Design, construction and validation of MATELab
A novel outdoor chamber for investigating occupant-facade interaction

Luna-Navarro, Alessandra; Overend, Mauro

DOI
10.1016/j.buildenv.2021.108092

Publication date
2021

Document Version
Final published version

Published in
Building and Environment

Citation (APA)
Luna-Navarro, A., & Overend, M. (2021). Design, construction and validation of MATELab: A novel outdoor chamber for investigating occupant-facade interaction. *Building and Environment*, *203*, Article 108092. https://doi.org/10.1016/j.buildenv.2021.108092

Building and Environment 203 (2021) 108092

Contents lists available at ScienceDirect

Building and Environment

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

Design, construction and validation of MATELab: A novel outdoor chamber for investigating occupant-facade interaction

Alessandra Luna-Navarro [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

A R T I C L E I N F O

Keywords:
Dynamic facades
Occupant comfort
Occupant interaction
Chamber
Test room

A B S T R A C T

Testing of novel facade technologies with human volunteers is essential for improving occupant interaction with novel dynamic facade systems and to increase satisfaction with its modulation of light, sound, heat and mass transfer between the outdoor and indoor environments. In the past 10 years, there have been noticeable attempts to develop chambers that endeavour to assess the influence of facade technologies on occupant environmental perception and occupant-facade interaction. This paper firstly reviews existing state-of-the-art chambers for occupant-facade interaction and establishes the principal design criteria and performance characteristics required for such facade test chambers. The paper then demonstrates how this information is used to design and construct MATELab, a facade test chamber in Cambridge, UK, devised for capturing occupant environmental perception to, and interaction with, the facade in a realistic, yet sufficiently accurate manner. Finally, results from a preliminary measurement campaign in MATELab are used to validate the experimental setup, in particular its ability to capture high-resolution data for assessing: (i) the influence of facades on Indoor Environmental Quality (IEQ); (ii) occupant environmental perception and interaction with the facade and (iii) do so similarly to typical office spaces. It was found that MATELab can successfully identify the correlations between facade performance and IEQ and that occupant response can be captured with sufficient frequency and in a realistic manner. However, further work is required to improve the experimental setup, in particular, to monitor luminance and direct solar radiation within the indoor space in a non-disruptive, yet experimentally efficient manner.

1. Introduction

The Indoor Environmental Quality (IEQ) plays a key role for occupant well-being and health in buildings [1], especially since urban inhabitants spend most of their time indoors. The aim of buildings is to provide a safe and comfortable environment for performing specific activities, however, despite the large amount of energy consumed to condition them [2], occupants often feel dissatisfied with the indoor environment [3].

The building envelope can minimise the energy needed to ensure comfortable indoor conditions by conveniently shifting thermal loads or controlling fresh air flow, daylight and solar radiation [4]. However, high-performance dynamic facades, which can dynamically modulate incident solar energy and thereby minimise lighting, cooling and heating demand [4] and improve occupant satisfaction [5], often fail to meet occupant demands and rarely communicate the energy-efficient strategy effectively to occupants. The challenge lies in the fact that occupant environmental perception of, and interaction with, facades is a multi-domain relationship and often some of the domain requirements are in conflict with another [6]. In addition, occupant-facade interaction (in terms of feedback, communication and personal control) also has a significant influence on the overall satisfaction with facade systems [6].

Experimental research on high-performance dynamic facade systems and associated controls must include occupants and should be performed in realistic scenarios in order to achieve occupant-centred solutions that can balance occupant multi-domain comfort and interaction expectations [6]. Laboratory tests are usually performed at component or product level but not at room level [7], therefore they cannot evaluate the influence of facades on IEQ and on occupant interaction, which requires realistic spaces and understanding of cross-modal effects between different domains. Several field studies have attempted to capture occupant-facade interaction in real-world buildings [8–13], but in such

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

https://doi.org/10.1016/j.buildenv.2021.108092
Received 15 May 2021; Received in revised form 21 June 2021; Accepted 22 June 2021
Available online 30 June 2021
0360-1323/

settings there are many confounding factors and it is therefore difficult to identify the effects of specific facade characteristics or control strategies without requiring statistical analyses on data from a large number of nominally identical tests [14]. It is therefore useful to test high-performance facades in research spaces that supports full scale testing of a representative portion of the facade, but where the researcher has full control over the experimental variables and can hence establish the effects on the dependent variables with relatively small amounts of data samples and human volunteers [15], which can help to reduce research costs and time. These realistic chambers provide a means for quantifying the impact of high-performance facades on comfort and compare alternative facade technologies in terms of occupant interaction.

There are several new research and development facilities that endeavour to test high-performance facades, but there are very few underlying design principles that are shared across these facilities. Fig. 1 shows the three broad categories of the relevant testing facilities. Some reviews on each of these categories are available in literature, namely: M. Schweiker et al. [1], and Pisello et al. [16] who reviewed the requirements for multi-domain comfort experiments and associated test rooms (A in Fig. 1); Cattarin et al.'s [17] review of outdoor test cells for characterising facade energy performance (B in Fig. 1). From these reviews it is evident that laboratories for multi-domain comfort (category A) are equipped to measure a large number of physical, psychological and physiological parameters, but facades are rarely installed in these settings since exposure to real weather conditions reduces the degree of control. On the other hand, the outdoor calorimetric test cells (category B) are equipped to capture the energy performance of complex facades exposed to real external environmental conditions, but the set-up does not include occupants. For instance, their geometrical dimensions and indoor appearance is often not suitable for hosting human volunteers. The EU-funded research network on Adaptive Facades [18] has also recently published a useful inventory of existing facilities for characterisation of high-performance dynamic facade, but it is limited to facilities within the European Union and it does not specifically focus on occupant comfort and interaction [7]. A review that acknowledges the need for attributes of both category A and category B in experimental facilities is work of Shafavi et al. [19], but this review focusses on methods for defining new visual comfort metrics rather than the multi-domain effect of alternative facade technologies.

The aim of the present paper is to establish the requirements of a facade research and development facility for capturing occupant environmental perception/interaction and to subsequently develop and validate such a test facility that meets these requirements. This is achieved by firstly reviewing existing experimental test chambers for capturing the effect of facades on occupants (C in Fig. 1) summarised in section 2, from which test chamber design requirements are extracted and listed in section 3. These requirements form the bases of the design and construction of the test chamber (MATELab, in Cambridge, UK),

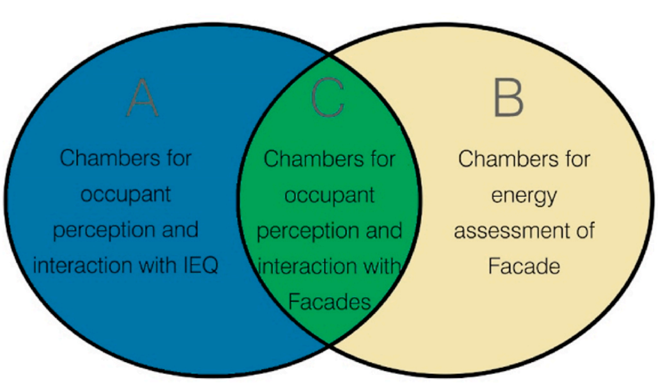

Fig. 1. Categories of facade-related or occupant-centred test facilities.

described in section 4. The associated methods for data collection are described in section 5, while the experimental validation of the novel test chamber is described in section 6.

2. Review of the existing laboratories for occupant-facade studies

Existing real-scale laboratories with occupant environmental perception and interaction capabilities are summarised in Table 1. These facilities were identified by one or more of the following:

- Communication and collaboration with experts in the Adaptive Facade community at the Working Group (WG) 2 of the "EU TU1403 Adaptive Façade Network COST Action".
- Communication and collaboration with experts on multi-domain occupant comfort and behaviour in the WG 1 of the IEA Annex 79;
- Searching in online databases of scientific literature (namely, Web of Science and Google scholar).

The communication and collaboration with experts included meetings and working groups, which led to two published reviews: the first focusing on facilities that investigate Adaptive envelopes performance [18] and the second on test rooms for multi-domain occupant comfort studies [15]. The keywords used in the online searches are listed in Appendix A and they were chosen to describe studies reporting test rooms or chambers for studying occupant multi-domain comfort and interaction with facades. Test rooms that did not explicitly demonstrate occupant environmental perception and interaction capabilities with facade technologies, such as type of shading devices, glass or facade control strategy, were excluded from the review.

In total, twenty-three facilities were identified that can capture the effect of facades on occupants, with varying degrees of control and flexibility. Several test chambers were designed for multi-domain comfort studies rather than specifically to test occupant-facade interaction and, therefore their application to facades is limited since they have a fixed and non-replaceable facade technology. Overall, three principal laboratory types were identified: 1) Indoor test rooms with artificial daylight simulator; 2) indoor test rooms located in the perimeter space of a building and therefore with access to daylight and view, or to the outdoor environment; 3) outdoor test cells.

Access to outdoor conditions provides realistic boundary conditions for investigating facade technology, since the amount and direction of incident solar radiation vary during the day, season and orientation. In addition, outdoor view is important for occupant environmental perception [20–22] and glare tolerance [23]. It is therefore not surprising that the majority (15 out of 23) of test chambers are located outdoors, either in a dedicated unobstructed site or on the roof of existing research facilities. Only one indoor test chamber with artificial daylight simulators was found [24]. The advantage of an artificial sun is that the amount and direction of incident solar radiation can be controlled, thereby replicating different geographical locations, but the environment is less realistic, especially in relation to outdoor view. The IEQ Lab at the University of Sydney overcomes this limitation by building an intermediate simulator corridor between the facade under investigation and the external wall of the test room in order to fully control incoming air temperature, air flow whilst allowing control of solar radiation by means of an artificial sun simulator. This solution ensures access to outdoor view [15]. Two other indoor test chambers, The Experience Room at the SenseLab (TU Delft) [25] and the Controlled Climatic chamber at Berkeley [22], use a similar approach to create a fully-controlled space whilst controlling the glass surface temperature and ensuring outdoor view access and thereby a realistic scenario. The IEQ Lab in Sydney, the SenseLab and the Controlled Climatic chamber in Berkeley have a fixed facade technology, whose replacement is restricted since the outer layer is part of the external facade of the building where the chambers are located.

Table 1
Summary of existing real-scale facilities with occupant-facade response capabilities.

Facility Name & Location	Description	Facade orientation	Facade-related characteristics	Occupant-related parameters and interfaces[a]	IEQ Domain	Controlled indoor parameters	Building services
Outdoor test rooms							
Demona, EPFL, Lausanne, Switzerland [38]	Two office-like test rooms of 6.55 x 3.05 × 2.65 m with white walls and grey floor	South or North	Fixed glass, one has an uncoated clear glass, the other an electrochromic glass WWR 0.45 to 0.62 Manual/Automated venetian blinds Possibility to change shading devices	HR, SCL, skin temp.	Visual Thermal	Opaque wall surface temp Humidity Air temp. Artificial Illuminance Air flow	Mechanically ventilated with heat recovery and humidity control Artificial lighting
CELLS, EPFL, Freibourg, Switzerland [44]	Two identical office like test rooms	South-West North-East	Fixed but possibility to automate shading devices	HR and skin temperature	Visual Thermal	Air temp. Ventilation rate Artificial Illuminance Air flow	Heat pump and radiant panels, mechanically ventilated
Btga-box Full Scale Wuppertal University, Wuppertal, Germany [45]	One office room of aprox. 2.82 × 7.06 m	South	Openable Fixed glass Possibility of changing automated shadings	HR, skin and core temp, corneometry	Visual Thermal	Air temp. Humidity Artificial Illuminance Air flow	Mechanically or Natural ventilated
FlexLab, LBNL, Berkeley, USA [46]	Two test rooms with flexible layout and variable ceiling and raised floor heights and interior partitions Each is overall 6 x 9 × 4.5 m	Variable	Flexible facade configuration	Not specified	Visual Thermal Air quality	Surface temperature Air temp. Humidity Artificial Illuminance Air flow	Interchangeable lighting and hvac systems
LOBSTER, KIT, Karlsruhe, Germany [26]	Two identical offices of 24 m^2 and 3 m height	Variable up to 355°	Fixed Automated facade 12.6 $m^{2,}$ Openable Triple glazed (U = 0.7 St = 0.5) Automated Venetian Blinds with daylight guidance	Interfaces for personal control of windows, blinds and HVAC or ceiling fans.	Thermal Air Quality Visual	Surface temperature Air temp. Humidity Artificial Illuminance Air flow	Two separated heat pumps for radiative heating and cooling, Ceiling fans or mechanically ventilated
VERU, Fraunhofer Institute, Stuttgart, Germany [30]	Three-storey test lab with 6 test rooms each floor. Each test room can change internal depth and they can be combined.	East, South or West	Flexible facade configuration	Not specified	Different user control interfaces Not specified	Surface temperature Air temp. Humidity Air flow	Fully conditioned with centralised system, thermally-activated slabs
The Cube, Aalborg University, Aalborg, Denmark [5]	Single room of 2.76 x 3.6 × 2.7 m	South	Flexible Facade configuration	Manually-controlled blinds	Thermal Air quality Visual	Surface temperature Air temp. Humidity Air flow	Fully conditioned with centralised system, active chilled beams and radiant panels
TRIUMF Laboratory, Aalborg university, Aalborg, Denmark [47]	Two identical test rooms of 4.7 x 2.9 × 3.08 m that are guarded	South	Flexible Facade configuration	Not specified		Air temp Surface temp. Air flow. Humidity	Centralised heating, ventilation and cooling
Facade System Interactions Lab, EURAC, Bozen, Italy [36]	Two test rooms of 8 x 4 × 3 m	Variable up to 360°	Flexible Facade configuration	Not specified	Thermal Visual Air quality Acoustic	Surface temperature Air temp. Humidity Air flow	Radiant panels and dedicated mechanical ventilated system
FACT, CEA – INES, Le Bourget du Lac, France [31]	Six test cells per floor in two storey facility	North, South, East or West	Flexible Facade configuration integrable with HVAC, PV/ST and BIPV. Possibility of studying DSF	Not specified	Thermal Visual Air quality	Air temp Air flow	Reversible heat pump system
Fraunhofer Daylight Laboratory, Fraunhofer ISE, Fribourg, Germany [27]	Two identical test rooms of 3.56 x 4.6 × 3 m on the roof of a research building	Variable	Flexible Facade configuration	Manually-controlled blinds	Visual	Air temp Air flow	Not specified
Danish Daylight laboratory, Copenhagen, Denmark [27],	Two identical test rooms of 3.6 x 6 × 3 m	South, North or East	Flexible Facade configuration	Manually-controlled blinds	Visual	Air temp Air flow	Not specified

(continued on next page)

Table 1 (*continued*)

Facility Name & Location	Description	Facade orientation	Facade-related characteristics	Occupant-related parameters and interfaces[a]	IEQ Domain	Controlled indoor parameters	Building services
Experimental Lighting Laboratory, Laboratorio de Ambiente Human y Vivienda, Mendoza, Argentina [37]	Two identical test room of 1.75 x 3.4 × 2.7 m	Variable	Fixed glass but changeable internal blinds	Manually-controlled blinds	Thermal Visual	Not specified	Not specified
ZEB Test Cells Laboratory, NTNU & SINTEF, Trondheim, Norway [43]	Two identical test rooms surrounded by a guarded box of 2.4 x 4.2 x 3.3	South	Flexible Facade configuration.	Not specified	Thermal Air quality	Air temp Surface temp. Air flow. Artificial Illuminance	Air handling units for heating cooling and ventilation. Pre-installation for radiant panels or HVAC terminals.
West Lafayette test rooms, Indiana, USA [41]	Two identical office spaces of 5 x 5.2 × 3.4 m	South	Flexible Facade configuration	Manually-controlled Interfaces	Thermal Visual	Not specified	Not specified
Indoor test rooms with no access to outdoors							
SinBerBEST Test Bed, BEARS, Singapore [24]	Fully configurable space of 100 m^2	Artificial orientation with LED daylight emulator	Flexible facade configuration	Interfaces for personal control of blinds and HVAC	Thermal Air Quality Visual	Surface temp. Air temp. Humidity Artificial solar radiation Outdoor temperature	Fully controlled Air Handling Unit
Indoor test rooms with access to outdoors							
BPS Test Facade, TU Eindhoven [42]	Fully configurable space of 11.8 x 5.4 × 2.7 m^3	West	Flexible facade configuration	Several interfaces for personal control	Thermal Visual	Air temp. Humidity Artificial Illuminance	Air-based heating system and electric Radiators, VAV for cooling
LESO Building Physics Lab, EPFL [48]	Two identical office rooms	South	Fixed facade with variable automated control	Not specified	Visual	Air temp Artificial Illuminance	Not specified
HCU Studio for Room Comfort, HafenCity University, Hamburg, Germany [28]	One test room at the third floor of 6.30 x 3.25 × 6 m	South	Flexible facade configuration	Not specified	Thermal Air quality Visual Acoustic	Air temp Air flow Artificial Illuminance	Not specified
Experience room, SenseLab, TU Delft [25]	Flexible lab space of 6.5 × 4.2 m	Not specified	Fixed operable facade	Not specified	Thermal Visual Air quality Acoustic	Air flow Air temp Illuminance Noise level	Air handling unit that can be used for displacement ventilation or mixed ventilation or natural ventilation
Laboratory, South china University of Technology, Guangdong, China [49]	Two test rooms of approximately 10 $m^{2,}$ built inside perimeter space of a 6 storey building.	East and South	Fixed glass Changeable Internal blinds	Not specified	Visual	Not specified	Not specified
Controlled Environmental Chamber, University of California, Berkeley [22]	Test room of 5.5 x 5.5 x 2.5	Fixed not specified	Fixed facade technology	Physiological sensors	Thermal Visual Air quality Window surface temperature	Air flow Air temp Humidity	Air handling unit
IEQ Lab, University of Sidney, Sidney, Australia [15]	Two chambers of 6.85 x 8.85 and 5.6 x 4.2 respectively. The chambers external wall is separated from the external facade by a corridor, where a sun simulator is also located.	South and North	Fixed facade technology	Physiological sensors	Thermal Air quality Visual Acoustic	Air flow Humidity Air temp. Artificial illuminance Solar radiation Outdoor temperature	Fully-conditioned with linear VAV diffusers or swirl UFAD diffusers
HiLo, Research and Innovation unit for NEST, Dübendorf, Switzerland [50]	Two Test rooms within the HiLo Living Lab.	South-East and South-West	Changeable, currently installed an adaptive solar facade	Not specified	Thermal Visual	Not specified	Not specified

[a] In addition to subjective ratings via Questionnaires.

Testing alternative facade components, systems and controls is an essential feature of an occupant-facade research facility. The influence of the facade changes depending on window size and WWR, therefore it is important to test with flexibility different facade configurations. Most of the outdoor test chambers reviewed have been designed and constructed so that facade technologies can be installed and replaced with relative ease. The exception is the LOBSTER facility [26], which has a fixed facade system but supports different control and interaction scenarios. Several test chambers are composed of two nominally identical and adjacent test chambers. This set-up is intended for simultaneously testing two alternative scenarios (e.g. two technologies or two control strategies with the same boundary conditions). This is often useful for experimental control purposes or to perform simultaneous objective measurements that would otherwise be disturbed by the presence of human subjects in the test chamber and vice versa [27]. Test chambers located in the perimeter of existing research facilities have limitations over the type of facade technology that can be tested and, even when full replacement is possible it tends to be costly and time consuming. In fact, only two such test chambers, the BPS Test Facade at TU Eindhoven and the HCU Studio for Room Comfort at HafenCity University can accommodate the complete replacement of the facade system. Lastly, only four facilities [28–32] are equipped for ventilated double skin facades, because they cater for heights of more than 4.5 m, which is required to activate the necessary stack effects in the double skin facades.

Previous research has already shown that orientation has an influence on occupant environmental perception and interaction with facade [33–35]. South orientation is the most common orientation of the test chambers reviwed, and half of the facilities can accommodate more than one orientation, either by rotating the test chamber [26,27,29,36,37] or by selectively installing the facade block-out panels in the unwanted orientations [27,30,31,38].

Occupant environmental perception of, and interaction with, facade technologies is a function of the orientation of the occupants with respect to the facade and their distance from it [39,40]. For this reason, almost all the test rooms have a flexible internal layout, but only half of them [15,22,24,25,27,29–31,36,41–43] have a floorplan depth larger than 4 m, which is the minimum required to study different occupant positions.

In terms of internal floor area and layout, outdoor test rooms are equally distributed in three sub-groups: one third has a floor surface below 15 m^2, just above one third has an overall floor surface between 20 and 25 m^2, and another third has a floor area than 32 m^2 (two of them have a surface between 30 and 50 m^2 and other two have more than one storey and a surface larger than 50 m^2 [30,31]). The smallest category imposes several limitations in terms of achieving a realistic indoor environment, since occupants tend to feel artificially constrained and testing occupant environmental perception at different distances from the facade is impeded.

75% of test rooms facilities that study the effect of facade on occupant comfort focus on occupant visual and thermal perception and this is also reflected in the control parameters available, which are usually air temperature, air flow and indoor artificial illuminance. Occupant-related parameters are usually investigated with subjective ratings via questionnaires. Few laboratories have also started to use physiological sensors [15,22,38,44,45] to capture occupant environmental perception or to test alternative control interfaces [24,26,42].

3. Design requirements

From the review of existing test facilities in section 2, it is evident that a new test facility for the comprehensive assessment of occupant-facade perception and interaction should meet the following design criteria:

1. Access to outdoors.
2. Internal floor area sufficient to ensure a realistic interior environment and therefore an indoor floor surface (with a minimum of 20 m^2).
3. Ability to test two facade technologies simultaneously by means of flexible partitioning of the internal space or having two identical chambers.
4. Ability to investigate different facade technologies over relatively short period by means of changing the facade technologies/panels with ease and in a time and cost-efficient manner
5. Ability to investigate facade technologies in different orientations either by rotating the facility or by means of a system to mount opaque infill facade panels for blocking undesired orientations
6. Ability to study different occupant locations and point of view by means of changing the internal layout with ease.
7. Provide occupants with unobstructed good quality view and, ideally, providing different types of views.
8. Ability to test different control strategies for facades.
9. Multi-domain sensing capabilities for monitoring dependent variables and control of the selected independent variables
10. Ability to test different occupant-façade interaction strategies.

The majority of facilities reviewed in section 2 fulfil several of the above criteria, but provides a combination all of these characteristics in one integrated facility. In addition, there is a dearth of published information on the required methods for capturing multi-domain data on the influence of the facade on indoor environmental quality, occupant environmental perception and interaction (design criteria 9). Therefore, the subsequent sections of this paper describe the design and validation of a novel lab, called MATELab and shown in Fig. 2. The design and construction of this new lab endeavours to fulfil the above-mentioned design criteria, as described in section 4 and that can be summarised on the below Performance Objectives (PO):

1. **PO1.** MATELab can capture the influence of the facade on the IEQ.
2. **PO2.** MATELab can evaluate occupant environmental perception of and interaction with the facade with adequate frequency.

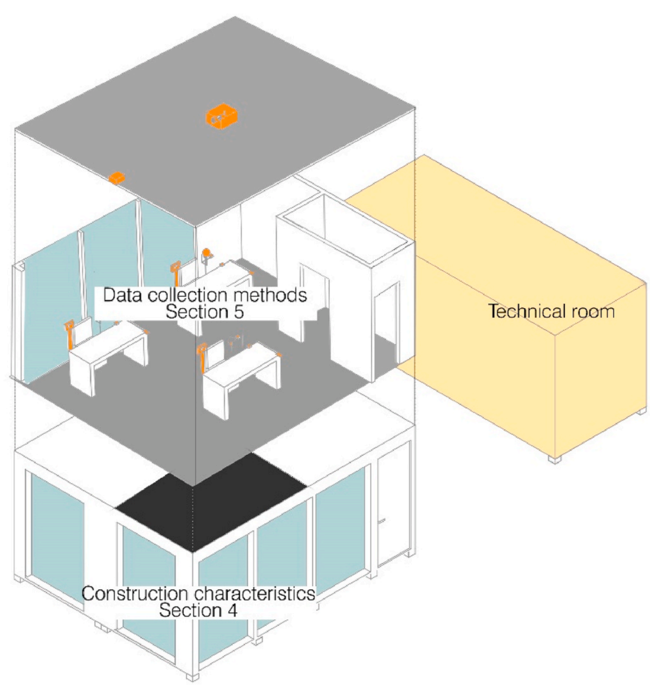

Fig. 2. Exploded view of MATELab. Details of the principal sub-components are available in the section indicated.

3. **PO3.** After a habituation time, occupants do not perceive working from MATELab different than when in typical open-space office

In addition, details of the data collection methods that are required to capture the influence of the facade on occupants are also provided in section 5. Finally, section 6 describes the validation of this new experimental lab in terms of these key performance objectives.

4. Design and construction of the lab

4.1. Construction characteristics

4.1.1. Geometrical description

MATELab was designed as an outdoor lab at ground floor level thereby providing maximum flexibility for changing facade system and orientation. MATELab has an overall internal floor plan of 30 m^2, an internal floor depth up to 5 m and an internal headroom of 2.5 m (details are shown in the plan in Fig. 3). The facility is located on a rural site 2.4 km East of Cambridge city centre, UK. The site is owned and managed by the University of Cambridge and it has dedicated services in the nearby University buildings, which also contains a staff canteen. The storage facilities and building services for MATELab are located in an adjacent plant room at the north side of MATELab. Walls and ceilings in MATELab are opaque white with reflectivity of 0.90 and 0.84, respectively, while the floor is a dark grey carpet with a reflectivity of 0.05.

4.1.2. Internal layout and variable orientation

The test chamber has a raised floor with a large number of power sockets and air vents to ensure a flexible use of the space. The vents' air flow can be adjusted according to the desired internal configuration, thereby supporting many different types of internal layout configurations. The flexible layout allows to change desk position and location according to the aim of the experimental study. For instance for glare research, a desk orientation of 45° with respect to the facade is often used [27]. MATELab has 8 full height removable facade panels; two in the South facade and three each in the East and West facades. The facade mounting system provides another important element of flexibility by allowing partial or full-height glazing independently in each of the eight facade panels. Each facade panel can also be infilled with opaque insulated panels externally (Fig. 4b) and corresponding internal wall covers (Fig. 4c), thereby allowing South (Fig. 4d2), East (Fig. 4d3, West (Fig. 4d4). orientations to be tested independently or simultaneously. The test chamber can also be partitioned in two identical adjacent rooms (Fig. 4d1) to allow simultaneous measurements of different facade technologies or a control room for objective measurements during human volunteers studies, as done by Wienold and Christoffersen [27].

4.1.3. Flexible facade configuration and building envelope features

Each of the eight facade bays has a maximum dimension of 1.5 × 2.3 m^2. The East and West walls are composed of three facade bays and, therefore they have a maximum Window-to-wall ratio of 90%, while the South has two facade bays and a maximum Window-to-Wall Ratio (WWR) of 70%. The South, East and West orientation have been designed with a reconfigurable wooden frame (a in Fig. 5) that also allows the facade system to be changed with ease. This operation requires two people and the MATELab glass lifter (b in Fig. 5). Replacement of each bay takes approximately 2 and 4 h for a single skin facade and a double skin facade, respectively. The non-removable parts of the building envelope are made of highly insulated panels. Floor, ceiling and walls have a U-Value of 0.20, 0.159 and 0.20 W/m^{2}K, respectively. The internal floor is raised by 0.90 m from the ground.

4.2. Outdoor view from south, East and West orientation

The location of MATELab was chosen to ensure an unobstructed location and a green view on at least two of the orientations: South and East (a. and b. in Fig. 6); while the West orientation faces an unappealing university storage building. These differences in view quality are helpful when studying the effect of view on occupant environmental perception and interaction. Visual targets e.g. signs with Landolt Charts could also be placed in the view to assess view clarity, as shown by Ko et al. [51].

4.3. Environmental services features

The heating, cooling and ventilation is provided by a heat-pump with heat-recovery unit made of two identical and separate systems in order to serve the two zones independently when the lab is partitioned in two test rooms. The ventilation strategy inside the test chamber is shown schematically in Fig. 8. The chamber has an internal floor-to-ceiling height of 2.5 m, therefore the ventilation system could either be an Under Floor Air Displacement (UFAD) system or a mixed ventilation system. A UFAD system was selected for MATELab because it is very effective in providing high levels of air quality, by supplying fresh air at the proximity with occupants and close to their breathing level and by upwardly displacing indoor air pollutants. In addition, UFAD systems are characterised by low air velocities and, therefore, minimise draft

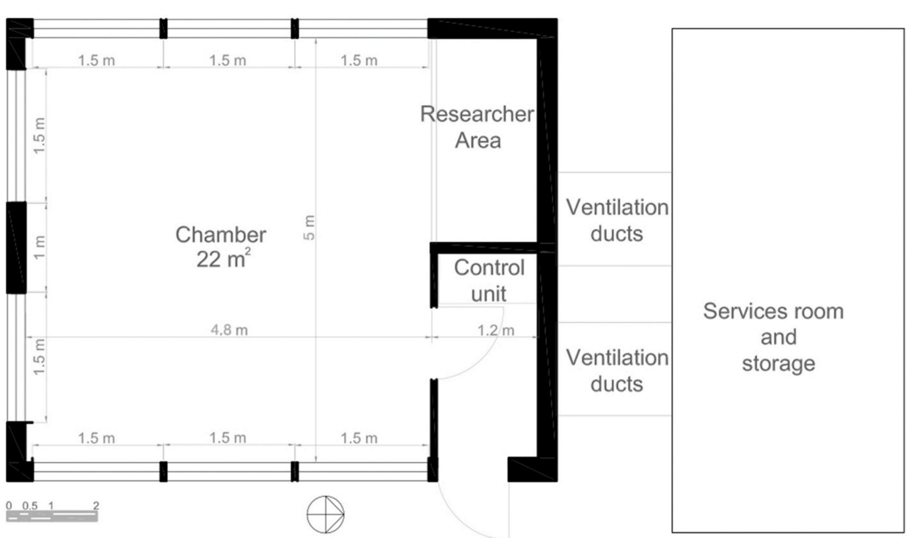

Fig. 3. MATELab floor plan.

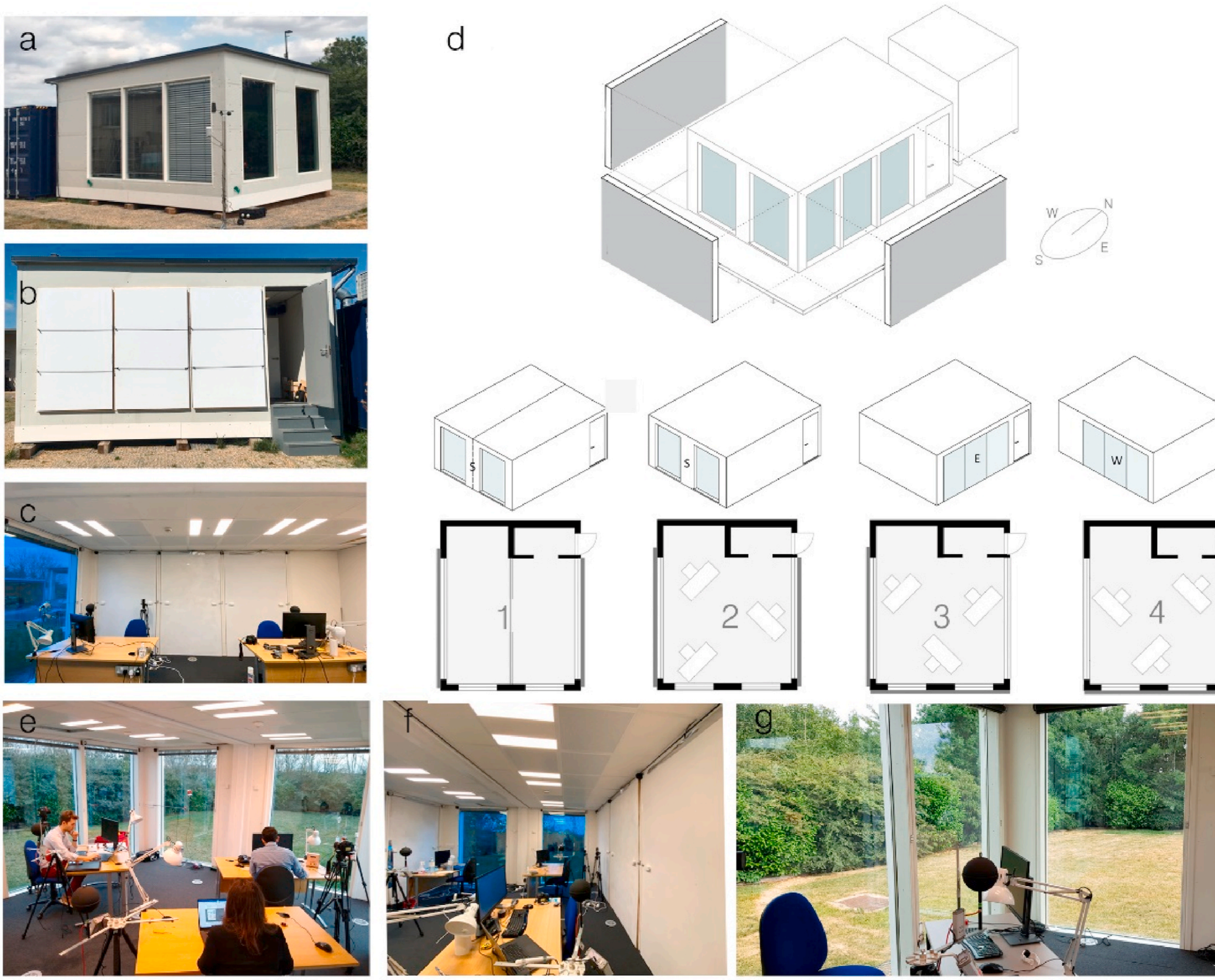

Fig. 4. a. View of MATELab with all glazing panels exposed. b. View of MATELab with one side covered with insulation panels. c. Internal view with internal cover panels. d. View and floor plan of all the possible permutations: (1) Configuration with two separate chambers for direct comparison at South orientation; (2) South orientation; (3) East orientation; (4) West orientation; e. Internal view of MATELab without cover panels; f. Internal view of MATELab with cover panels from the back; g. Internal view of MATELab's façade corner without panels.

risks and acoustic discomfort. However, the limitation of adopting this system in MATELab are discussed in Appendix B. A ventilation system with low air velocity can help to isolate the influence of the facade, although occupants could feel higher discomfort when solar heat gains from the facade are high because this HVAC system is slower in compensating overheating.

The artificial lights are also split in two independent circuits per half-test room to allow control in the single chamber and in the partitioned chamber configurations (as shown in Fig. 7). The luminaires are ceiling-mounted LED technology "Aura Lunaria" [52] 600 × 600 mm suitable for computer work, complying with EN-12464 [53] and with tuneable white for adjustable colour temperature in relation to the time of the day. By default, the lighting system is triggered by movement sensors and dimmed by illuminance sensors on the luminaire. Control interfaces for the building services are described in Section 5.2.

4.3.1. Building automation characteristics

The HVAC, lighting and facade control and automation systems are integrated in a single control unit, which uses a KNX communication protocol [54]. The control integration of the facades and the building services systems is essential to achieve the high-efficiencies expected in modern buildings. Indoor environmental sensors and one of the two weather stations (refer to section 5) are also connected to the same control unit to inform control strategies in real time with the measured data. This integrated and modular sensor/control set-up allows the sensing devices for a particular facade technology to be increased or modified with ease e.g. include multiple facade sensors or location-specific occupant sensors.

The MATELab single control unit is also used as power meters, one for each half test room and to log the interaction of occupants with the facade and the building services. For instance, in the case of venetian blinds, the control unit can be used to monitor the height position of the bottom bar and the tilt angle of the slats.

5. Data collection methods

MATELab is equipped with a wide range of sensors in order to capture the multi-domain influence of facades on IEQ, occupant environmental perception and interaction with the facades. Data is collected by objective measurements of IEQ and by direct and indirect assessment of occupant environmental perception and interaction. Data on energy consumption is also collected by power meters. The two halves of the lab

Fig. 5. Reconfigurable facade (a). Reconfigurable wood frame. (b). External view of the façade panel with the glass lifter before the removal; and (c) Removal of the glass panel with the glass lifter.

Fig. 6. View from the South (a), the East (b) and the West (c) orientations.

have independent power meters for lighting, hvac, facade controls and plugs respectively.

The local environmental conditions at the occupant position are influenced by the building services and the outdoor environmental conditions. The latter are in turn moderated by the building envelope and the facade in particular. In order to evaluate the influence of the facade, environmental data needs to be collected outdoors, at the facade location, at the occupant position and at the level of the building services [55], as shown in Fig. 9. Table 2 shows the selection of environmental parameters that are monitored in a typical experimental setup in MATELab, when evaluating the influence of a facade on IEQ, multi-domain occupant environmental perception and interaction. Details of the sensing devices are reported in Table 3. The selection of the environmental parameters was informed by the review of existing facilities reported in this paper (Section 2) and by previous work of the authors [14]. Outdoor weather conditions are monitored by three different weather station (see Fig. 12). On the roof, there are two weather stations that monitor solar radiation and illuminance: the first one has a sun tracker and it can measure direct beam solar radiation, the second one is a typical weather station that is used in commercial buildings to control the facade.

When measuring the IEQ around an occupant, it is challenging to place sensors very close to the occupant without disrupting the occupants and introducing biases in their responses. For this reason, indoor environmental measurements are performed at a position and distance from the occupants to minimise disruption and simultaneously capture the indoor environmental conditions experienced by the occupant. This is not normally an issue for some environmental parameters, such as relative humidity and air temperature, where the values do not vary significantly in a small and enclosed space, however for other environmental parameters, such as luminance or irradiance, the difference could be significant. For this reason, in MATELab measurements of solar radiation and light can be taken by either by using the lab as one whole space, or by dividing the lab in two identical chambers (configuration 1 in Fig. 4D), placing the occupant in one chamber and taking the IEQ measurements in the adjacent chamber, as shown in Wienold and Christoffsen [27]. However, in this setup each chamber measures 2.5 × 3 m^2 and only one occupant per time can be tested.

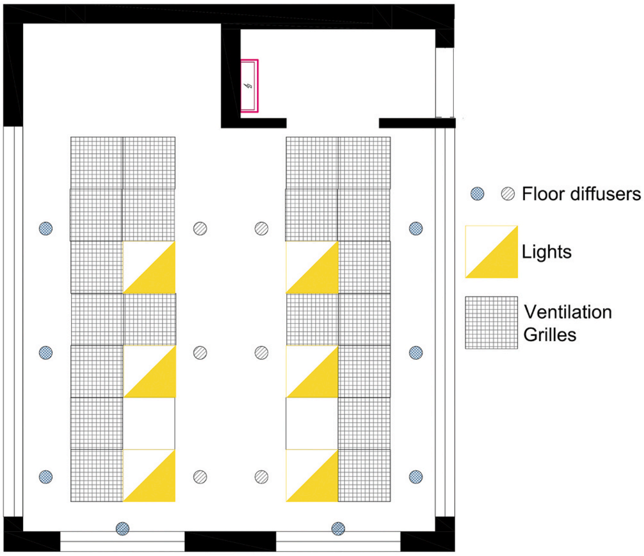

Fig. 7. Overall plan of the artificial lights system and ventilation diffusers and grilles.

5.1. *Influence of facade transmitted irradiance on IEQ, occupant environmental perception and interaction*

Direct solar radiation on the occupant body often induces thermal discomfort [56], since occupants under direct solar radiation can experience heat gain equivalent to 8 °C rise in Mean Radiant Temperature (MRT) [57]. In addition, solar heat gains can also indirectly induce overheating and severe thermal discomfort by raising the indoor air temperature. The latter could be controlled by the HVAC system at the expenses of energy efficiency, however HVAC can rarely minimise the impact of overheating at the position of the occupant and the zones close to the facade usually have higher operative temperatures than the rest of the floor plan [56]. Measuring the solar radiation transmitted by the facade is therefore important when evaluating the influence of the facade. In this experimental setup, a pyranometer is installed parallel to and at the centre of the glazing (TI in Table 2 and Fig. 11) in order to monitor the amount of transmitted solar radiation. However, the exact position of the solar beam within the room is not monitored because measuring the direct solar radiation on the occupant is very challenging without being disruptive or intrusive (e.g. by using cameras). In a previous study, the authors attempted to use the horizontal irradiance on the desk as a proxy [14], however this could be noticeably different from the actual direct solar radiation on the occupant and therefore this measurement is not included in this experimental setup.

5.2. *Influence of surface temperature of facades on IEQ, occupant environmental perception and interaction*

Glazing can absorb significant amount of solar radiation, which in-turn leads to relatively high glass surface temperature and the re-radiated heat component, particularly in the cooling season. In addition, glazing usually has a higher thermal transmittance than opaque envelopes and it therefore experiences relatively low surface temperatures in the heating season. Glazing can therefore create asymmetrical radiative conditions, where cold or warm surfaces asymmetrically act on the occupant's body radiant exchange with the surrounding environment. As a consequence, some portion of the body can often become considerably cooler or warmer than the rest. Surfaces that are significantly colder or warmer than the surrounding air can also induce a downward or upward air flow respectively, thereby causing drafts in the vicinity of the glazed facade. Thermally efficient double and triple glazing have reduced the significance of cold asymmetrical surfaces, but advanced dynamic (switchable) glazing, can still result in very high surface temperatures since they can have high solar absorptance in their darkened state.

In this experimental setup, surface temperature (ST in Table 2 and Fig. 11) is therefore monitored at three points on the internal glazing surface (at the top, mid-height and bottom) by shielded thermistors. The surface temperature of internal shading devices can also be significant e.g. when using metallic venetian blinds, therefore surface temperature on the blinds can also be monitored.

The surface temperatures of the surrounding opaque walls can also be monitored. Although, given the low thermal transmittance of the opaque wall, these surfaces are not expected to largely differ from the indoor air temperature. Alternatively, the indoor surface temperatures can be monitored by means of infrared imaging, such as the system developed by Revel et al. [58]. Drafts along the glazing surfaces can be monitored by placing air flow meters along the vertical direction of the glass. However, since the height of the indoor space in MATELab is only 2.5 m no significant induced drafts are expected since chimney effects due to buoyancy require higher heights to develop.

5.3. *Influence of air flow velocity and temperature from an opening within the facade on IEQ, occupant environmental perception and interaction*

The presence of vents and openings have a significant effect on the air distribution on the room and the thermal comfort of the occupant. The experimental setup in Fig. 11 does not include air flow meters at the facade since the facade under investigation had non-operable windows. In the case of openable vents, the use of air flow meters to measure air velocity and turbulence is recommended. The draft air temperature and quality can be measured outdoors, close to the facade.

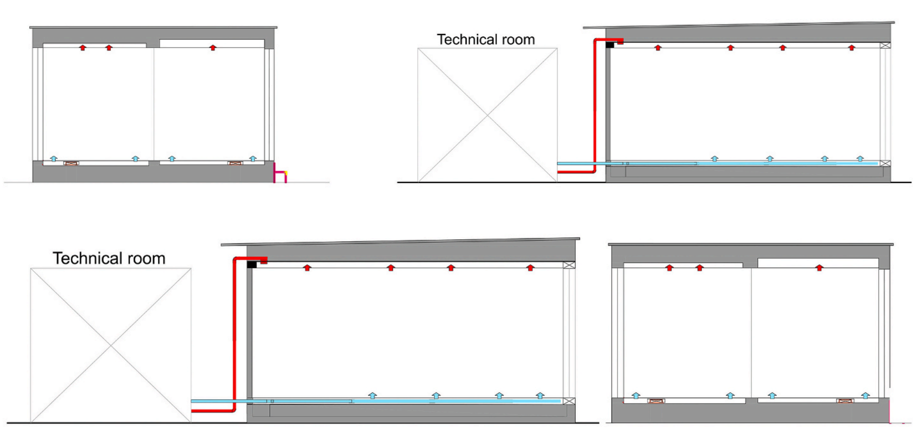

Fig. 8. Schematic representation of the displacement ventilation mode inside the test room.

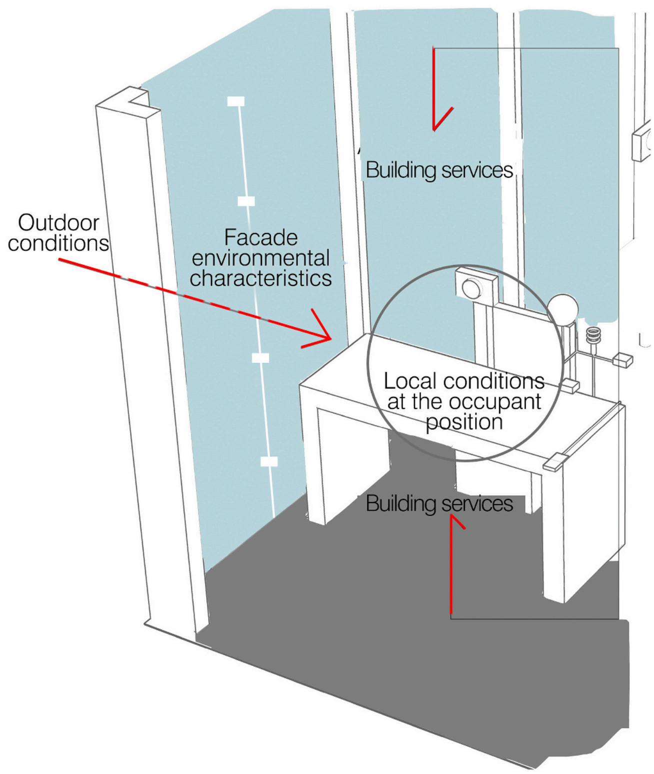

Fig. 9. Diagram of the locations where the measurements are required when evaluating the influence of the facade on IEQ, occupant comfort and interaction.

5.4. Influence of transmitted illuminance from a facade on occupant environmental perception and interaction

Facades are the primary source of daylight in buildings. Facades transmit daylight according to their visual transmittance, while a portion is reflected or absorbed. Visual transmittance can change in time for dynamic facades. To effectively evaluate the contribution of daylight on the indoor lighting, the amount of daylight transmitted by the facade is monitored by measuring the vertical illuminance (VI in Table 2 and Fig. 11). As shown in Fig. 11, the vertical illuminance sensor is placed parallel to the centre of the glazing and after the internal shadings, in order to monitor the actual transmitted illuminance. When studying glazings that are not colour neutral, the use of illuminance colorimeters is important to evaluate the daylight spectrum. In the setup described in Fig. 11, the glass is colour neutral and therefore no colorimeter is used but their usage could be implemented for future work.

Excess of daylight can also be a cause of discomfort. However, for this the luminance from the occupant location and point of view is measured and no measurements are taken at the facade level.

5.5. Thermal quality parameters at the occupant location

The thermal quality is captured at occupant location by measuring air temperature, air velocity and the globe temperature (respectively AT, AV and GT in Table 2 and Fig. 10). Therefore, the operative temperature and the mean radiant temperature (MRT) can be computed as described by the ASHRAE 55 [59]. The MRT indicated the mean temperature of the surfaces around the occupant and, therefore, even if it is influenced by the surface temperature of the facade, it does not allow to isolate the contribution of the facade in the long-wave thermal exchange between the occupant and the surrounding environment. In order to quantify the long-wave radiative contribution of the facade, a net radiometer is also installed close to the occupant and facing the facade. In environment with low air flow, the net radiometer allows to measure the plane average radiant temperature with the direction of the heat flow, which if combined with the air temperature measurement allows also to measure the planar radiant asymmetry as described by the ISO 7730 [60]. At the centre of the room, the air temperature and the relative humidity are also measured.

5.6. Visual quality parameters at the occupant location

The visual quality at the occupant location is monitored by measuring the luminance from the location and point of view of the occupant (Glare unit in Table 2 and Fig. 11), considering a fixed point of view perpendicular to the desk, and the horizontal illuminance on the

Table 2
Environmental parameters monitored at the facade, centre of the test room, occupant position and outdoor location.

Comfort domain	Facade location	Occupant position	Building services	Centre of the test room	Outdoor
Thermal comfort	Surface Temperature (**ST**) at multiple locations Air Temperature (**AT**) Global Transmitted vertical Irradiance (**TI**) Heat Flux meter[a] (**HF**)	Air Temperature (**AT**) Globe Temperature (**GT**) Air Velocity (**AV**) Net Radiation (only at the closest position to the facade) (**NR**) Surface temperature of walls close to the occupant[a] (**ST**)	Inlet Air Temperature before entering the plenum (**IAT**) Air Flow Rate before entering the plenum (**AFR**)	Air Temperature (**AT**) Relative Humidity (**RH**)	Solar beam radiation (**SB**) Horizontal global Irradiance (**GHI**) 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 Iluminance at eye level (**VI**)[b] Luminance map of fixed view[b] (**Glare unit**)	Illuminance at the Luminaire (**IL**)		Horizontal Illuminance (**HI**) Vertical Illuminance (**VI**)
Air quality comfort			CO_2 level (**CO_2**)	CO_2 level (**CO_2**) VOC levels (**VOC**)	
Acoustic comfort				Noise Level (**NL**)	
Interaction	Facade State (**FS**) e.g., blind position and height or glass				

[a] Optional.
[b] See limitations in Section 5.6.

Table 3
Characteristics of the environmental sensing devices in MATELab.

Parameter	Technical characteristics of the sensor
Air and Surface Temperature	4 wires Pt100 technology DIN A (Class A EN60751) Measurement range: $-50 \div 70$ °C Resolution: 0.01 °C Accuracy: 0,15 °C (at 0 °C)
Global transmitted an incident irradiance	Second class pyranometer ISO 9060 Spectral measurement range: 285 to 3000 $\times 10^{-9}$m Rated operating temperature -40 to $+80$ °C Temperature response $< \pm 3\%$ (-10 to $+40$ °C) Calibration uncertainty $< 1.8\%$ (k = 2)
Heat Flux meter	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: $-50 \div 70$ °C Resolution: 0.01 °C Accuracy: 0,15 °C (at 0 °C)
Air velocity	Hot wire anemometer Measurement range: $0.01 \div 20$ m/s Resolution: 0.01 m/s Accuracy: $0 \div 0{,}1$ m/s
Net Radiation	Thermopile Measurement range: $-1500 \div 1500$ W/m^2 Spectral range: $0{,}3 \div 50$ μm Accuracy: 5%
Illuminance	Photodiode with filter for human eye response (Vlambda CIE) Cosine corrected Accuracy: 3% At the desk level: Measurement range: $0 \div 25{,}000$ lux Resolution: 3 lux At the facade: Measurement range: $0 \div 150{,}000$ lux Resolution: 10 lux
Relative humidity	
Luminance	HDR-imaging calibrated with spot luminance meter 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: $0 \div 5000$ ppm
VOCs	Electrochemical cell technology Range: $0 \div 20$ ppm
Noise Level	Sound Level Meter Range: 30–130 dB Resolution: 0.1 dB Accuracy class ISO 961-200 Weighting A
Direct normal irradiance on the roof	Pyrheliometer Spectral range: 200–4000 nm Field of view: $5 \pm 0.2°$ 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
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
Global and vertical illuminance on the roof	Photodiode with filter for human eye response (Vlambda CIE) Cosine corrected Accuracy: 3% Range: 0–100,000 lx
Wind speed	Range: $0 \div 75$ m/s (damage limit) Accuracy: $\pm$ 0,5 m/s (0–10 m/s), 2,5% (>10 m/s)
Wind direction	Range: $0 \div 360°$ Accuracy 3°
Sun Tracker and Sun Sensor	Fully automatic Sun Tracker Integrated GPS receiver, BSRN level performance Pointing accuracy <0.1

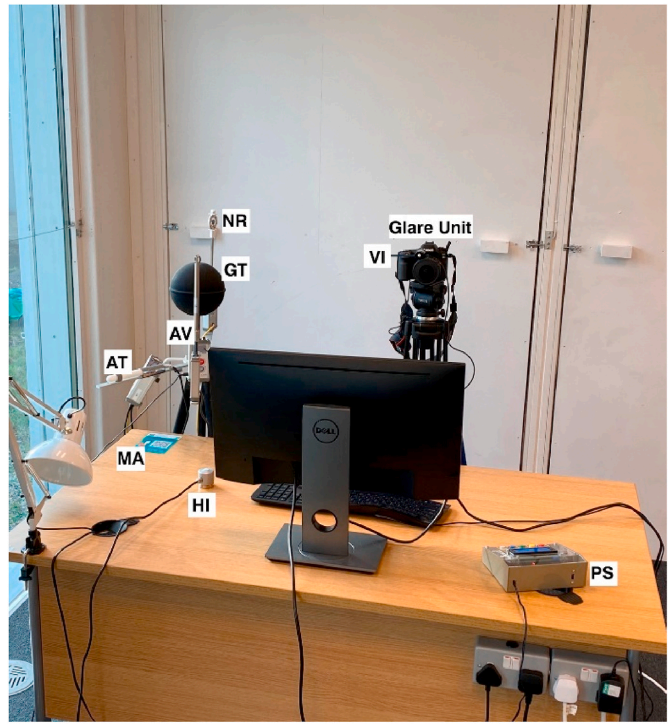

Fig. 10. Environmental setup at the occupant location.

desk (HI in Table 2 and Fig. 11). The horizontal illuminance on the desk is chosen since MATELab is an office space and existing standards recommend minimum values of horizontal illuminance on the surface where the task is performed [53,61] and a minimum level of daylight contribution on the horizontal illuminance [62]. This is a useful proxy to evaluate the daylight potential of alternative facade technologies and control strategies.

Excess of daylight is often a source of visual discomfort in proximity of facades by causing discomfort glare. To characterise the presence of glare, measurement of luminance levels in the field of view of the occupant and of vertical illuminance at the eye level are required. Measurement from the occupant location can also provide information on the different effects of specular or diffusive light transmission.

Capturing the actual luminance map from the field of view of the occupant is challenging in the presence of the occupant. Wienold and Christoffersen addressed this by measuring the luminance and illuminance levels in an identical space beside the experimental chamber where the human volunteers were [27]. The measurements are performed by a Glare unit composed of: a DSLR Camera, a vertical illuminance sensor and a luminance meter. The Glare unit is placed at the position of the occupant and at the height of the occupant eyes. However, when occupants are present in the experiment the camera and the sensor are positioned just beside and behind the occupant, although this can provide an error on the measurement because the field of view is displaced. Alternatively, MATELab can be divided in two identical chambers to measure the luminance in parallel to the human volunteer experiment.

The luminance maps are derived following the procedure described by Pierson et al. [63]. The HDR images are created by an automated script that is implemented by a Raspberry-pi 3b [64], similarly to previous work by McNeil [65], but luminance spot measurements are here used to perform the photometric calibration. Fig. 13 shows the full setup of the Glare unit. The camera is connected to the Raspberry-pi usb port, while the illuminance sensor is connected to a bespoke board with a BNC connector and the ADS122C04 [66], a 24 bit precision analogue-to-digital converter (Fig. 13a). The HDR is created by using HDRgen and then applying the correction algorithm to account for

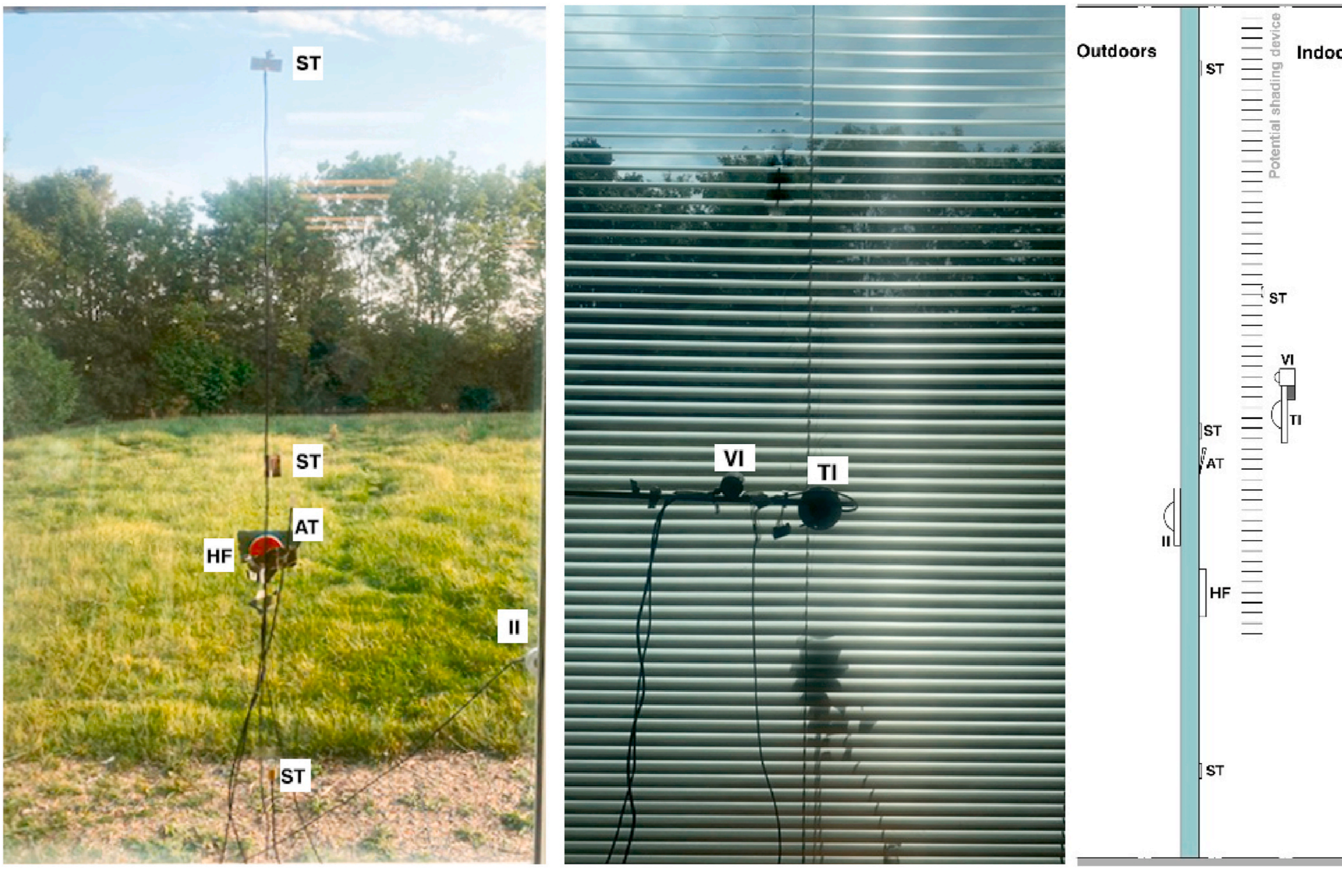

Fig. 11. Measurement setup at the facade.

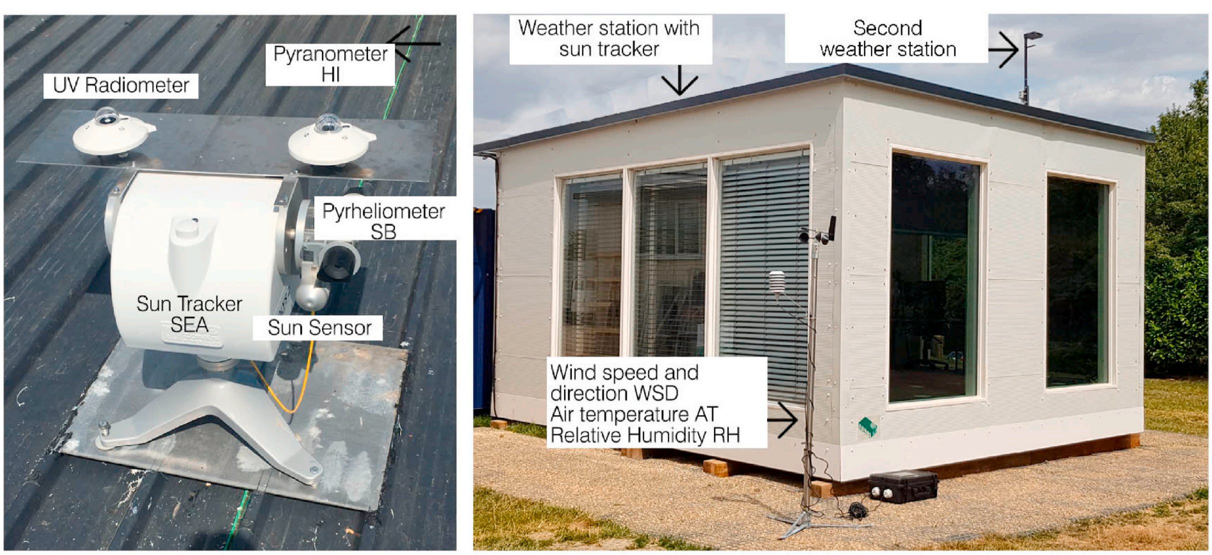

Fig. 12. Weather stations.

vignetting, reprojection and, in presence of neutral density filter, for the chromatic shift. The script prepares also the image for Evalglare in Radiance [67], checking and correcting the header. The vertical illuminance is then used to do a validity check, while the photometric calibration is manually performed by doing a spot measurements on a grey target in the scene and then using Photosphere [68]. This process can be challenging when measuring luminance for long-term, since it requires luminance spot measurements. As an alternative, absolutely calibrated DSLR cameras can be used but are not present in MATELab since experiments in this space are not intended to be long-term but short term. When the luminance range is too high and underexposed images cannot be captured neither with the fastest exposure, a neutral density filter of Wratten 3.0 is used.

Another limitation of this glare unit is that occupants can change their direction of view during the experiment and this would not be captured by the glare unit, which is positioned to measure one fixed

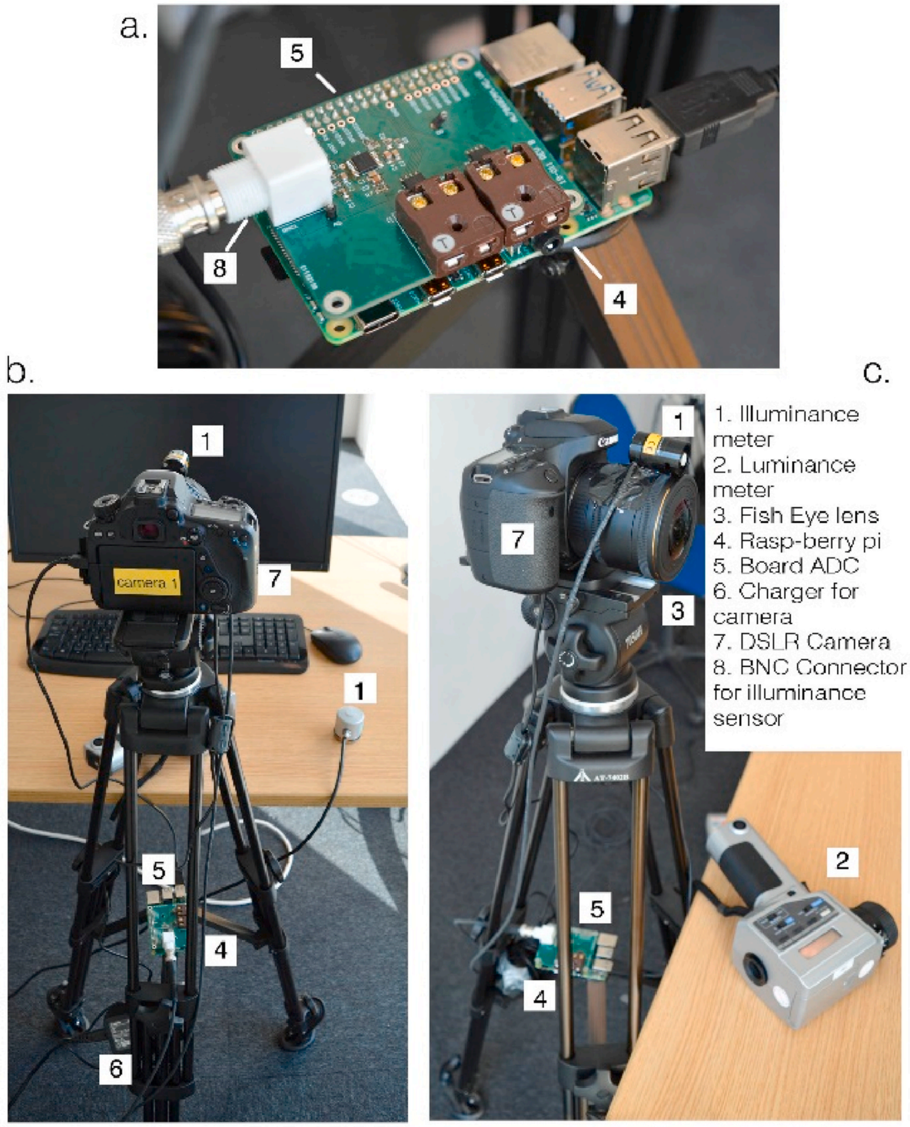

Fig. 13. Glare unit of MATELab: a. Raspberry-pi with bespoke electronic board for the data collection; b. Back view of the Glare unit; c. Side view of the Glare unit.

view. New systems that use eye-tracking have been recently developed [69] but are not implemented in this lab.

5.7. Air quality parameters at the centre of the room

The quality of the indoor air has a significant effect on occupant comfort, productivity and health [95], [96]. In addition to relative humidity (RH) and air temperature, carbon dioxide (CO_2), Volatile Organic Compounds (VOCs) and formaldehydes (CH2O) are common indicators used to assess air quality. However, several other contaminants may need to be monitored in specific cases [97]. In MATELab, air quality monitoring is limited to CO_2 and VOCs at the centre of the room. One measurement at the centre of the room is adequate since the space has floor surface of just 30 m^2. CO_2 is a common proxy for air freshness and it is used to indicate minimum air changes per hour. Several materials can emit VOCs, which could have a long-term chronic effect on occupant health. For instance, facade materials, such as polymeric adhesives and sealants [99], could emit VOCs.

5.8. Acoustic quality parameters at the occupant location

Different physical and subjective parameters have an influence on acoustic comfort [70]. Subjective factors, such as sound privacy, can impact the acoustic quality in addition to sound levels [71]. The objective acoustic physical parameters in turn depend on a wide range of environmental characteristics such as noise level, frequency spectrum of the noise, duration of exposure, presence of interval noises, and reverberation time. Facades affect the acoustic environment in two ways: they are a filter between outdoor and the indoor acoustic environments, and they also influence the indoor reverberation time depending on the facade sound absorptance and reflectivity. The acoustic environment should be evaluated by the frequency spectrum, since different types of noise can impact the acoustic perception of the occupant. However, in this experimental setup only noise levels are monitored. Given the limited volume of the indoor space (75 m^3), the absence of openable vents and the constant airborne sound insulation power and absorptance of the facade in this initial setup, the noise level was placed at the centre of the room. In addition, MATELab is located in a quiet estate, where no external sources of noise are present and high acoustic disturbance, such as in open space office, are not expected since the maximum occupancy is three people.

5.9. Indirect and direct methods for capturing occupant environmental perception of and interaction with the facade

Occupant environmental perception and interaction in MATElab is captured by soliciting feedback directly from occupants and by monitoring their interaction with the facade. Feedback on occupant levels of satisfaction, preference or other aspects of interest is collected by using a polling station and mobile app in Fig. 14. a. The polling station is based on an Internet of Things approach and was specially developed by the authors for a related field-study a real-world office [14]. Data is collected in two ways: (i) by soliciting the occupants to input a value from 1 to 5 and to answer a specific set of questions displayed on the integrated LCD screen; (ii) by expressing their discomfort at any time during the day by pressing the buttons located on the polling station. Each button has a specific colour code corresponding to one of the following domains: thermal discomfort (red), visual discomfort (yellow), acoustic (green), air quality (blue) and personal control (grey). These buttons allow occupants to effortlessly express their discomfort at a specific time of the day. The data recorded is a binary (presence or absence of discomfort) and the time of day at which the button was pressed. The LCD screen is also used to ask occupants about other factors that could affect their perception of the environment, such as level of workload, rest or fitness. The occupants express the degree to which they agree/disagree with the question by using the slider located beside the LCD screen. An alternative and equivalent system for occupant feedback has also been developed for MATELab. This consists of a specially developed mobile app, which is accessible by QR code or NFC tags that are unique for each occupant desk. The mobile app provides an electronic version of the polling station and incorporates the same occupant questions as those displayed on the LCD screen. The additional capability of the app, is that it allows occupants to leave general comments.

Occupant interaction with the facade is monitored by the control system of the facade, which logs any control action of the occupant (e.g. lowering or raising of blinds or changing the tilt angle). Control actions on the facade can be requested either through switches or via a control touchscreen (Fig. 14), located at the entrance of the chamber. In addition, this touchscreen interface is also accessible from a web page, therefore occupants can also use their personal laptop or mobile to control the facade. Switches are located beside each of the facade bays. Control actions on the artificial lighting or HVAC system can only be placed through the web application. The choice of control interface and the degree of control that occupants have on the environments depends on the experimental design. The two control interfaces for the facades are shown in Fig. 14b and 14. c.

Lastly, occupancy is monitored by a magnetic door contact sensor at the entrance door and a movement sensor in the office space. Occupant level of clothing is self-reported by the occupants. In the current version of MATELab, heart rate monitoring is possible by using a smart watch [72] and sensors for reading the Skin Galvanic Response are also available, but the use of these and other physiological devices for monitoring the influence of a facade on occupant environmental perception and interaction is still under assessment.

5.10. Data storage

A digital central platform was setup in MATElab to retrieve, synchronise and store data from sub-platforms, such as data from the BMS, bespoke sensing devices and weather station. The environmental sensors at the facade, outdoors, at centre of room and occupant location record data every minute by averaging the measurements taken every 10s. The data is then stored in a local computer and from there automatically stored in a cloud time series database, which has an automated dashboard to visualise the data. The same cloud storage is used to save data from the Glare Unit and the polling stations, which is automatically sent via Message Queuing Telemetry Transport (MQTT). Data from the BMS and the control system of the facade, the lighting and the HVAC is retrieved by and stored in a local server and then automatically uploaded on the cloud database at the end of each day. The control and monitoring system of the BMS is based on KNX communication protocol [54]. The control and local data storage system of MATELab can also be accessed remotely to supervise the procedure or retrieve specific data. (see Fig. 15).

6. Verification of performance and preliminary monitoring results

The principal purpose of MATELab is to provide a means of assessing the influence of facade technologies on IEQ and on occupant environmental perception and interaction with the facade in a realistic but controlled space for human volunteers. The extent to which this has been achieved in the current version of MATElab is assessed in terms of the three key performance objectives listed in section 3.

6.1. Verification experiment

A preliminary monitoring of occupant environmental perception to, and interaction with, facades was conducted in MATELab in February 2020 and in September 2020 in order to validate the design of the test chamber. The study was approved by the Ethical Committee of the Department of Engineering at the University of Cambridge. The test

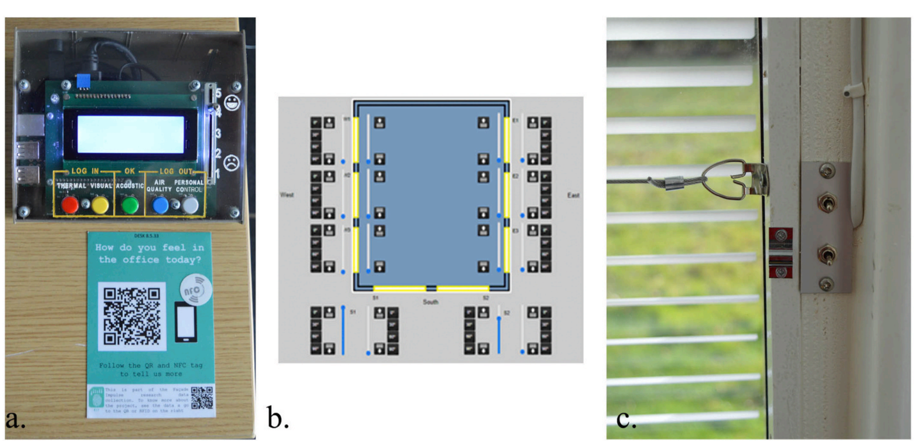

Fig. 14. a.Interfaces for gathering occupant feedback: polling station (top) and mobile app (bottom) b. interface for the touchscreen control unit or accessible by web browser; c. Switch to action the facade located beside the facade bay.

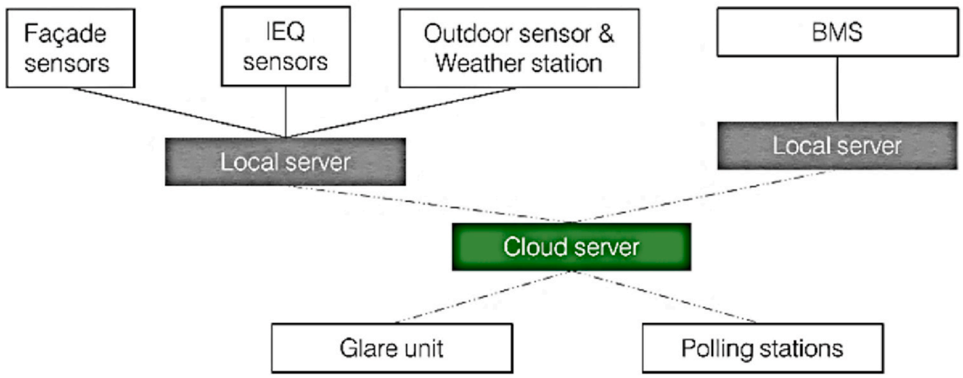

Fig. 15. Architecture of the data retrieving and storage system.

chamber was configured with glazed facades in the south orientation. The characteristics of the facade are listed in Table 4. In February 2020, the chamber had a multiple occupancy with three volunteers per session, each orientated perpendicularly to the facade and located at different distances from it, as shown in Fig. 17B. Conversely, in September the space had a single occupancy and the volunteers sit at 1 m from the facade, as shown in Fig. 17C. The IEQ was always monitored at three locations from the facade, as shown in Fig. 17A. The facade was fitted with internal venetian blinds that could be operated manually (Fig. 16). The HVAC and the artificial lights were controlled by the building automation system (details shown in Table 4) and occupants were not provided with override controls.

In February 2020, 12 volunteers (7 female and 5 male, aged between 25 and 32 years) were assigned in four groups of 3 subjects, while in September 10 volunteers (1 per time, 6 female and 4 men) were invited to work in MATELab. Volunteers were asked to work during one whole day for 8 h (from 9 a.m. to 5 p.m. with a lunch break of 30–60 min duration). At the start of the experiment (Time 1 = 9:00 a.m.), volunteers completed an initial online questionnaire which included providing their consent, obtaining a personal identification code and random allocation of a desk location for the day. The volunteers were then asked to express their discomfort whenever and however often it occurred during the day. In addition, at three specific times of the day (Time 2 = 11 a.m., Time 3 = 1 p.m., Time 4 = 3 p.m.) the volunteers were asked to complete a 3 min questionnaire using the specially designed mobile app described in Section 4. The volunteers were also invited to reply to the questions displayed by the polling station, described in Section 5, as often as they wanted to. Every hour the questions would appear on the screen, they were invited to reply at least four times a day. At the end of the experiment day (Time 5 = 5pm), they were asked to fill a final online questionnaire. The questions of this questionnaire are reported in Appendix B.

Fig. 16. Detail of the facade.

Table 4
Characteristics of the Building services and the Facade.

	Type of control and settings
Building services	
HVAC	Automated from 7 a.m. to 5 p.m. Air Temperature setpoint of 22 °C
Lights	Activated by occupancy sensors,
Facade	Double Glazed Unit
characteristics	2 × 4mm laminated glass +15 mm cavity +6 mm
Light transmissivity	0.50
Solar transmissivity	0.27
g-value	0.31
U-value	1.1 [W/m^2 K]
Weight	25 [kg/m^2]
Colour rendering index	94 (neutral)
Blinds	Internal venetian blinds with 35 mm spaced by 35 mm, flat slats light grey matte slightly curved
Control allowed	Up and down, no slat rotation

6.2. PO1. MATELab can capture the influence of the facade on the IEQ

This performance objective was assessed from the environmental data captured in multiple locations inside and outside MATELab during February and September 2020 in the configuration shown in Section 5. A representative sample of the data captured is shown in Fig. 18. This shows the transient levels of the selected environmental parameters, described in Table 2 at the facade location and at three internal stand-off distances from the facade (1 m, 2.5 m and 4 m) during 3 days in September (from the 22nd to the 25th of September - single-occupied configuration). The indoor environmental parameters that are known to be affected by changes in facade environmental characteristics, such as the air velocity at 1 m from the facade and the horizontal illuminance, the air and globe temperature at the three different distances from the

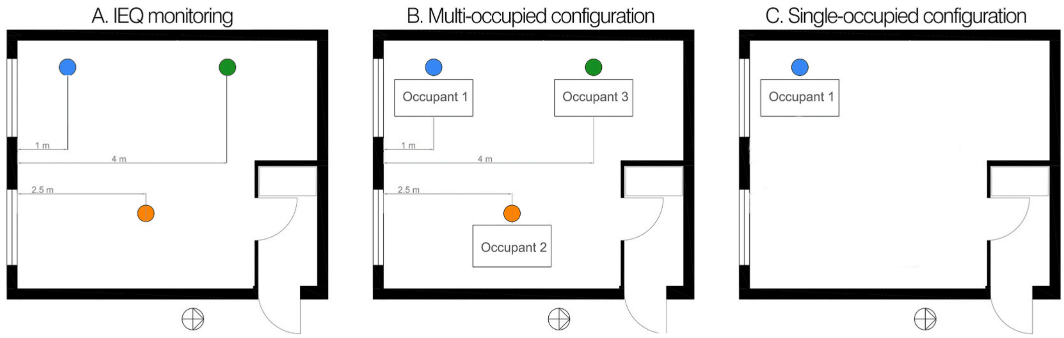

Fig. 17. MATELab Experimental setup: A. Setup for the IEQ monitoring and unoccupied space; B. Multi-occupant setup in February 2020; C. Single-occupied setup in September 2020.

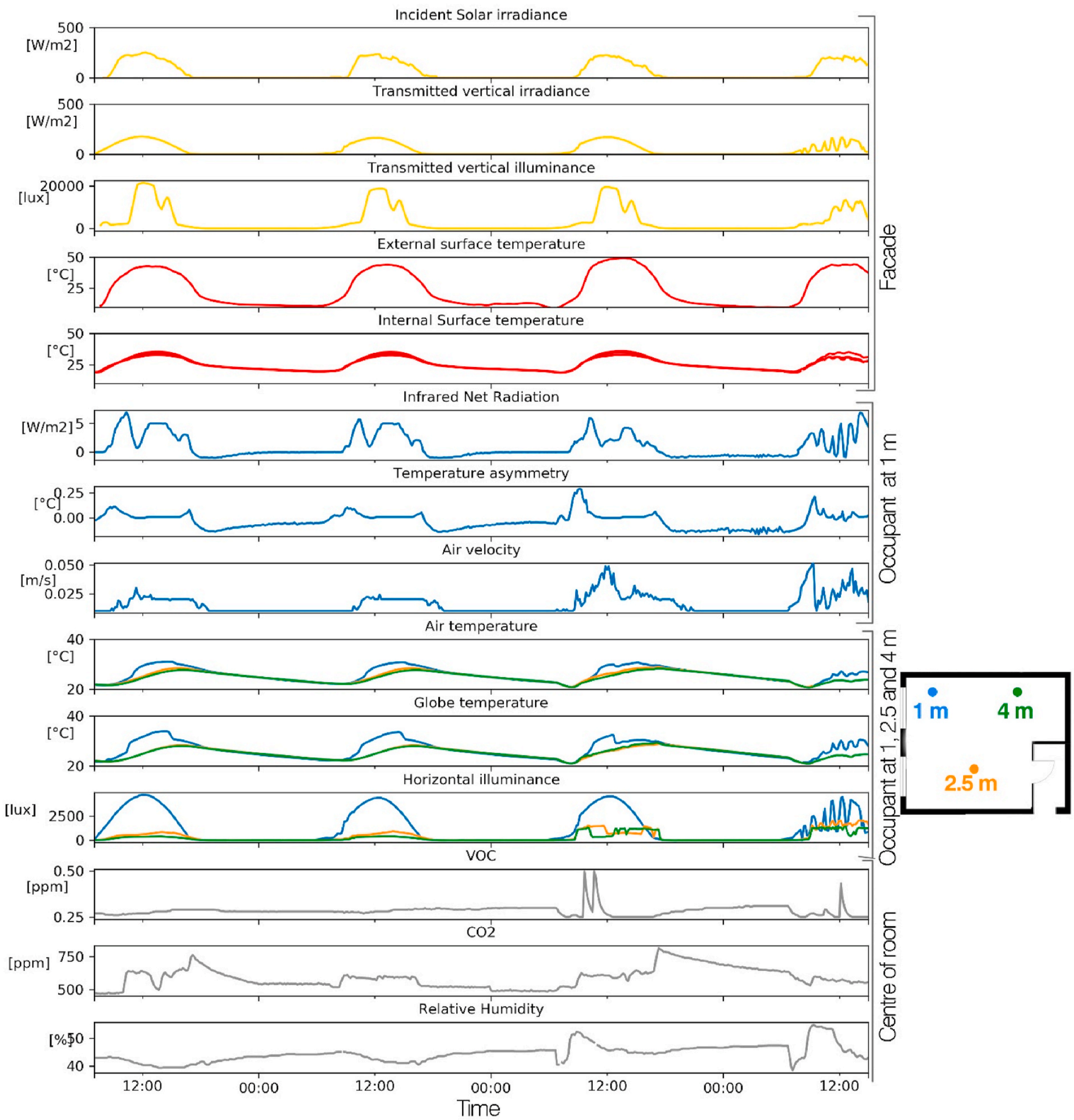

Fig. 18. Variation over 3 day period in selected environmental parameters at the facade location and at different facade distances.

facade, show a similar trend and variation in time, that correlates with the variations in facade environmental characteristics (surface temperature, transmitted irradiance and transmitted illuminance). This demonstrates that the experimental setup of MATELab is capable of measuring changes in indoor environmental parameters due to changes in facade environmental characteristics.

The glare unit was also used to monitor the luminance levels from the point of view of Occupant 1, which was located at 1.5 m from the facade during the 22nd of September. On that day the sky was partially overcast. A selection of luminance maps is shown in Fig. 19. The luminance maps were then used to compute the DGP, which is plotted in Fig. 20 and shows the average trend of DGP and vertical illuminance during the day, which is deemed to be sufficient for the validation since it can describe the average trend during the day. The luminance maps were developed at an interval of 15 min, but higher frequency is also possible depending on the experimental design.

6.3. PO2: habituation of occupants to the space

A linear mixed model analysis was performed to assess the influence of time on occupant habituation with the office space, considering also the interaction effect of working in a group against working alone on the habituation of occupants in time. Occupants were asked to express their level of agreement on a scale of 1 (strongly disagree) to 5 (strongly agree) with the following statement: "I feel familiar with this office space" during the day. Time was found to be the main parameter for the habituation of occupants ($p < 0.001$) and being in a group or not was found to have a statistically significant effect on the level of habituation in time ($p < 0.05$). Fig. 21 shows the level of agreement of occupants during the time and depending on whether MATELab was used as a single-occupied space or as a multi-occupied space. When working alone in the test room, volunteers feel significantly more familiar with the office space than volunteers working in Group when just arrived (Just arrived, Time = 9 a.m.). Space habituation is achieved more quickly

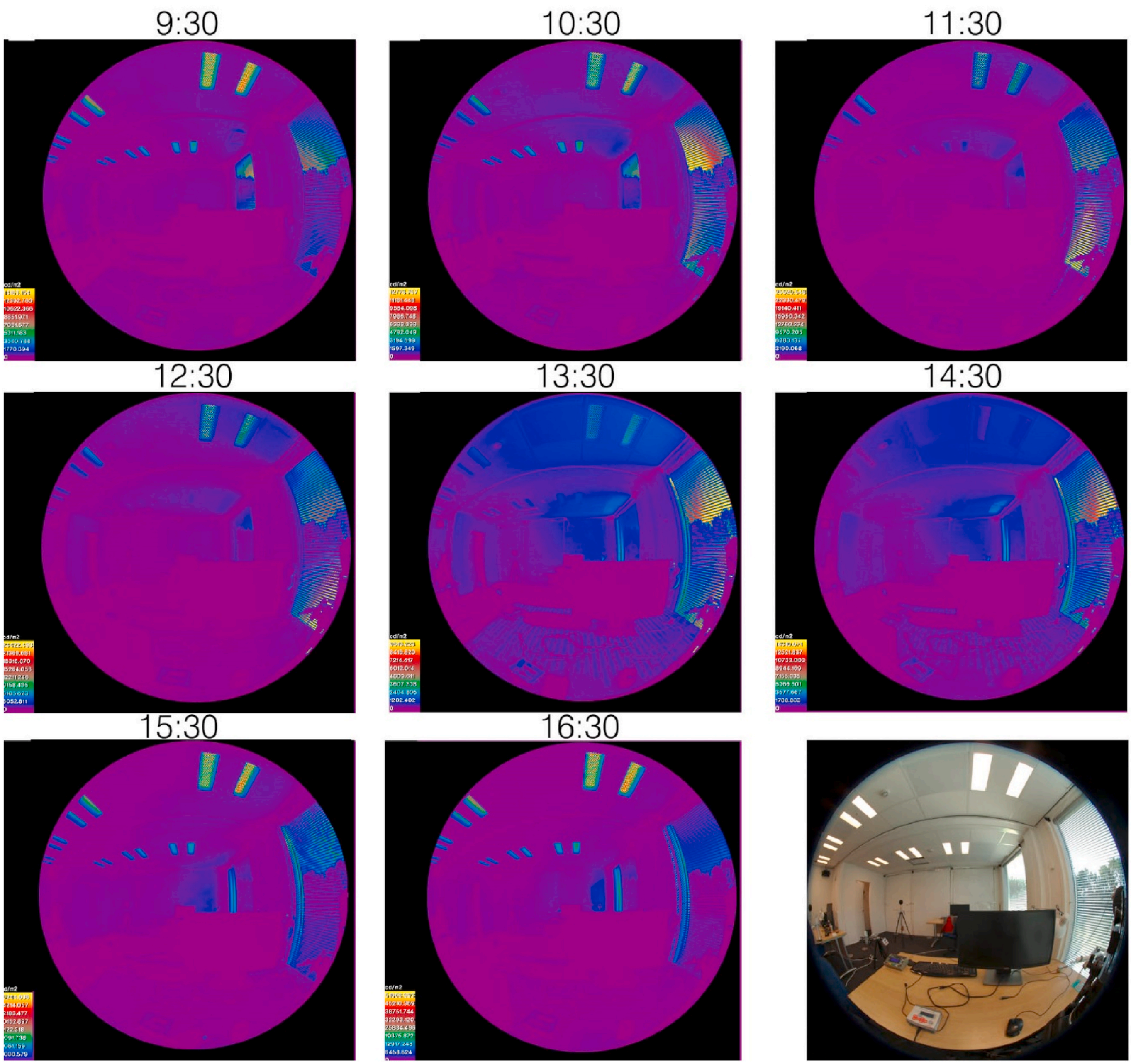

Fig. 19. Selected luminance maps from the 22nd of September from Occupant 1 point of view.

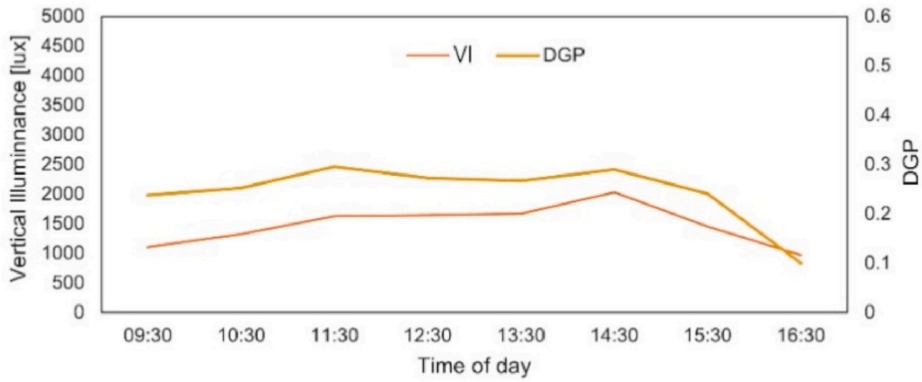

Fig. 20. Average vertical illuminance (VI) and DGP for the 22nd of September from the point of view of Occupant 1 (1.5 m from the facade).

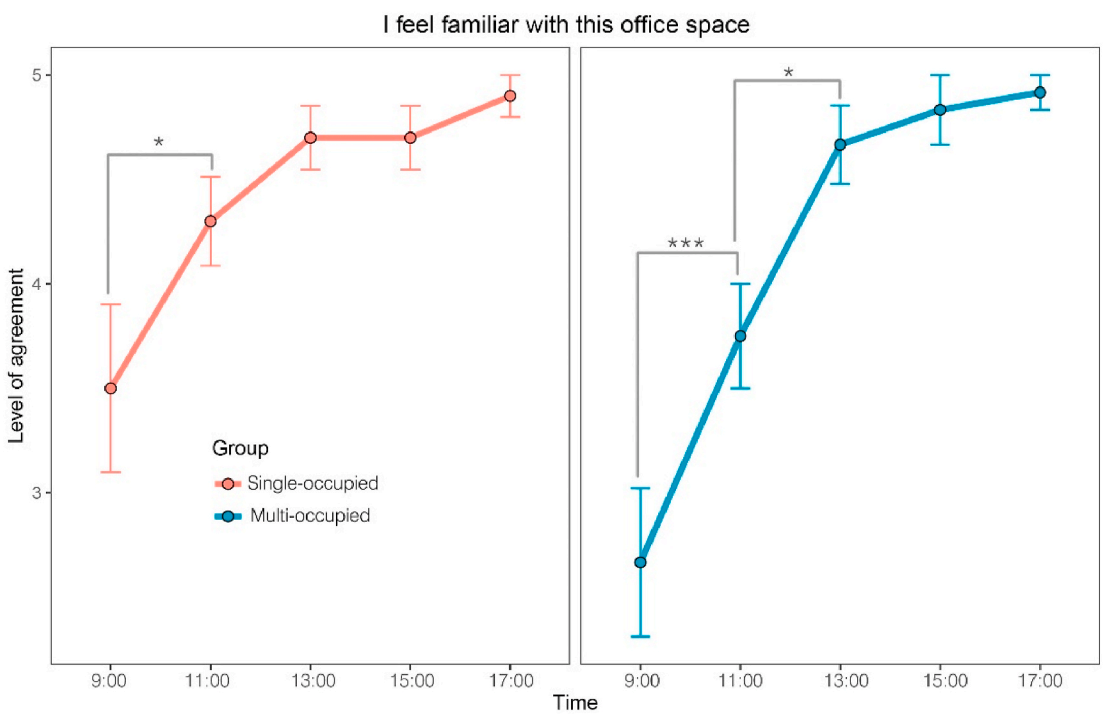

Fig. 21. Mean votes and error of the variance in time for both subjects in group (Y) and without (N). Level of significance *** = $p < 0.001$ and * = $p < 0.05$.

when volunteers work alone. When working in a group, the average level of agreement at 9:00 is significantly lower if comparing with the level at 11:00 ($p < 0.0001$) and at 13:00 ($p < 0.05$), while when working alone after 11:00 there are not significantly differences in the level of occupant habituation ($p < 0.05$).

In addition to the question on habituation, single-office volunteers were asked about their level of agreement at the end of the day and with the following statement: "I feel MATELab is similar to a typical office space". Overall, MATELab was considered similar to an office space. The overall mean was found to be 4.1, with a standard deviation of 1.165. Fig. 22 shows the distribution and mean of the vote. Volunteers were then asked to express in what they feel working in MATELab could be different than working in a typical office space. 50% of volunteers stated that they did not commonly have an outdoor view of greenery from their real-world office spaces. One volunteer also listed the acoustic environment as being a main difference between MATELab and a typical office, while two volunteers mentioned the fact that there were few people "around" the office and the environment outside was different to other typical office spaces. 30% of the volunteers mentioned that the lighting in the room was more "natural and better" than typical office

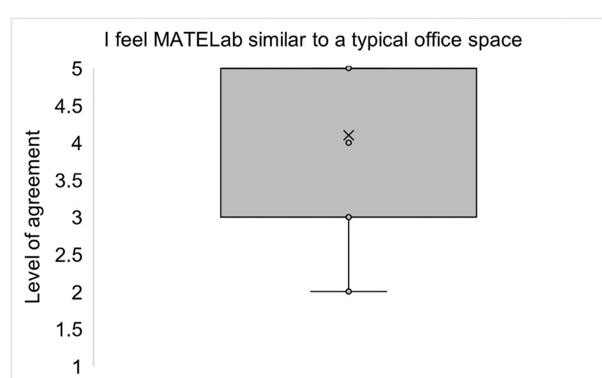

Fig. 22. Distribution of level of agreement votes to the sentence "I found MATELab similar to a typical office space".

spaces.

6.4. PO3: providing representative insights on occupants' environmental satisfaction, discomfort and interaction with facades

Information on occupant discomfort and satisfaction with the indoor environment was collected with the polling station during the day in February 2020. Information on occupant environmental satisfaction was collected either by the mobile app or by occupant' responses to the questions displayed by the polling station. Fig. 23 a shows the frequency with which volunteers responded to the questions provided by the polling station over the total number of experimental sessions. For almost half of the experimental days, volunteers were replying to the questions 5 times a day (approximately every 2 h) and for 35% of the sessions at least 3 times a day (approximately every 3 h). The 15% of the days, volunteers had replied only twice to the polling station prompts (every 4 h).

Presence of discomfort was logged every time volunteers would press the discomfort buttons. Fig. 23 b shows the frequency in which occupants were expressing discomfort during the day. Overall, discomfort was expressed with lower frequency than the information on perception or satisfaction. The majority of experimental days, discomfort was expressed between 1 and 3 times a day and, rarely, for a very large number of times e.g. 14 times for 10% of the days. However, the interaction of occupants with discomfort buttons depends also on the presence of environmental discomfort and, therefore, a lower frequency of interaction can be due to the absence of discomfort rather than to a low engagement with the interface. Therefore, the frequency with which volunteers replied to the satisfaction questions prompted by the polling stations is a better indicator of occupant engagement and effectiveness of the data collection procedure, rather than the counting of pressed discomfort buttons.

The data collected through the polling station was also useful to quantify the level of discomfort and environmental satisfaction of the occupants. Fig. 24 shows the average results of occupant thermal, daylight and glare perception per time of the day in MATELab, when the office was multi-occupied. Occupants closer to the facade were significantly more satisfied with the level of daylight (Fig. 24a). Satisfaction with glare was higher when occupants were sitting further from the facade and it changed across the day. Occupants experienced a significant decrease in glare satisfaction in the afternoon with respect to the morning or evening levels. This was especially true for the closest and the intermediate positions from the facade. This can be explained by the fact that the facade under investigation was manually controlled and relies on an internal venetian blind to prevent glare discomfort, which is often not effective in preventing glare discomfort. In terms of thermal satisfaction, occupants closer to the facade seemed significantly more thermally dissatisfied than occupants far from it.

The use of coloured-code buttons on the polling station (Section 5.2) for track the presence of discomfort was successful and provided insights on the frequency of discomfort during the day per comfort domain and location from the facade. Fig. 25 shows the results for the multi-occupied scenario and at the three different locations from the facade. The facade system was unable to prevent discomfort glare and overheating during the measurement campaign. As expected, thermal and visual discomfort events primarily took place during the afternoon. This was due to the orientation of the facade and its limited capability to prevent overheating and glare discomfort. Fig. 25 also reveals that occupants closer with the facade experienced thermal discomfort more frequently than those further to the facade. Visual discomfort was often encountered at further distances from the facades.

The system for logging occupant interaction (described in Section 5.2) with the facade was also found to be successful. Fig. 26 indicates the position of the blind (0 for open blind and 1 for close blind) as operated by the occupants. Slat rotation was not allowed during this validation test. MATElab is capable of recording instantaneously facade movements, however Figure 27 shows the facade movements at 15 min intervals for simplicity. During the February monitoring period (i.e. when the office was multi-occupied), occupant interaction was consistent with previous research on manually operated blinds [14], wherein occupants do not interact often with the facade and the blinds are left down for longer periods than is deemed necessary.

7. Discussion and conclusion

The use of realistic full-scale test chambers to investigate the effect of facade systems on occupant environmental perception and interaction helps to identify and quantify the facade system characteristics that can maximise occupant satisfaction whilst minimising resource-consumption. These chambers represent an intermediate step between very accurate, but unrealistic laboratories and field studies in real-world office spaces, in which it is difficult to identify and quantify facade effects due to the high number of uncontrolled boundary conditions that affect occupant environmental perception and behaviour.

The full effect of a facade technology and control system on occupants in real-world offices will depend on several factors that are unrelated to the facade system, such as building typology, climate, occupant demographics and preferences, orientation or external conditions. It is not expected that results from MATELab will be directly transferrable to real office spaces, even if the geographical location, the facade technologies and control strategies are the same. However, it is expected that the results from a monitoring and experimental campaign in MATELab can inform the choice of the most occupant-centred facade technologies by allowing the relative comparison among alternative

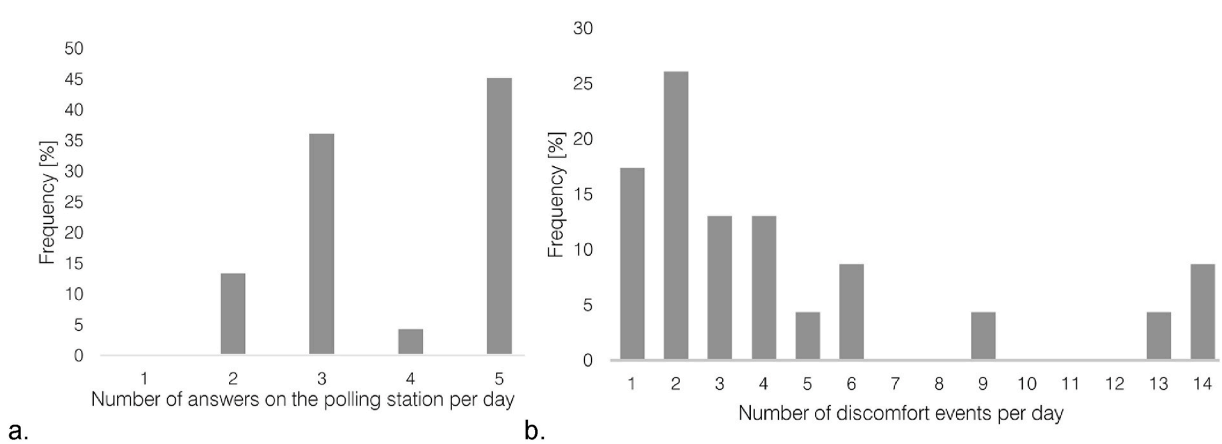

Fig. 23. Frequency of occupant interaction with the polling station: a. Answers to the polling station questions; b. Use of discomfort buttons per day.

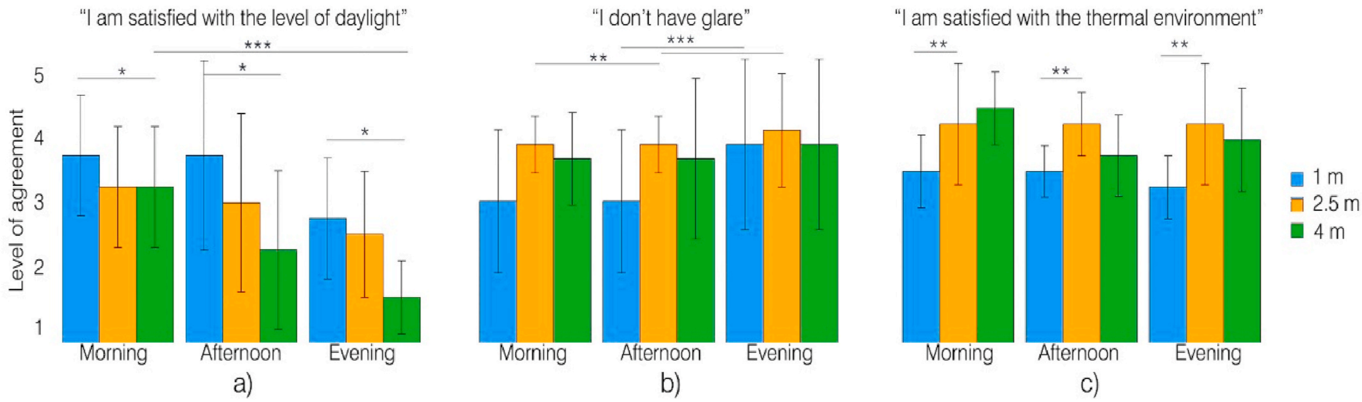

Fig. 24. Average occupant environmental satisfaction in MATELab. Levels of significance are expressed as follows: *** = $p < 0.001$; ** = $p < 0.01$, * = $p < 0.05$.

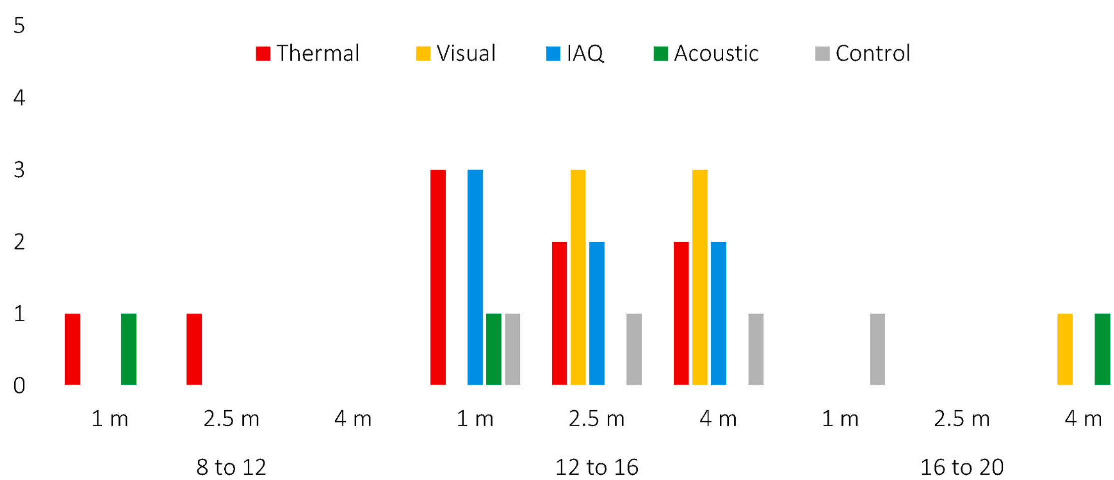

Fig. 25. Frequency of environmental discomfort events in MATELab throughout the day.

solution. For instance, this could be especially useful when developing novel control algorithms for dynamic facades, which can then be fine-tuned in the real office spaces during the commissioning stage.

This paper firstly reviewed existing test-chambers that evaluate the effect of facade systems on occupant environmental perception and interaction. The principal characteristics of the test-rooms were also identified from the review. It was found that twenty-three test chamber exist world-wide that can capture occupant environmental perception/interaction with the facade in more than environmental domain and by fulfilling several of the above characteristics. However, none of these facilities provides and combines all of the required characteristics in one integrated facility or provide detailed information on the required methods for capturing multi-domain occupant environmental perception/interaction with the facade.

Secondly, a new full-scale test chamber for capturing the effect of facade systems on occupant environmental perception and interaction, called MATELab and located in Cambridge (UK), was developed on the basis of the design requirements of MATELab. The paper goes onto to describe the construction and instrumentation of MATELab. A comprehensive description of the required environmental monitoring and occupant-related data collection methods is provided.

Data from two preliminary monitoring campaigns with volunteers are then used to validate the capabilities of MATELab and the associated data collection procedure. The aim of the validation was: 1) to verify that the experimental design allows to capture the influence of facades on IEQ with adequate resolution in time and space, 2) to test the level of habituation of volunteers with MATELab in time in order to understand if the test room provides a sufficiently realistic environment and to quantify how long volunteers need to feel habituated; 3) To verify that the experimental design captures data with adequate frequency and space resolution on occupant environmental perception and interaction with the facade.

The IEQ data collected in MATELab showed that it was possible to identify and rank the most influential facade environmental characteristics and occupant-related environmental parameters. Volunteers found MATELab to be sufficiently similar to a real-world office space, and volunteers became habituated with the space after an adaptation time between 2 h (when the space is single-occupied) and 4 h (when the space is multi-occupied).The data collection methods applied in MATELab allowed to capture occupant environmental perception and interaction with sufficient granularity. Occupant interaction with the facade could easily be monitored in a non-disruptive manner thanks to the logging system associated to the facade control. Comparison between the closest (1 m) and furthest position (4 m) from the facade provided useful insights on the effect of distance for the influence of the facade. Data was also captured with sufficient time frequency to describe the influence of the facade during the day.

Future work will need to extend the measurement campaign and increase the number of testing scenarios in order to evaluate differences in perception and interaction of occupants with alternative facade systems, at different orientations and seasons. Geometrical limitations due to the structure of the lab limited the headroom to 2.5 m, however because of the relatively small floor area occupants still perceived the space as a realistic office space. Nevertheless, this could be overcome in future design. An identical maximum WWR would have been also preferrable, especially when studying alternative orientations over a short

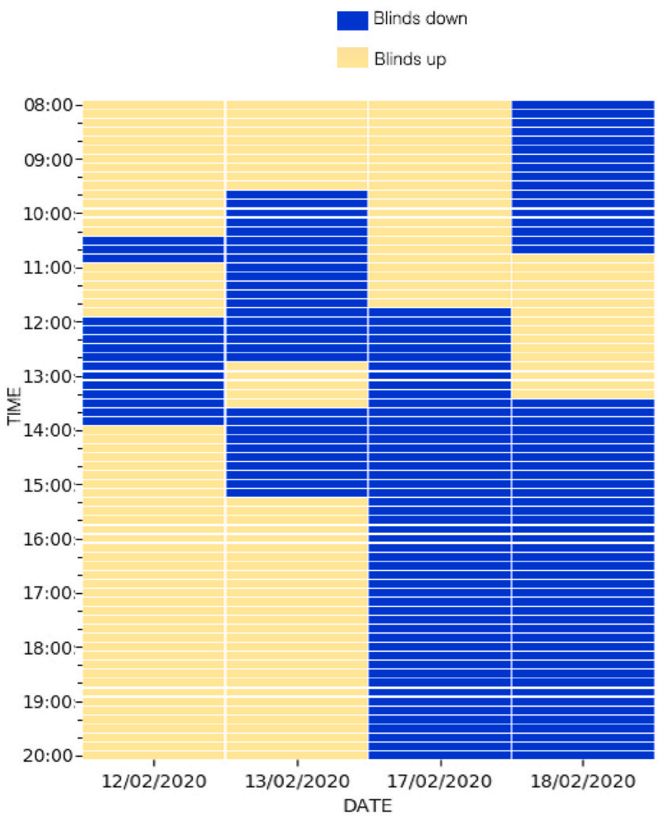

Fig. 26. Comparison of occupant interaction with internal blinds in MATELab and in a real office environment.

period of time. The following measurements will need further development: (i) Automated luminance measurements close to the occupant position and in a non-disruptive manner; (ii) Level of solar radiation on the body of the occupant in a non-disruptive manner; (iii) Noise frequency spectrum; (iv) Physiological parameters by means of non-disruptive wearables sensors.

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 gratefully acknowledge EPSRC Doctoral Training Account, the CDBB, OVE ARUP and Permasteelisa Group for their support. The authors would also like to acknowledge Mr. Martin Touhey, Mr. Phil McLaren, Mr. Dave Layfield, Dan and Steve, Mr. Doug Ross for all the help and support in building and setting up MATELab. The authors are also thankful to Mr. Henk DeBleecker, Dr. Dieter Callewaert and Mr. Jorrit Grunewald for all their support in setting up MATELab.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.108092.

References

[1] M. Schweiker, et al., "Review of multi-domain approaches to indoor environmental perception and behaviour, Build. Environ. 176 (2020), 106804.
[2] IEA, Energy Technology Perspectives 2020, 2020.
[3] 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 (2) (2012) 119–131.
[4] F. Favoino, M. Overend, Q. Jin, The optimal thermo-optical properties and energy saving potential of adaptive glazing technologies,", Appl. Energy (2015).
[5] 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.
[6] 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.
[7] M. Favoino, F. Goia, R.C.G.M. Loonen, F. Babich, C. Bedon, Doya, *building performance Simulation and Characterisation of adaptive facades - adaptive facade network*, TU Delf Open (2018).
[8] 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).
[9] K. Konis, S. Selkowitz, Effective Daylighting with High-Performance Facades, 2017, pp. 251–269.
[10] F. Haldi, D. Robinson, Interactions with window openings by office occupants,", Build. Environ. (2009).
[11] F. Favoino, F. Fiorito, A. Cannavale, G. Ranzi, M. Overend, Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates, Appl. Energy 178 (2016) 943–961.
[12] P. Correia da Silva, V. Leal, M. Andersen, Occupants interaction with electric lighting and shading systems in real single-occupied offices: results from a monitoring campaign, Build. Environ. 64 (2013) 152–168.
[13] G.F. Menzies, J.R. Wherrett, Windows in the workplace: examining issues of environmental sustainability and occupant comfort in the selection of multi-glazed windows, Energy Build. (2005).
[14] M. Luna-Navarro, P. Fidler, S. Torres, Law A., Overend, "Building Impulse Toolkit (BIT): a novel IoT system for capturing occupant-façade interaction in real office environments, Build. Environ. 193 (2021), 107656.
[15] R. De Dear, A. Nathwani, C. Cândido, D. Cabrera, The Next Generation of Experientially Realistic Lab-Based Research: the University of Sydney's Indoor Environmental Quality Laboratory,", in: Architectural Science Review, 2013.
[16] A.L. Pisello, et al., "Test rooms for human comfort in buildings: a review of controlled experiments and facilities, Renew. Sustain. Energy Rev. (2021), 111359, https://doi.org/10.1016/j.rser.2021.111359.
[17] G. Cattarin, F. Causone, A. Kindinis, L. Pagliano, Outdoor test cells for building envelope experimental characterisation - a literature review,", Renew. Sustain. Energy Rev. (2016).
[18] F.W. Laura Aelenei, Marcin brzezicki, ulrich knaack, andreas luible, marco perino, adaptive facade network, TU Delft (2015).
[19] N.S. Shafavi, Z.S. Zomorodian, M. Tahsildoost, M. Javadi, "Occupants visual comfort assessments: a review of field studies and lab experiments, Sol. Energy (2020).
[20] M.B.C. Aries, J.A. Veitch, G.R. Newsham, Windows, view, and office characteristics predict physical and psychological discomfort, J. Environ. Psychol. 30 (4) (2010) 533–541.
[21] L. Karlsen, P. Heiselberg, I. Bryn, Occupant satisfaction with two blind control strategies: slats closed and slats in cut-off position, Sol. Energy (2015).
[22] W.H. Ko, et al., The impact of a view from a window on thermal comfort, emotion, and cognitive performance, Build. Environ. (2020).
[23] N. Tuaycharoen, P.R. Tregenza, View and discomfort glare from windows, Light. Res. Technol. 39 (2) (2007) 185–200.
[24] N.K. Kandasamy, G. Karunagaran, C. Spanos, K.J. Tseng, B.H. Soong, Smart lighting system using ANN-IMC for personalized lighting control and daylight harvesting, Build. Environ. (2018).
[25] P.M. Bluyssen, et al., The creation of SenseLab: a laboratory for testing and experiencing single and combinations of indoor environmental conditions, Intell. Build. Int. (2018).
[26] H.M. Schweiker M, S. Brasche, Presenting LOBSTER, an Innovative Climate Chamber, and the Analysis of the Effect of a Ceiling Fan on the Thermal Sensation and Performance under Summer Conditions in an Office-like Setting, in: Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World Cumberland Lodge, Windsor, UK, 10-13 April 2014, Network for Comfort and Energy Use in Buildings, London, 2014.
[27] J. Wienold, J. Christoffersen, Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, Energy Build. 38 (7) (2006) 743–757.
[28] Wellershoff F., Friederich M., Schweers K., "HCU Studio for room Comfort Real-scale test Room with Reconfigurable Facade," in Building Performance and characterisation of Adaptive Facades - Adaptive Facade Network, B. F. Favoino F., Loonen R., Doya M., Goia F., Bedon C., Ed. TU Delf Open, 2018.
[29] S. McNeil A, C. Kohler, E.S. Lee, Selkowitz, High Performance Building Mockup in FLEXLAB, 2014.
[30] Fraunhofer IBP Institute, VERU Modular Test Facility for Energy and Indoor Environments [Online]. Available, https://www.ibp.fraunhofer.de/content/dam/ibp/en/documents/VERU_Flyer_e_tcm1021-85279.pdf, 09-Nov-2020.
[31] L. Bianco, P. Schneuwly, E. Wurtz, A. Brun, Design of a new full-scale facility for building envelope test: FACT (FACade tool), in Energy Procedia (2017).
[32] O.K. Larsen, P.K. Heiselberg, "Experimental Set-Up and Full-Scale Measurements in the 'Cube, 2008.

[33] M.S. Rea, Window blind occlusion: a pilot study, Build. Environ. 19 (2) (1984) 133–137.
[34] V. Inkarojrit, "Balancing Comfort: Occupants' Control of Window Blinds in Private Offices, UC Berkeley, 2005.
[35] A. Mahdavi, A. Mohammadi, E. Kabir, L. Lambeva, "Occupants' operation of lighting and shading systems in office buildings, J. Build. Perform. Simul. 1 (1) (2008) 57–65.
[36] EURAC, Facade System Interactions Lab. [Online]. Available, http://www.eurac.edu/en/research/technologies/renewableenergy/Infrastructure/Pages/Façade-System-Interactions-Lab.aspx, 09-Nov-2020.
[37] J.Y. Garretón, R. Rodriguez, A. Pattini, Effects of perceived indoor temperature on daylight glare perception, Build. Res. Inf. (2016).
[38] G. Chinazzo, J. Wienold, M. Andersen, Combined effects of daylight transmitted through coloured glazing and indoor temperature on thermal responses and overall comfort, Build. Environ. (2018).
[39] J. Carmody, S. Selkowitz, E. Lee, D. Arasteh, T. Willmert, Window Systems for High Performance Buildings, First, Norton, New York, 2004.
[40] A. Luna Navarro, et al., Occupant-Centred Control Strategies for Adaptive Facades: Preliminary Study of the Impact of Shortwave Solar Radiation on Thermal Comfort, in: In Proceedings of Building Simulation, 16th Conference of IBPSA, 2020, 2019.
[41] I. Konstantzos, Y.-C. Chan, J.C. Seibold, A. Tzempelikos, R.W. Proctor, J. B. Protzman, View clarity index: a new metric to evaluate clarity of view through window shades, Build. Environ. 90 (2015) 206–214.
[42] L.G. Bakker, E.C.M.H. 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.
[43] Francesco Goia, Alessandro Nocente, Steinar Grynning, in: M. Favoino, F. Goia, R. C.G.M. Loonen, F. Babich, C. Bedon, Doya (Eds.), "ZEB Test Cells Laboratory," in *Building Performance Simulation and Characterisation of Adaptive Facades - Adaptive Facade Network*, TU Delft Open, 2018.
[44] EPFL, "CELLS." [Online]. Available, https://www.epfl.ch/labs/hobel/home-2/facilities/controlled-environments-for-living-lab-studies-cells/, 09-Nov-2020.
[45] M. Schweiker, S. Brasche, W. Bischof, M. Hawighorst, K. Voss, A. Wagner, Development and validation of a methodology to challenge the adaptive comfort model, Build. Environ. (2012).
[46] S.E.S. Andrew McNeil, Christian Kohler, S Lee Eleanor, High Performance Building Mockup in FLEXLAB, 2014.
[47] R.L. Jensen, TRIUMF Laboratory Two Room Indoor Environment & Energy Universal Facade, in: M. Favoino, F. F Goia, R.C.G.M. Loonen, F. Babich, C. Bedon, Doya (Eds.), Building Performance and Characterisation of Adaptive Facades - Adaptive Facade Network, TU Delft Open, 2018, p. 147.
[48] M. Benedetti, L. Maierová, C. Cajochen, A. Motamed, M. Münch, J.L. Scartezzini, Impact of Dynamic Lighting Control on Light Exposure, Visual Comfort and Alertness in Office Users, in: Journal of Physics: Conference Series, 2019.
[49] Y. Bian, T. Luo, Investigation of visual comfort metrics from subjective responses in China: a study in offices with daylight, Build. Environ. (2017).
[50] B. Svetozarevic, et al., Dynamic photovoltaic building envelopes for adaptive energy and comfort management, Nat. Energy (2019).
[51] W.H. Ko, G. Brager, S. Schiavon, S. Selkowitz, Building Envelope Impact on Human Performance and Well-Being: Experimental Study on View Clarity, 2017.
[52] "Aura Lunaria Pro G4." [Online]. Available, https://www.auralight.com/en/luminaires/aura-lunaria-pro-g4. (Accessed 24 February 2021).
[53] Light Cen, lighting, Lighting of work places, Indoor work places EN 12464-1:2011 (2011).
[54] KNX Communication Protocol [Online]. Available, https://www.knx.org/knx-en/for-professionals/index.php, 24-Feb-2021.
[55] A. Luna-navarro, M. Overend, Towards Human-Centred Intelligent Envelopes : A Framework for Capturing the Holistic Effect of Smart Façades on Occupant Comfort and Satisfaction, in: 7th International Building Physics Conference IBPC2018, 2018.
[56] C. Huizenga, H. Zhang, P. Mattelaer, T. Yu, E. Arens, L. P, Window Performance for Human Thermal Comfort, 2006.
[57] 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.
[58] G.M. Revel, M. Arnesano, F. Pietroni, Development and validation of a low-cost infrared measurement systemfor real-time monitoring of indoor thermal comfort, Meas. Sci. Technol. (2014).
[59] ANSI/ASHRAE, "ANSI/ASHRAE 55:2017 Thermal Environmental Conditions for Human Occupancy," Ashrae, 2017.
[60] ISO, Ergonomics of the Thermal Environment Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria ISO 7730, 2005.
[61] IES and ANSI, Office Lighting ANSI/IES RP-1-12, 2013.
[62] Cen, Daylight in Buildings EN 17037:2019, 2019.
[63] C. Pierson, C. Cauwerts, M. Bodart, J. Wienold, Tutorial: luminance maps for daylighting studies from high dynamic range photography, LEUKOS - J. Illum. Eng. Soc. North Am. (2019).
[64] E. Upton, H. Gareth, Raspberry Pi User Guide, 2014.
[65] A. Mcneil, System for High Dynamic Range Image Capture and Glare Analysis, 2017.
[66] Texas Instrument, "ADS122C04".
[67] C.J. Wienold J, C. Reetz, T.E. Kuhn, Evalglare - a new radiance-based tool to evaluate daylight glare in office spaces, in: 3rd International Radiance Workshop, 2004.
[68] Anyhere Software, "Photosphere".
[69] M. Sarey Khanie, J. Stoll, W. Einhäuser, J. Wienold, M. Andersen, Gaze and discomfort glare, Part 1: development of a gaze-driven photometry, Light. Res. Technol. (2016), 1477153516649016.
[70] L. Claudi, M. Arnesano, P. Chiariotti, G. Battista, G.M. Revel, A soft-sensing approach for the evaluation of the acoustic comfort due to building envelope protection against external noise, Meas. J. Int. Meas. Confed. 146 (2019) 675–688.
[71] J. Kim, R. de Dear, Workspace satisfaction: the privacy-communication trade-off inopen-plan offices, J. Environ. Psychol. (2013) 18–26.
[72] Mobvoi, "Ticwatch S & E: A Truly Optimized Smartwatch by Mobvoi — Kickstarter," Kickstarter, 2017.
[73] HM Gov, Part L: Conservation of Fuel and Power," Design, 2006.
[74] CIBSE, CIBSE Guide A: Environmental Design," *Envrionmental Design*, 2015.
[75] F.S. Bauman, Underfloor Air Distribution (UFAD) Design Guide, 2003.