuracy: 0 ÷ 0,1 m/s
Net radiation	Thermopile Measurement range: 1500 ÷ 1500 W/m^2 Spectral range: 0,3 ÷ 50 μm Accuracy: 5%
Illuminance	Photodiode with filter for human eye response (Vlambda CIE) Cosine corrected Accuracy: 3% At the desk level: Measurement range: 0 ÷ 25000 lux Resolution: 3 lux At the façade: Measurement range: 0 ÷ 150000 lux Resolution: 10 lux
Relative humidity	Measurement range: 0 ÷ 100% Accuracy: ±1% RH (5–95%) Response time: 10 s (1 m/s air flow) Resolution: 0.1%
Luminance	HDR-imaging calibrated with spot luminance metre Canon EOS80D with Sigma fish eye lens with neutral density Filter 3.0 when needed Konika Minolta LS-150
CO_2	Infrared absorption method Range: 0 ÷ 5000 ppm
VOCs	Electrochemical cell technology Range: 0 ÷ 20 ppm
Noise level	Sound level meter Sauter SU 130 Range: 30–130 dB Resolution: 0.1 dB Accuracy: ± 1 dB Class II (ref.)
Direct normal irradiance on the roof	Pyrheliometer Spectral range: 200–4000 nm Field of view: 5 ± 0.2° Maximum Solar Irradiance: 4000 W/m^2
Global horizontal irradiance on the roof	ISO 9060 spectrally flat Class A Spectral range: 200–360 nm Sensitivity: 7–14 μV/W/m^2 Maximum Solar Irradiance: 4000 W/m^2 Response time 5s

(*continued on next page*)

Table A1 (*continued*)

Parameter	Technical characteristics of the sensor
Total UV radiometer	Spectral range: 280–400 nm Sensitivity: 300–500 μV/W/m^2 Response time < 1s Maximum UVA/UVB irradiance: 400 W/m^2
Wind speed	Range: 0 ÷ 75 m/s (damage limit) Accuracy: ± 0,5 m/s (0–10 m/s), 2,5% (>10 m/s)
Wind direction	Range: 0 ÷ 360° Accuracy 3°
Sun tracker and sun sensor	Fully automatic Sun tracker Integrated GPS receiver, BSRN level performance Pointing accuracy <0.1

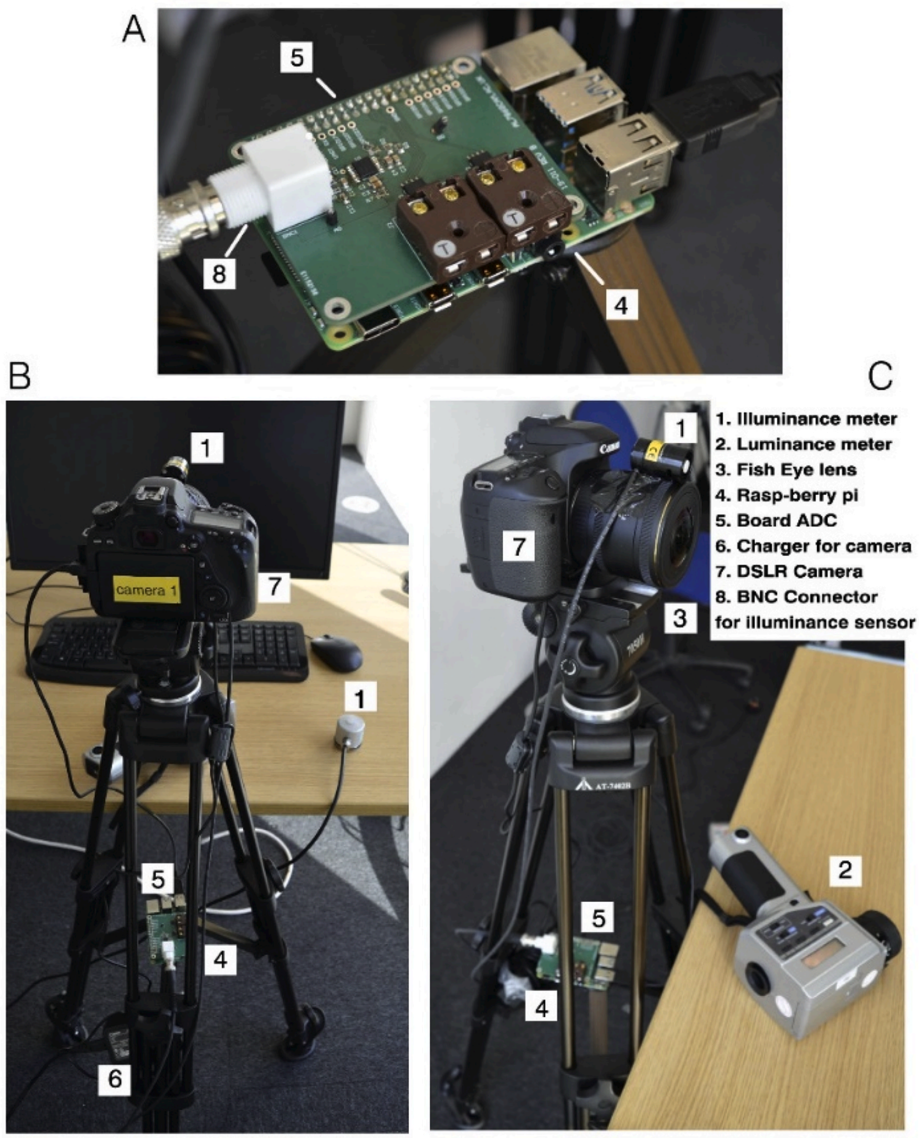

Fig. A1. Glare monitoring setup, located behind the occupant (after Luna-Navarro and Overend [18]).

Appendix B. Questions displayed on the polling station or the mobile-app

The questions displayed on the mobile app and on the screen of the polling station were designed in collaboration with the Department of Psychology at the University of Cambridge to measure the attitude of the volunteer towards a statement on the satisfaction with the environment and on statements concerning personal control, productivity, and concentration. The merits and rationale that underpin the design of this questionnaire have been established in previous work [10,48,49]. Posing the questions to volunteers in terms of their agreement towards a statement was preferred by the authors over directly posing the question on satisfaction to volunteers because direct questions on the level of satisfaction tend to be undiscriminating, in that they often give highly favourable results [50].

- To what extent do you agree with this sentence (1 strongly disagree to 5 strongly agree):
  1. I feel well with my workload
  2. I like my office space
  3. I feel happy
  4. I feel well-rested
  5. I am satisfied with my level of fitness
  6. I feel productive
  7. I find it easy to concentrate
  8. I find the thermal environment satisfactory
  9. I find the daylight in the office satisfactory
  10. I am satisfied with the outdoor view from my desk
  11. I don't have glare in the office
  12. I find the control of the environment satisfactory
  13. I find the air quality in the office satisfactory
  14. I find the acoustic environment in the office satisfactory
  15. I feel familiar with the office space
  16. I am enjoying my work task
- For how long have you been sitting at the desk?
- Please feel free to leave a comment

Appendix C. External weather during the three scenarios

Scenarios A and B were tested during the same period (September) and under similar outdoor conditions (sun elevation, outdoor radiation and temperature). Scenario C was tested in October and early November, therefore presenting some differences (e.g. of outdoor temperature, solar radiation and sun elevation) from the outdoor conditions of scenarios A and B. Figure C1 shows the incident vertical irradiance on the south façade, the average solar altitude and the key statistics associated with outdoor temperature distribution during scenarios A-B and C (Fig. C2). Because of the differences in outdoor temperature, a comparison of the thermal quality between scenarios A-B and C presents some limitations – this is discussed in Section 5. The solar radiation levels are evidently comparable across the three scenarios, particularly towards the middle of the day. In terms of visual satisfaction, the lower solar altitude in scenario C has the potential to cause a larger glare discomfort than in scenarios A-B and, therefore, create slightly detrimental visual conditions for scenario C. This limitation is also discussed Section 5. Due to the differences in solar irradiance and solar altitude, the automated control of the blinds in scenarios B and C was also slightly different since: i) in scenario C the threshold of irradiance was, on average, not met before 11:30 h, leaving the blinds raised for longer periods in the first part of the morning, whereas in scenario B the threshold vertical irradiance was already exceeded early in the morning; and ii) in scenario C the solar altitude is on average lower, causing the blind slat to be at angles exceeding 110° (as shown in Fig. 2.a.) and thereby reducing the level of daylight or view in comparison to scenario B.

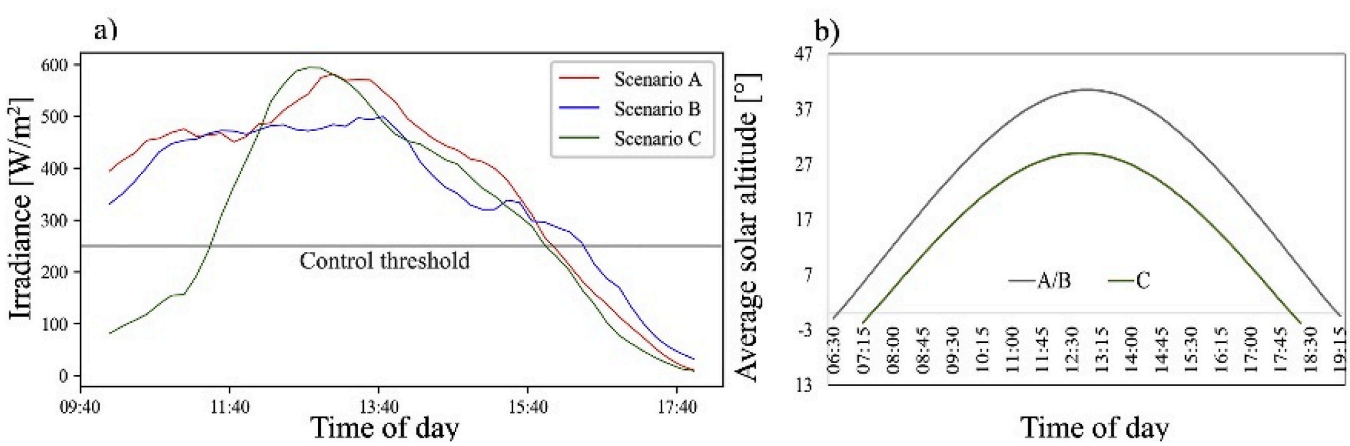

Fig. C1. Outdoor conditions during the façade test scenarios: a) external incident vertical irradiance; b) average solar altitude (retrieved from Ref. [51]).

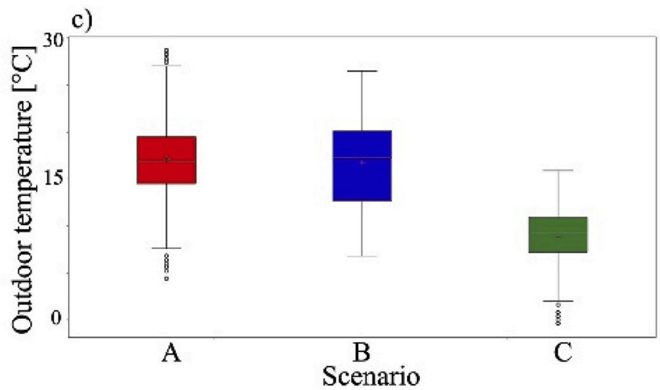

Fig. C2. Plot of the outdoor temperatures during the three scenarios - the coloured rectangles represent the second and third quartiles of the data distribution, the vertical bars indicate the interquartile range, the data points represent the outliers, the cross the average and the horizontal line the median. .

Appendix D. Air quality monitoring results

As shown in Fig. D1 and Fig. D2, the air quality was monitored by measuring the CO_2 and the Volatile Organic Compound (VOC) levels throughout the day. However, no significant differences were found across the scenarios.

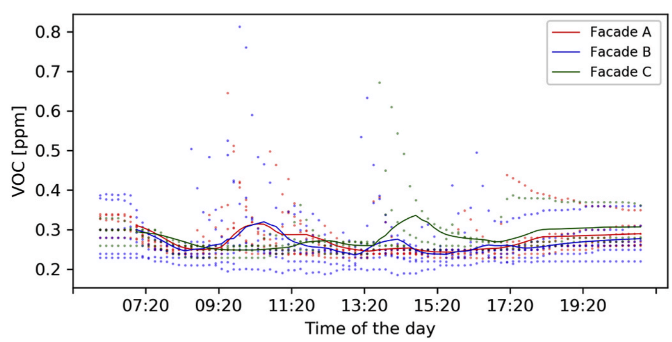

Fig. D1. Monitored levels of VOC throughout the day.

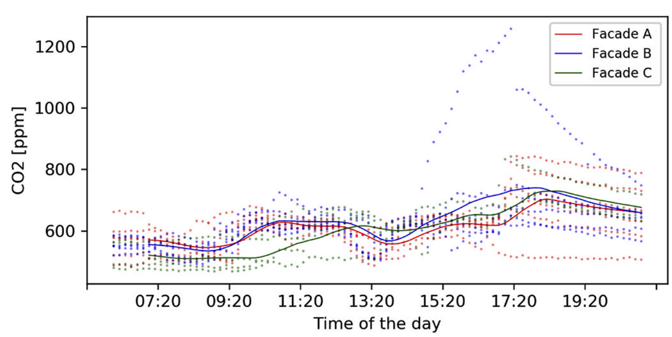

Fig. D2. Monitored levels of CO_2 throughout the day.

Appendix E. Occupant environmental satisfaction between the scenarios averaged over the whole day

As shown in Figure E1, in scenario C the occupants reported lower levels of satisfaction with the workload, task and rest, while in the scenario with façade B, occupants reported lower levels of rest and higher enjoyment of task relative to façade A. These results indicate that the operation of façade B, which was noisier, slightly affected the level of concentration but did not appreciably affect the perceived level of productivity. The satisfaction with the office space (Figure E1.b) was very similar between the scenarios.

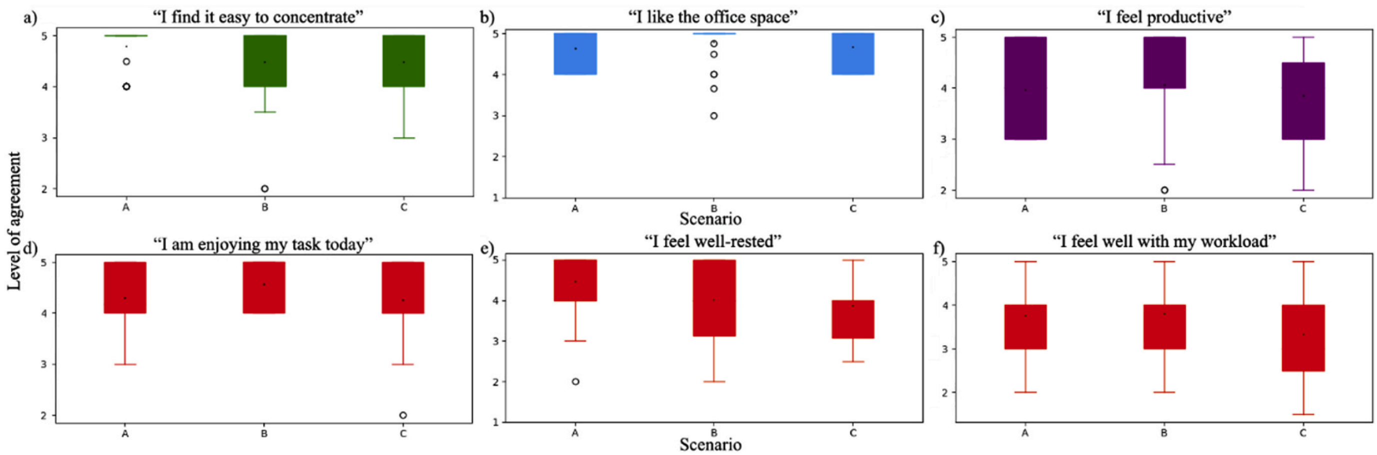

Fig. E1. Level of agreement with the statement given at the top of each subplot.

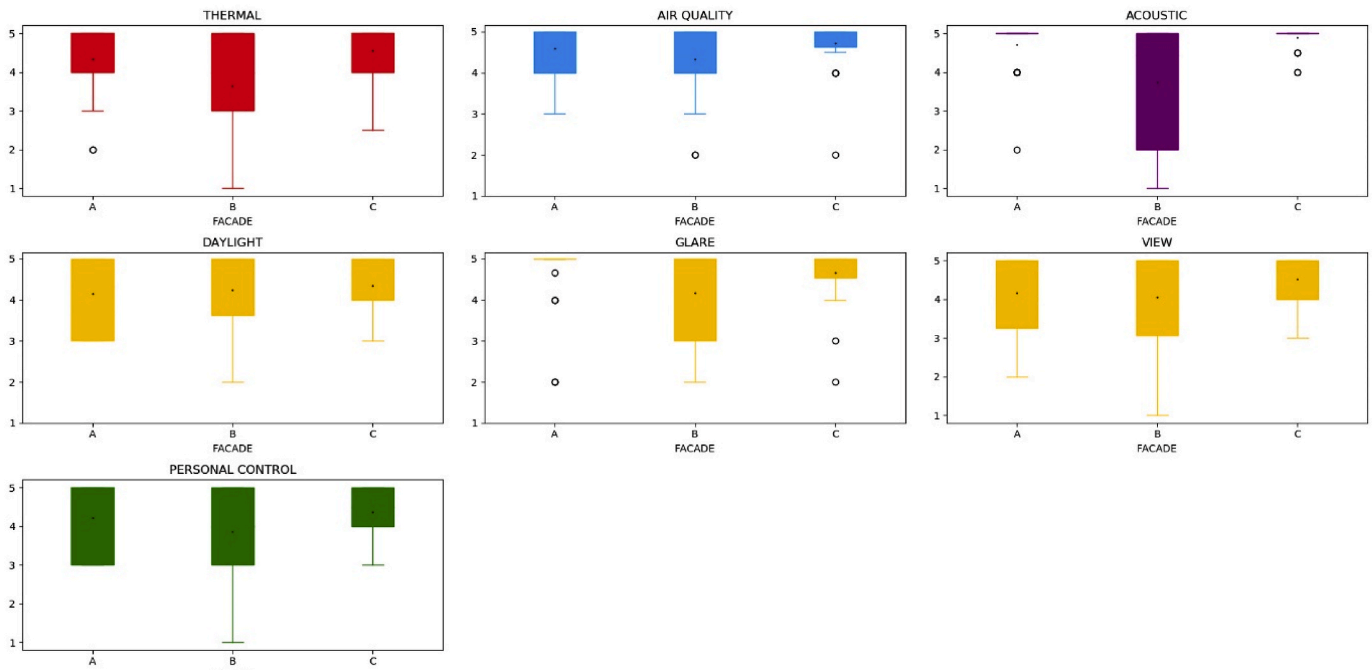

Fig. E2. Occupant satisfaction with the indoor environmental quality for whole day across the scenarios.

As mentioned in section 5.4, differences in the satisfaction of occupants with the indoor environmental quality when considering the average for the whole day were not significant (Figure E2), except for the thermal and the acoustic quality. Even if not significant, satisfaction with control, daylight and view was higher in scenario C, while occupants were overall more satisfied with glare mitigation in scenario A. However, considering the average for the whole day can underestimate severe uncomfortable conditions experienced at a specific time of the day.

References

[1] F. Favoino, M. Overend, Q. Jin, The optimal thermo-optical properties and energy saving potential of adaptive glazing technologies, Appl. Energy 156 (2015) 1–15, https://doi.org/10.1016/j.apenergy.2015.05.065.

[2] N. Lolli, A. Nocente, J. Brozovsky, R. Woods, S. Grynning, Automatic vs manual control strategy for window blinds and ceiling lights: consequences to perceived visual and thermal discomfort, J. Daylighting. 6 (2019) 112–123, https://doi.org/10.15627/jd.2019.11.

[3] E. Vine, E. Lee, R. Clear, D. DiBartolomeo, S. Selkowitz, Office worker response to an automated Venetian blind and electric lighting system: a pilot study, Energy Build. 28 (1998) 205–218, https://doi.org/10.1016/s0378-7788(98)00023-1.

[4] L.G. Bakker, E.C.M. Hoes-van Oeffelen, R.C.G.M. Loonen, J.L.M. Hensen, User satisfaction and interaction with automated dynamic facades: a pilot study, Build. Environ. 78 (2014) 44–52, https://doi.org/10.1016/j.buildenv.2014.04.007.

[5] S.A. Sadeghi, P. Karava, I. Konstantzos, A. Tzempelikos, Occupant interactions with shading and lighting systems using different control interfaces: a pilot field study, Build. Environ. 97 (2016) 177–195, https://doi.org/10.1016/j.buildenv.2015.12.008.

[6] B. Meerbeek, M. te Kulve, T. Gritti, M. Aarts, E. van Loenen, E. Aarts, Building automation and perceived control: a field study on motorized exterior blinds in Dutch offices, Build. Environ. 79 (2014) 66–77, https://doi.org/10.1016/j.buildenv.2014.04.023.

[7] A. Guillemin, N. Morel, Experimental results of a self-adaptive integrated control system in buildings: a pilot study, Sol. Energy 72 (2002) 397–403, https://doi.org/10.1016/S0038-092X(02)00015-4.

[8] K. Konis, Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in San Francisco, California, Build. Environ. 59 (2013) 662–677, https://doi.org/10.1016/j.buildenv.2012.09.017.

[9] A. Luna-Navarro, R. Loonen, M. Juaristi, A. Monge-Barrio, S. Attia, M. Overend, Occupant-Facade interaction: a review and classification scheme, Build. Environ. 177 (2020) 106880, https://doi.org/10.1016/j.buildenv.2020.106880.

[10] A. Luna-Navarro, P. Fidler, S. Torres, A. Law, M. Overend, Building Impulse Toolkit (BIT): a novel IoT system for capturing occupant-façade interaction in real office

environments, Build. Environ. 193 (2021) 107656, https://doi.org/10.1016/j.buildenv.2021.107656.

[11] J. Kim, S. Schiavon, G. Brager, Personal comfort models – a new paradigm in thermal comfort for occupant-centric environmental control, Build. Environ. 132 (2018) 114–124, https://doi.org/10.1016/j.buildenv.2018.01.023.

[12] C. Huizenga, H. Zhang, P. Mattelaer, T. Yu, E. Arens, L. P, Window performance for human thermal comfort. https://escholarship.org/uc/item/6rp85170, 2006.

[13] M. Frontczak, S. Schiavon, J. Goins, E. Arens, H. Zhang, P. Wargocki, Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design, Indoor Air 22 (2012) 119–131, https://doi.org/10.1111/j.1600-0668.2011.00745.x.

[14] S. Attia, S. Garat, M. Cools, Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades, Build, Environ. Times 157 (2019) 268–276, https://doi.org/10.1016/j.buildenv.2019.04.054.

[15] E. Lee, L. Fernandes, B. Coffey, A. McNeil, R. Clear, T. Webster, F. Bauman, D. Dickerhoff, D. Heinzerling, T. Hoyt, A post-occupancy monitored evaluation of the dimmable lighting , automated shading, and underfloor air distribution system in the New York Times Building. https://escholarship.org/uc/item/3km3d2sn, 2013.

[16] S. Nundy, A. Ghosh, Thermal and visual comfort analysis of adaptive vacuum integrated switchable suspended particle device window for temperate climate, Renew. Energy 156 (2020) 1361–1372, https://doi.org/10.1016/j.renene.2019.12.004.

[17] J.H. Choi, V. Loftness, D. Nou, B. Tinianov, D. Yeom, Multi-season assessment of occupant responses to manual shading and dynamic glass in a workplace environment, Energies 13 (2019) 60, https://doi.org/10.3390/en13010060.

[18] B. Meerbeek, M. te Kulve, T. Gritti, M. Aarts, E. van Loenen, E. Aarts, Building automation and perceived control: a field study on motorized exterior blinds in Dutch offices, Build. Environ. 79 (2014) 66–77, https://doi.org/10.1016/j.buildenv.2014.04.023.

[19] A. Luna-Navarro, M. Overend, Design, construction and validation of MATELab: a novel outdoor chamber for investigating occupant-facade interaction, Build. Environ. (2021) 108092, https://doi.org/10.1016/j.buildenv.2021.108092.

[20] L. Karlsen, P. Heiselberg, I. Bryn, Occupant satisfaction with two blind control strategies: slats closed and slats in cut-off position, Sol. Energy 115 (2015) 166–179, https://doi.org/10.1016/j.solener.2015.02.031.

[21] J.K. Day, B. Futrell, R. Cox, S.N. Ruiz, Blinded by the light: occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies, Build. Environ. 154 (2019) 107–121, https://doi.org/10.1016/j.buildenv.2019.02.037.

[22] S. Stevens, Intelligent facades: occupant control and satisfaction, Int. J. Sol. Energy 21 (2001) 147–160, https://doi.org/10.1080/01425910108914369.

[23] S. Grynning, N. Lolli, S. Wågø, B. Risholt, Solar shading in low energy office buildings - design strategy and user perception, J. Daylighting. 4 (2017) 1–14, https://doi.org/10.15627/jd.2017.1.

[24] M. Zinzi, Office worker preferences of electrochromic windows: a pilot study, Build. Environ. 41 (2006) 1262–1273, https://doi.org/10.1016/j.buildenv.2005.05.010.

[25] B.W. Meerbeek, C. de Bakker, Y.A.W. de Kort, E.J. van Loenen, T. Bergman, Automated blinds with light feedback to increase occupant satisfaction and energy saving, Build. Environ. 103 (2016) 70–85, https://doi.org/10.1016/j.buildenv.2016.04.002.

[26] R. Kelly Waskett, B. Painter, J. Mardaljevic, K. Irvine, R. Kelly, Retrofit electrochromic glazing in a UK office, J. Sustain. Des. Appl. Res. 2 (2014), https://doi.org/10.21427/D7WQ75.

[27] Z. Li, J. Ju, W. Xu, Daylighting control performance and subject responses to electrochromic windows in a meeting room, Procedia Eng. 121 (2015) 27–32, https://doi.org/10.1016/j.proeng.2015.08.1014.

[28] L.G. Bakker, E.C.M. Hoes-van Oeffelen, R.C.G.M. Loonen, J.L.M. Hensen, User satisfaction and interaction with automated dynamic facades: a pilot study, Build. Environ. 78 (2014) 44–52, https://doi.org/10.1016/j.buildenv.2014.04.007.

[29] T. Inoue, T. Kawase, T. Ibamoto, S. Takakusa, Y. Matsuo, The development of an optimal control system for window shading devices based on investigations in office buildings, Build. Eng. 94 (1988) 1034–1049, https://doi.org/10.1007/s13398-014-0173-7.2.

[30] K. Konis, S. Selkowitz, Effective Daylighting with High-Performance Facades, Springer International Publishing, 2017, https://doi.org/10.1007/978-3-319-39463-3.

[31] F. Stazi, F. Naspi, G. Ulpiani, C. Di Perna, Indoor air quality and thermal comfort optimization in classrooms developing an automatic system for windows opening and closing, Energy Build. 139 (2017) 732–746, https://doi.org/10.1016/j.enbuild.2017.01.017.

[32] E.S. Lee, E.S. Claybaugh, M. Lafrance, End user impacts of automated electrochromic windows in a pilot retrofit application, Energy Build. 47 (2012) 267–284, https://doi.org/10.1016/j.enbuild.2011.12.003.

[33] C. Goovaerts, F. Descamps, V.A. Jacobs, Shading control strategy to avoid visual discomfort by using a low-cost camera: a field study of two cases, Build. Environ. 125 (2017) 26–38, https://doi.org/10.1016/j.buildenv.2017.08.030.

[34] C.F. Reinhart, K. Voss, Monitoring manual control of electric lighting and blinds, Light. Res. Technol. 35 (2003) 243–258, https://doi.org/10.1191/1365782803li064oa.

[35] IQL, international quarter London, (n.d.). https://www.internationalquarter.london/. (Accessed 11 July 2021).

[36] Y.C. Chan, A. Tzempelikos, Efficient Venetian blind control strategies considering daylight utilization and glare protection, Sol. Energy 98 (2013) 241–254, https://doi.org/10.1016/j.solener.2013.10.005.

[37] European Union Commission, Common European framework of reference for languages, (n.d.). https://europa.eu/europass/en/common-european-framework-reference.

[39] ANSI/ASHRAE, ANSI/ASHRAE 55:2017 thermal environmental conditions for human occupancy, Ashrae (2017), https://doi.org/10.1007/s11926-011-0203-9.

[40] E. Arens, T. Hoyt, X. Zhou, L. Huang, H. Zhang, S. Schiavon, Modeling the comfort effects of short-wave solar radiation indoors, Build. Environ. 88 (2015) 3–9, https://doi.org/10.1016/j.buildenv.2014.09.004.

[41] CEN, Light and Lighting. Lighting of Work Places. Indoor Work Places EN 12464-1: 2011, 2011.

[42] A. Nabil, J. Mardaljevic, Useful daylight illuminances: a replacement for daylight factors, Energy Build. 38 (2006) 905–913, https://doi.org/10.1016/j.enbuild.2006.03.013.

[43] J. Wienold, Dynamic daylight glare evaluation, in: Elev. Int. Build, . Perform. Simul. Conf., Glasgow, UK, 2009, pp. 944–951.

[44] CEN, EN 61672 Electroacustic - Sound Level Meters, 2013.

[45] ISO, ISO 1996-1 Acoustics - Description, Measurement and Assessment of Environmental Noise, 2014.

[46] S. Gauthier, B. Liu, G.M. Huebner, D. Shipworth, Investigating the effect of {CO}2 concentration on reported thermal comfort, in: Proc. {CISBAT} 2015 {International} {Conference} {Future} {Buildings} {Districts}, {Sustainability} from {Nano} to {Urban} {Scale} ({Eds}. {Scartezzini}, {J}.-{L}., Al., 2015.

[47] M. Frontczak, P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments, Build. Environ. 46 (2011) 922–937, https://doi.org/10.1016/j.buildenv.2010.10.021.

[48] A. Luna-Navarro, M. Overend, Design and validation of MATELab: a novel full-scale test room for investigating occupant perception to and interaction with façade technologies, Sol. Energy (2021).

[49] A. Luna-Navarro, M. Allen, M. Meizoso, M. Overend, BIT-Building Impulse Toolkit: a novel digital toolkit for productive, healthy and resource efficient buildings, J. Phys. Conf. Ser. 1343 (2019), https://doi.org/10.1088/1742-6596/1343/1/012139.

[50] J. Bourke, et al., Survey & Questionnaire Design : Collecting Primary Data to Answer Research Questions, NuBooks, 2016.

[51] Suncalc, (n.d.). www.suncalc.org. (Accessed 1 April 2020).