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Building Impulse Toolkit (BIT): A novel IoT system for capturing the influence of façades on occupant perception and occupant-façade interaction

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ABSTRACT

The design and operation of responsive resource-efficient buildings requires high resolution data in space and time on building performance and the associated occupant response, but capturing this high quality data has traditionally been technologically challenging, costly and disruptive to building occupants. Recent developments in Internet of Things (IoT) technologies provide an opportunity to monitor holistic indoor environmental quality (IEQ) and related occupant perception and behaviour in a more cost-effective and less disruptive manner whilst providing higher granularity data in space and time. Façades have a significant and dynamic influence on IEQ and building performance, and occupants often interact with them, but there is a dearth of IoT solutions for monitoring the façade-induced effects. This paper describes the development, deployment and assessment of the Building Impulse Toolkit (BIT), a prototype IoT system for capturing the holistic and transient influence of façades on IEQ and occupants. The methodology adopted in the design and development of the BIT prototype is first explained. The results obtained from a 9-month deployment in a real-world office are then reported and discussed, in particular the capabilities and limitations of the BIT prototype in: 1) capturing the influence of the façade on IEQ in space and time; 2) monitoring occupant environmental discomfort and satisfaction and in a non-disruptive manner; 3) monitoring occupant interaction with the façade. It was found that BIT is largely successful at meeting these objectives, but occupant engagement could be improved in the next generation prototypes.

1. Introduction

By 2050 the United Nations endeavours to achieve net zero carbon emissions [1]. This ambitious target coincides with a projected surge in urban population of approximately 2 billion people [2]. Cities account for 36% of global energy demand and produce 40% of the global energy-related emissions [3] and this is largely driven by the need to provide comfortable and productive indoor environments for human activities, such as heating, cooling and lighting. Achieving decarbonised, yet comfortable, cities is one of the predominant challenges of the 21st century. Dynamic building components and smart controls offer possible solutions to this challenge because they provide a degree of customisation and allow tuning of building performance [4] whilst optimising resource-consumption [5] through real-time data analytics and automated controls. However, these smart dynamic building components often fail to meet occupant needs and they can result in high levels of occupant dissatisfaction [6]. One of the reasons for this, is the lack of adequate interfaces and devices that respond to, and interact with, occupants in an effective manner [6,7]. Occupant environmental perception is holistic [6,8], involving several physical domains (Fig. 1a),

Abbreviations: C_2HCl_3, Trichloroethylene; C_2Cl_4, Tetrachloroethylene; C_6H_6, Benzene; $C_{10}H_8$, Naphthalene; CO, Carbon Oxide; CO_2, Carbon Dioxide; CH_2O, Formaldehyde; C1A / C1B VOC, Carcinogenic Volatile Organic Compounds; DGP, Daylight Glare Probability; D_T, Target Daylight Factor; DR, Draft Rate; E_T, Equation of time; HDR, High Dynamic Range; RH, Relative Humidity; IEQ, Indoor Environmental Quality; IoT, Internet of Things; Leq, Equivalent Continous Sound Level; MQTT, Message Queuing Telemetry Transport; MRT, Mean Radiant Temperature; NO_2, Nitrogen dioxide; PAHs, .Polycyclic aromatic hydrocarbons; PMV, Predicted Mean Vote; PPD, Predicted Percentage Dissatisfied; PD, Percentage Dissatisfied; Rn, Radon; SPL, Sound Pressure Level; T_{op}, Operative Temperature; T_{op}*, Adjusted Operative Temperature; TVOC, Total Volatile Organic Compounds; UDI, Useful Daylight Illuminance.

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that are location-specific and transient [9], so interfaces and devices need to capture the multi-physical characteristics of the environment with high-granularity in both space and time. Holistic data with high time and spatial resolution is particularly important when assessing façade-induced changes to IEQ and occupant satisfaction [10], since façades effect many of the IEQ domains and the influence varies in time and across the internal floor plan [11]. Façades also provide a significant scope for occupant interaction [6]. Therefore, any such data collection platforms have the potential to inform occupant-centric and customised control strategies for dynamic façade technologies [12]. Furthermore, achieving the high levels of data granularity in time and space in a cost effective and human-centred manner could lead to the development of a new generation of smart building technologies [13], because the appropriate actuation of the smart building technology is inextricably linked to the quality of the data that is used to trigger the actuation. Internet of Things (IoT) solutions have recently provided useful low-cost means for gathering Indoor Environmental Quality (IEQ) data [14–16] and occupant feedback [11,17–21] since they enable a higher frequency and less-intrusive data collection over relatively long monitoring periods.

Even if the accuracy of IoT solutions is lower than traditional laboratory-grade devices, their pervasiveness and continuous monitoring capabilities provide representative insights on IEQ variability in time and space [22]. Cost-effective sensing solutions are nowadays often combined with mobile-app platforms for gathering occupant feedback [23,24]. However, only two IoT solutions to-date are known to focus specifically on the occupant-façade interaction [11,25]. The first IoT solution [11] captures the façade effects on the thermal and visual indoor environment by measuring workplace illuminance and operative temperature at each occupant position, by means of temperature, luminance and vertical illuminance sensors and an analogue interface for gathering occupant feedback. However, other important environmental characteristics, such acoustics and air quality, are not captured and no sensors are placed on the façade. The second IoT solution [25] consists of a novel sensor for assessing Mean Radiant Temperature and surface temperatures within the whole indoor environment. It integrates the data collection with the Building Management System (BMS) and smart façade sensing platforms. However, this solution is limited to single-spot measurements of illuminance and CO_2 in the indoor environment and does not include acoustic quality or luminance-based measurement devices for glare monitoring or occupant feedback platforms.

The initial concept of a Building Impulse IoT toolkit to capture occupant response to the façade has been presented by the authors [26], where the toolkit was evaluated in terms of its level of intrusiveness relative to traditional web-based questionnaires. The present study is a natural and significant progression from the previous work by the authors; in it we describe the final development of the IoT toolkit called the Building Impulse Toolkit (BIT – Fig. 1b). The additional new features beyond those found in Refs. [11,25,26] create the missing link between key façade-induced environmental parameters and corresponding response and IEQ at the occupant location, that could among other things inform occupant-centred controls in future applications. The present study also includes the first ever systematic validation of the Building Impulse toolkit in terms of the accuracy and resolution of the data gathered.

Similar IoT toolkits could be constructed to assess the influence of other building elements on occupants, but the façade was selected in this study because: (1) facades affect multiple comfort domains simultaneously, and are therefore ideally suited for testing the holistic multi-domain approach that could potentially be achieved by IoT solutions; (2) Facades are often source of a broad range of occupant responses environmental discomfort (e.g. glare or overheating) but also of satisfaction (e.g. daylight access and outdoor view) and therefore collecting data that capture this broad range of conflicting responses provides a sophisticated, high-threshold test for the IoT solution; (3) Occupants often interact with facades to form a dynamic synergistic loop, thereby providing significant scope for testing the capabilities of the IoT solutions in capturing the dynamic occupant interaction. BIT consists of 3 sensor groups: An array of sensing devices on the façade (BIT Façade) and two devices per occupant workstation, one for monitoring glare and façade shading devices (BIT Glare) and a polling station with integrated environmental sensors (BIT Station). The possibility of facial action unit monitoring or other means for indirect occupant data collection, previously suggested in Ref. [26] was not developed further and is therefore not included in the current BIT prototype.

BIT is based on the Raspberry Pi single-board computer [27] and uses Wi-Fi networking for data transfer. The development of the IoT sensing devices and the user interaction platform are described in sections 2 and 3 respectively leading to the overall architecture of BIT, described in section 4. The validation of the toolkit was performed by deploying BIT in a real-world office for 9 months and is described in section 5. During

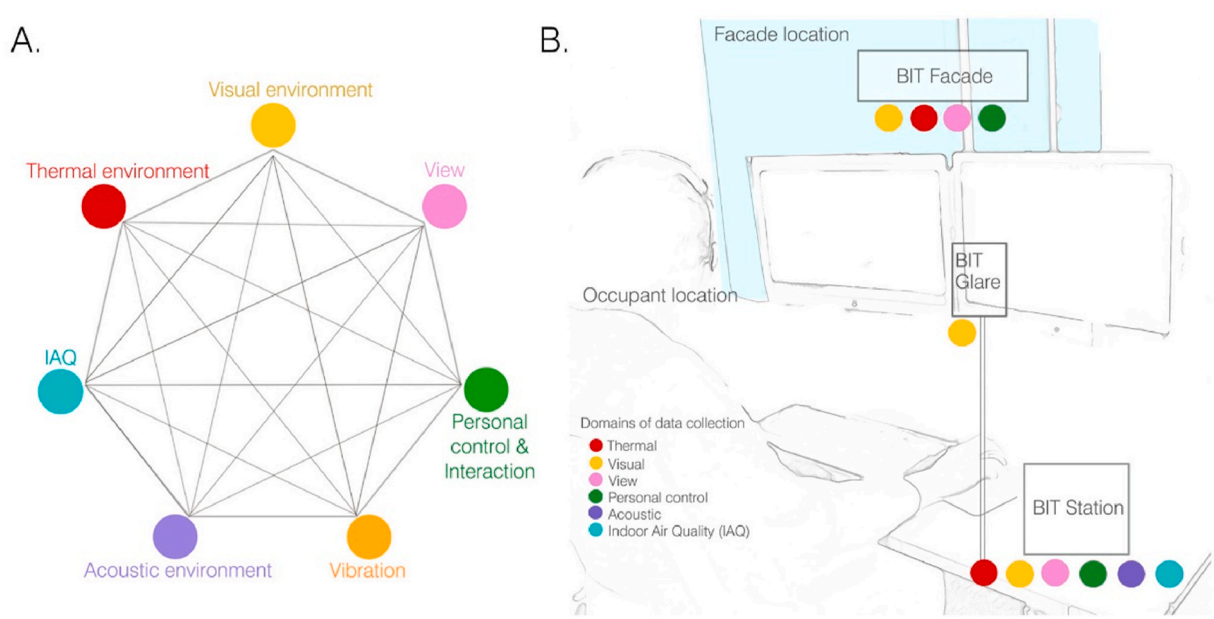

Fig. 1. a) Environmental domains in the indoor environment after [6], b) Schematic representation of the domains monitored by BIT and their respective locations.

this deployment period BIT was assessed in terms of its ability to meet the following functional objectives:

O#1: BIT can adequately capture the transient effect of façades on the IEQ at different distances from the façade.

O#2.:BIT can adequately capture occupant data: on environmental discomfort (O#2.1) and satisfaction (O#2.2) in time and at different locations with respect to the façades, and do so in a non-disruptive manner (O#2.3).

O#3. BIT can capture occupant interaction with the façade at sufficiently high frequency.

Details on the development of BIT, in particular: the selection of the environmental sensors and the rationale for their selection; the development of the occupant response interface; the IoT system architecture and ethical considerations are described in turn in sections 2, 3 and 4. Section 5 describes the validation of BIT and its deployment in a real world office with a particular emphasis on the ability of BIT to meet the above-listed functional objectives. This is followed by conclusions and possible future developments of BIT in section 6.

2. Development of the environmental sensing of IoT toolkit

2.1. Selection of key environmental parameter and toolkit development

There are several international standards that specify requirements of sensing devices and sampling frequencies for short and long term monitoring of comfort [22]. The most comprehensive guidelines in terms of overall IEQ measurements in office spaces are the European Standard for Energy performance of buildings [28] and ASHRAE's protocols for Performance measurements in commercial buildings [29]. However, the aim of these standards is to define minimum levels of IEQ for energy efficiency in buildings rather than to capture the effect of façades on comfort [28]. Therefore, a review of a broad range of existing standards and guidelines was undertaken in this study to inform the key requirements of BIT. Table 1 shows the salient outcomes of this review, namely the environmental parameters and related metrics suggested for each comfort domain by international standards. No standard or guideline directly addresses the measurement of façade characteristics for comfort purposes, therefore existing scientific research [6,10,13,30] was used to identify the façade-related environmental parameters that

Table 1
Environmental parameters to be monitored to characterise the impact of façades on comfort according international standards and after previous work [10].

Comfort domain	Occupant-centred metrics	Façade characteristics	Environmental parameters at the façade	Environmental parameters at occupant position
Thermal comfort [28,41,42]	PMV [28,41,42]		Surface temperature [41,42]	
	PMV[a] [43] [a]		Air temperature [41,42]	
	PPD [28,41,42]		Irradiance [43] [a]	
	Top [28,40,41]	U-Value [45–49]	Solar beam direction [43] [a]	
	DR [28,41,42]	g-value [50–53]	Air velocity [41,42]	Air temperature [28,41,42]
	PD [28,41,42]	Thermal inertia [54]	Air flow rate [28,41,42]	MRT [28,41,42]
	RH [44]Degree Hours [44]	Air tightness [55–58]	Air flow temperature [28,41,42]	Irradiance on the occupant [43] [a]
	PPDweighted [44]	Vent location and dimension	Air flow rate moisture content [28,41,42]	Air velocity [28,41,42]
Visual comfort [59–61]	DT [59]	Light transmittance [51–53,62]		
	ET [59]	Light reflectance [51]		Horizontal illuminance at desk level [59,60,64]
	fDGP, exceed [59]	Openings size and location [59]		Contrast illuminance [60]
	DGP [59]	Shading factor [63]	Illuminance [60]	Vertical Illuminance at eye level [59]
	DGPe [59]	Blinds Openness coefficient [63]	Light beam direction	Luminance [59]
	View out [59]	Blinds Colour rendering index [63]	Light colour [60]	View [59]
Air quality comfort [28,65–67]	PD [28]			
	CO2 (ppm) [28,65]			
	TVOC (μg/m3) [28]			
	CH2O (μg/m3) [28,66]			
	C1A/C1B VOC (μg/m3) [28]			
	R value [28]			
	CO (mg/m3) [66]			
	C6H6 [66]			
	C10H8 (μg/m3) [66]			
	NO2 (μg/m3) [66]			
	PAHs [66]			
	C2HCl3 [66]	Air tightness [55–58]	Air flow rate [28]	Air pollutant content [28,66]
	C2Cl4 (μg/m3) [66]	Vent location and dimension [28]	Air flow pollutant content [28,66]	Air moisture content [28]
	Rn (Bq/m3) [66]	Material pollutant emission [68]	Air flow moisture content [28]	Air CO_2 content [28]
Acoustic comfort [28,69,70]	L_{eq} [dbA] [28]	Airborne Sound Insolation [58,71]		
		Sound absorption [72]	Noise level	Noise level [28,73]
		Sound reflectance [72]	Noise frequency characteristics	Noise frequency characteristics
Interaction		Type of actuation system	Not applicable	Not applicable
		Mode of actuation		
		Level of automation		
		Interactive scenario		
		Interface		
Vibration [74,75]		Mass [58]	Acceleration (tri-axis) [77,78]	Acceleration (tri-axis) [77,78]
		Stiffness of the façade [58,76]		

[a] Only calculation methods not reference to experimental measurements.

are associated with the specific comfort domain and the corresponding standard for measuring the parameter.

For static façades (façades with no actuation mechanisms) the façade characteristics are constant, however the magnitude of the respective environmental parameter varies over time due to transient outdoor and indoor conditions. For dynamic façades both the magnitude of the façade characteristic and the environmental parameters vary over time. The choice of the environmental parameters to be monitored depends on the façade technological characteristics, e.g. the presence of openable vents or the solar control technology. The BIT prototype described in this paper is intended for façades with non-openable vents. The parameters were selected accordingly and are shown in Table 2 together with the corresponding standards that specify the accuracy, range and method of the sensing solution. Table 2 also indicates whether BIT complies with the relevant sensing standard. Each individual sensor has been calibrated against the correspondent reference lab-graded sensor using a linear regression model to assess the instrument accuracy and uses the Standard Error of the Estimates as absolute measure of fit [22]. Further details on the design and calibration of each sensor device are described in turn in sections 2.2 to 2.5.

2.2. Thermal comfort parameters, metrics and related sensing devices

There are three main types of heat transfer between façades and the indoor environment [30]: longwave radiation, shortwave (solar) radiation and convection (due to thermal asymmetries or air flows from leakages and openable vents). A fraction of long-wave radiation is exchanged between indoor environment and the portion of visible sky, but this is less relevant for comfort measurements. The convection and long-wave radiation between the glass and the indoor environment can be assessed by measuring air and surface temperatures respectively close to and on the façade. Therefore, BIT Façade measures the surface temperature and air temperature at three different locations along a vertical line on the surface of the glazing panel (Fig. 2). These are measured by 1-wire digital thermistors DS18B20 [31] and thermocouples using a MAX31856 digital converter [32]. All the measurement locations are shielded against solar radiation with Aluminium foil covers. Shortwave radiation from façades typically has a significant impact on occupant comfort [33]; this is measured in BIT by means of a photodiode at the mid height of the glazing panel in the façade. The use of photodiodes to capture solar irradiance in the scientific community is not new [34], but it is not one of the conventional methods listed in Ref. [35]. Therefore, this measurement is reported as a non-compliant measurement in Table 2. Photodiodes are frequently omitted from conventional methods because unlike thermopile-based pyranometers they require careful

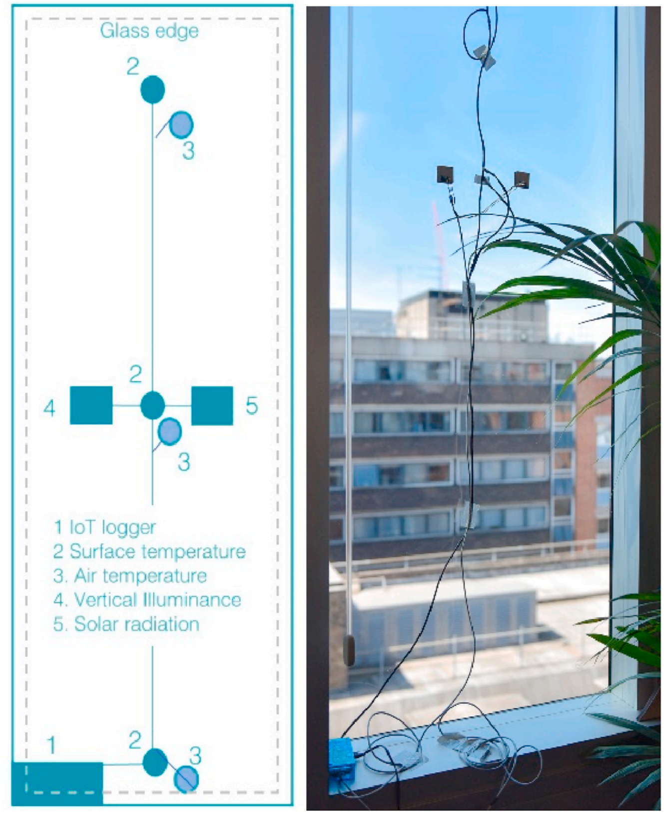

Fig. 2. Diagram of BIT Façade (left) and a photograph of BIT Façade as installed on a typical window pane (right).

corrections during post-processing in order to obtain reliable solar irradiance data measurements [36]. Another problem is that many photodiodes fail to capture the entire spectrum of the solar radiation [37]. BIT includes a correction algorithm that post-processes the signal from its SI1145 photodiode [38]. Comparisons with high-accuracy thermopile pyranometers were performed by the authors and showed a measurement error of 22.3%. At each desk location the following thermal parameters are monitored: global horizontal solar radiation on the desk; globe temperature; air temperature and humidity. Global radiation is measured in the same manner as that measured at the façade location, whereas humidity and air temperature are measured by means of a BME280 temperature and humidity sensor (RH ±3%, Temperature

Table 2
Environmental parameters and metrics monitored by BIT vs standards to abide by for instrumentation requirements.

Comfort domain	BIT Façade	BIT Station (Occupant position)		BIT Glare (Occupant position)	
	Parameter	Parameter	Metric	Parameter	Metric
Thermal comfort		Air temperature [41,79] ✓	T_{op} [28,41]	–	–
	Surface temperature [41,79] ✓	Globe temperature [41,79] ✓	T_{op}* [12,43]		
	Air temperature [41,79] ✓	Global Horizontal irradiance on desk [35] X			
	Global transmitted vertical irradiance [35] X	Humidity [41,79] ✓			
Visual comfort	Vertical illuminance transmitted [80] ✓	Horizontal illuminance on desk [80] ✓	UDI [81]		$f_{DGP, exceed}$ [59] DGP [59]
				Vertical illuminance at eye level [80] ✓	DGP_e [59] ✓
				Luminance from a fixed view ✓	View extension [59] ✓
Air quality comfort		CO_2 level [82,83] ✓	CO_2 (ppm) [28,65]		
Acoustic comfort		Noise level [28,73] X	L_{eq} [db] [28,73]		
Interaction				Blind position	Occlusion Index

✓ Compliant X Not compliant

±0.5%) [39] and globe temperature by means of PT100 sensor [40]. The sampling frequency requirements and instrument positioning in ASHRAE 55 [41] are more prescriptive than EN 7730 [42] and require a "representative" location and temporal sampling (for at least two occupied hours for temperatures, with air speed averaged over 3 min or less and other parameters over 5 min or less) [22]. The BIT Station (Fig. 3) is positioned beside the occupant in order to assess the thermal environment close to the occupant and temperatures and humidity are captured every 15 min averaging across 1 min, thereby complying with the requirements of ASHRAE 55 for long-term monitoring [41].

2.2.1. Measurement of Mean Radiant Temperature and operative temperature

The dimension of the globe affects the measurements of the Mean Radiant Temperature (MRT). A smaller globe is more significantly affected by air temperature and air velocity, resulting in less accurate measurements [79]. The globe temperature of BIT has a diameter of 70 mm and a black matte rough surface. The MRT is calculated as indicated by the ISO 7726 [79], taking into account the different diameter and the condition of forced mechanical ventilation. Details of the calibration of the BIT globe are shown in Appendix A. The error relative to the 150 mm globe sensor was estimated to be ±0.4 °C in the measurement of the MRT. Since the MRT takes into account only the long-wave radiation contribution, the use of the MRT adjusted with the short-wave contribution was also included as described by Arens et al. [33] and following previous studies [12]. From this, the Adjusted Operative Temperature (T_{op}*) may be calculated. Details are reported in Appendix A. BIT prototype is intended for façades without openable vents, therefore in order to achieve a cost-effective toolkit, air flow meters are not included. However in mechanically ventilated buildings, air flow can occur through infiltration in the façade and/or it can be induced along the façade due to thermal asymmetries between the façade surface temperature and the indoor air temperature [84]. In fact, several hot wires close to the occupant and the façade would be needed in order to obtain meaningful airflow results from thermal asymmetries and low-level infiltration. This set up was deemed too costly and too cumbersome for real-world offices and is therefore excluded from this BIT prototype.

2.3. Visual comfort parameters, metrics and related devices

BIT Façade monitors the transmitted vertical illuminance at the mid-span of the façade using the TI OPT3001 [85] light sensor, which measures the intensity of visible light. The OPT3001 was chosen due to its low-cost and ability to match the photopic response of the human eye and includes significant infrared rejection. The colour rendering index (CRI) could also be important in defining the visual performance of a glass façade, especially for a glass with coloured coatings electrochromic infills [86]. BIT does not monitor CRI but it should be possible to install low cost Light Colour temperature sensors in future prototypes of BIT. BIT station uses the same sensor as that in BIT Façade in order to monitor the horizontal illuminance at the desk level close to the occupant. Measurements of horizontal illuminance do not fully capture the visual quality of a space, but this is the most commonly used metric for assessing whether the illumination levels are sufficient for executing offices tasks [87]. Since BIT continuously monitors illuminance levels at each location, the device is able to compute the contribution of the artificial lighting system and the daylight over time and may therefore be used to calculate the Useful Daylight Illuminance (UDI) [81]. Lastly, BIT Façade uses a supervised classification algorithm to learn over time the illuminance range of typical clear, midcast or overcast conditions throughout the year, and it can be used to classify whether the sky is clear, overcast or midcast.

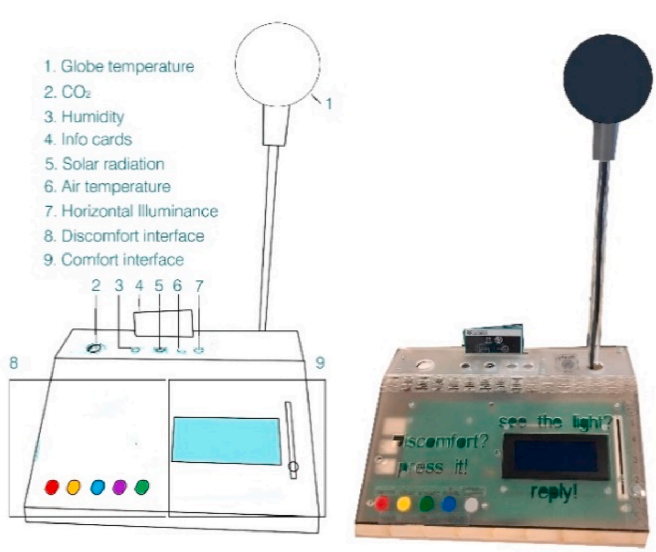

Fig. 3. Diagram showing the features of BIT Station (left) and a photograph of the device (right).

2.3.1. BIT glare

Another common concern in office environments is the excessive daylight from façades that leads to glare conditions [88]. Discomfort glare produced by façades varies in brightness, changes in size and position, and it is strongly dependent on the position and orientation of the occupant with respect to the façade. Long-term monitoring in real office spaces using conventional sensors and experimental setups is too disruptive to be practical because it requires continuous sampling of the observer's entire field of view in order to quantify the luminance, position, and size of the glare source(s) present [11]. Furthermore, positioning the DSLR camera and Luminance meter at the exact position of the occupant's eye is not feasible in real-world scenarios [89]. BIT Glare (Fig. 4) is an the IoT solution developed in this study to assess glare. The IoT technology is a camera system based on the Raspberry Pi single-board computer [90] with an OPT3001 calibrated vertical illuminance sensor and a fish eye lens. Recent research has shown that Raspberry Pi-based cameras can be used to monitor luminance distribution [91]. The calibration of the HDR image in this study is performed in a simplified manner by means of vertical illuminance measurements. Since this method can induce large errors in luminance measurements, two preliminary tests were performed to assess the accuracy of BIT Glare against conventional methods - one in a daylit environment and one in an artificially lit environment. The detailed results are shown in Appendix B. The errors incurred in DGP amount to 5.8% and 10% for daylight and artificially lit environments respectively. The focal length of the camera is not adjustable, and the field of view is reduced by 86% compared to a DSLR camera with a fish-eye lens. BIT Glare has an automated processing algorithm (reported in Appendix B) to create the HDR images with HDRgen [92], which is also used by BIT Glare to compute the camera response curve. The algorithm used by BIT includes the camera settings and the postprocessing steps required to correct the image for cropping and resizing, nullification of the exposure value, re-projection, vignetting correction and calibration. The recommendations recently published by Pierson et al. [93] were followed to correct and calibrate the HDR images for luminance measurements. The image is instantaneously post-processed and the DGP calculated with Evalglare [94]. BIT can therefore assess whether the DGP value of 0.45 (f_{dgp}) is exceeded for more than the 5% threshold of the occupied hours indicated in standards [59].

2.4. Air quality comfort measurements

The quality of the indoor air has a significant effect on occupant comfort, productivity and health [95,96]. Table 1 shows the list of air contaminants and their maximum indoor levels permitted by

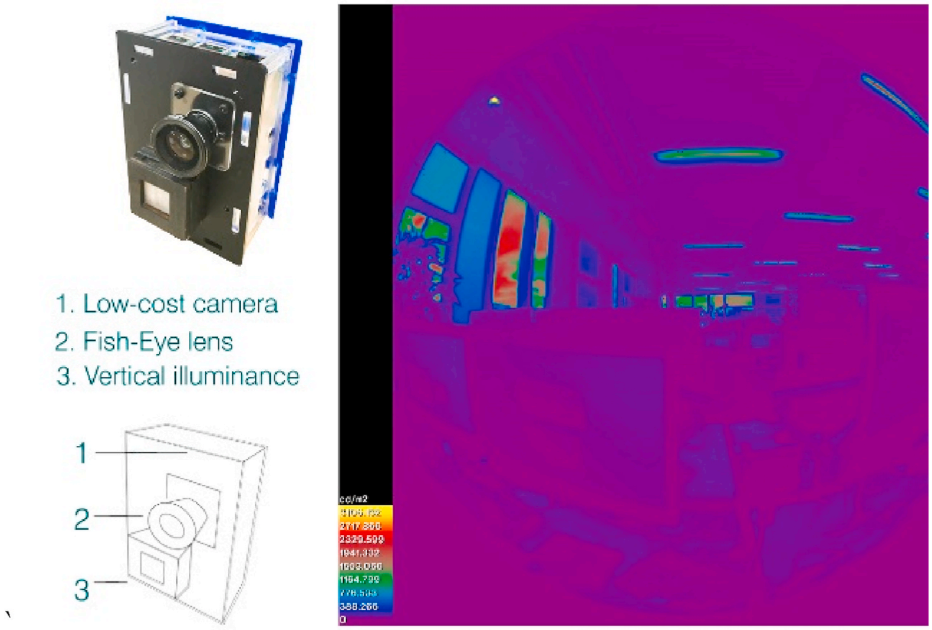

Fig. 4. Diagram showing the BIT Glare device (left) and an example output image (right).

international standards [28,66] for occupant comfort, productivity and health. In addition to RH and air temperature, CO_2, VOCs and formaldehydes (CH_2O) are common indicators used to assess air quality. However, several other contaminants may need to be monitored in specific cases [97]. This first prototype of BIT is limited to monitoring CO_2 levels, which is the most common proxy for poor air quality since it provides a direct measure of the air changes per hour and it is commonly used by international standards and certification bodies [98]. Previous IoT solutions for IEQ have shown that it is possible to monitor other contaminants in a cost effective manner [22] and it should be possible to extend the capabilities of future BIT prototypes by monitoring a wider range of contaminants, for example the VOCs emitted by façade materials, such as polymeric adhesives and sealants [99].

BIT includes a low-power self-calibrating CO_2 sensor COZIR LP [100] which monitors CO_2 levels with an accuracy of ± 30 ppm and communicates through UART interface. The CO_2 sampling occurs for 1 min every 15 min. BIT CO_2 sensor was calibrated using the outdoor level of CO_2 as the 400 ppm point.

2.5. Measurements for acoustic comfort and related devices

Acoustic quality is the result of a combination of different physical and subjective parameters rather than just one physical parameter [101]. For instance, in addition to objective noise levels, subjective factors such as sound privacy are important in defining the acoustic quality of open space offices [102]. 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. Façades 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 façade sound absorptance and reflectivity. The selection of physical environmental measurement capabilities of BIT was based on the consideration of which parameters would vary over time and space and therefore needed to be measured in multiple locations in a typical office environment. Since the façade typology considered has non-openable vents and its airborne sound insulation power and absorptance can be considered to constant in time, acoustic sensors were only placed at the occupant position. International standards [28,70] indicate maximum thresholds of noise levels on the basis of the A-weighted sound pressure level (SPL) given in decibels (dBA) [28,73]. Therefore, BIT monitors the A-weighted SPL by means of an analogue voltage sound level sensor with an electret microphone and a two-stage amplifier. This provides an accuracy of 2 dBA worse than a Type-2 sound level meter, and therefore not compliant with the standards in Table 2.

3. Development of occupant response interfaces

Direct occupant feedback on IEQ in real buildings is usually obtained from questionnaire (paper or web-based) performed either as a once-in-time post-occupancy study [103] or as part of a periodic assessment over longer periods of time. Two international standards suggest collecting occupant data using a long-term survey either for thermal satisfaction [41] or IEQ [29]. These long-term assessments are performed either every 6-months or once every heating/cooling season and are therefore unable to capture changes in occupant feedback resulting from high frequency changes in the indoor environment. This is a well-known limitation of questionnaires. In fact, previous studies have proposed novel interfaces or methods for gathering high-frequency occupant data. Several studies provide web-based daily surveys at multiple times a day over long monitoring periods such as [104] but this system is not feasible for permanent installations because prompting occupant response at short intervals can result in survey fatigue [105]. Other studies have deployed mobile-app applications where users can voluntarily express their feedback on the environment [23,106,107]. This is very effective since a large majority of occupants have mobile devices and their position across the floorplan at the instant of expressing their feedback can be tracked. However, the frequent use of mobile apps could become a source of distraction in the workplace. Similarly to mobile-app devices, smart watches have also been used for longitudinal studies [19]. Lastly, physical survey interfaces or polling stations for gathering occupant feedback in longitudinal studies has also been proposed in previous studies. Konis [108] developed a physical device to collect occupant feedback on thermal and visual environment in office spaces. The system can either be operated by the occupants whenever they are feeling uncomfortable or to automatically when occupant feedback is desired by the BMS. Similarly, Pedersen and Petersen [18] developed a 7-point scale physical polling station for gathering feedback on air quality, thermal and lighting levels. Lassen et al. [109] recently assessed the potential of publicly located satisfaction polling stations in offices for real-time evaluation of occupant's satisfaction with the indoor climate and found that they can provide valuable continuous recordings of the occupant's satisfaction with the indoor climate, even if the fact that no responses are registered does not imply that occupants were not uncomfortable and, therefore, it could bias the results. Alavi et al. [17] also proposed an interactive polling station device to overcome the limitations of traditional questionnaires.

Polling station systems have also have been used by Berquist et al., to conduct longitudinal survey on thermal comfort in a sport facility [110]. Occupant feedback need not be a direct and explicit response from the respondents, but it could be indirectly inferred from either: occupant physiological state [111–113], facial expressions [114] or interaction with environmental controls, such as blinds or openable windows [6], thermostats, switches [115] etc. These indirect methods have the advantage of being less disruptive to the occupants, but they often raise ethical/privacy concerns.

BIT combines methods for direct collection of occupant feedback with the tracking of occupant interaction with the façade as a proxy of occupant response. For the purpose of this study, occupant response to the façade is defined as: i) frequency of environmental discomfort at different distances from the façade; 2) the level of satisfaction with the indoor environment at different distances from the façade, 3) interaction event with the façade. In addition, perceived levels of self-reported productivity and ease of concentration are also captured, but they do not represent the main focus of the study. The following cofounding variables are also considered: gender, age, perceived level of fitness, perceived satisfaction with workload, perceived satisfaction with the level of rest. In addition, season, time of the day and time spent sitting at the desk is also recorded. The toolkit is designed for real office environments were the pool of participants is fixed in time and hence only repeated measurements rather than independent measures are possible. Occupant feedback is anonymised by using randomly assigned identification codes. Occupant interaction with the façade blinds is monitored without tracking the identification code.

BIT is designed for office spaces, therefore metabolic activity rate of the occupant can be considered to be 1.2 MET [41,42] while clothing levels could be predicted from the outdoor mean temperature and the indoor operative temperature [116].

3.1. Interfaces for direct occupant feedback and data visualisation

Fig. 5 shows the interfaces for gathering direct occupant feedback. The first interface is a one-off web-based questionnaire of 15 questions to collect demographic information and data on their general level of satisfaction with the IEQ and the office environment. On completion of this initial survey, occupants receive their identification code.

The second interface is a physical polling station "BIT Station" (Fig. 5c), which has two interfaces: one on the left consist of colour coded buttons for collecting information on discomfort events and labelled with the prompt "Discomfort? Press it!"; and one on the right, a slider for gathering feedback on the level of satisfaction with the IEQ. Every time volunteers are in discomfort in the thermal, visual, air quality, acoustic or personal control domain, they can express their dissatisfaction by pressing the corresponding colour-coded button: Pressing of multiple buttons is permitted to signal multi-domain discomfort events, but pressing the same button multiple times in quick succession is filtered to minimise bias. Feedback on occupant level of environmental satisfaction is gathered every 2 h by means of a light on BIT station that flashes to remind the occupant to express feedback by using the slider and to answer questions on the LCD screen. Occupants are asked to express their level of agreement on a set of questions using a 5-point scale. BIT station also allows the occupant to provide unsolicited feedback. A set of infographic cards, attached to the station, provide instructions on how to use BIT Station (c in Fig. 5).

The third interface is a mobile-app, accessible by QR Codes and RFID Tags. This is also a source of occupant feedback (Fig. 5d). Each code and RFID tag is unique to each desk. Occupants can then visualise the environmental data by using the fourth interface: a web-based visualisation app (Fig. 5e). The dashboards in this app are easily customisable since they are based on the open source Grafana software [117].

The current version of the BIT Station interface was developed over 18 months by trials with volunteers and in collaboration with the Department of Psychology and the User Interface team at Arup. During

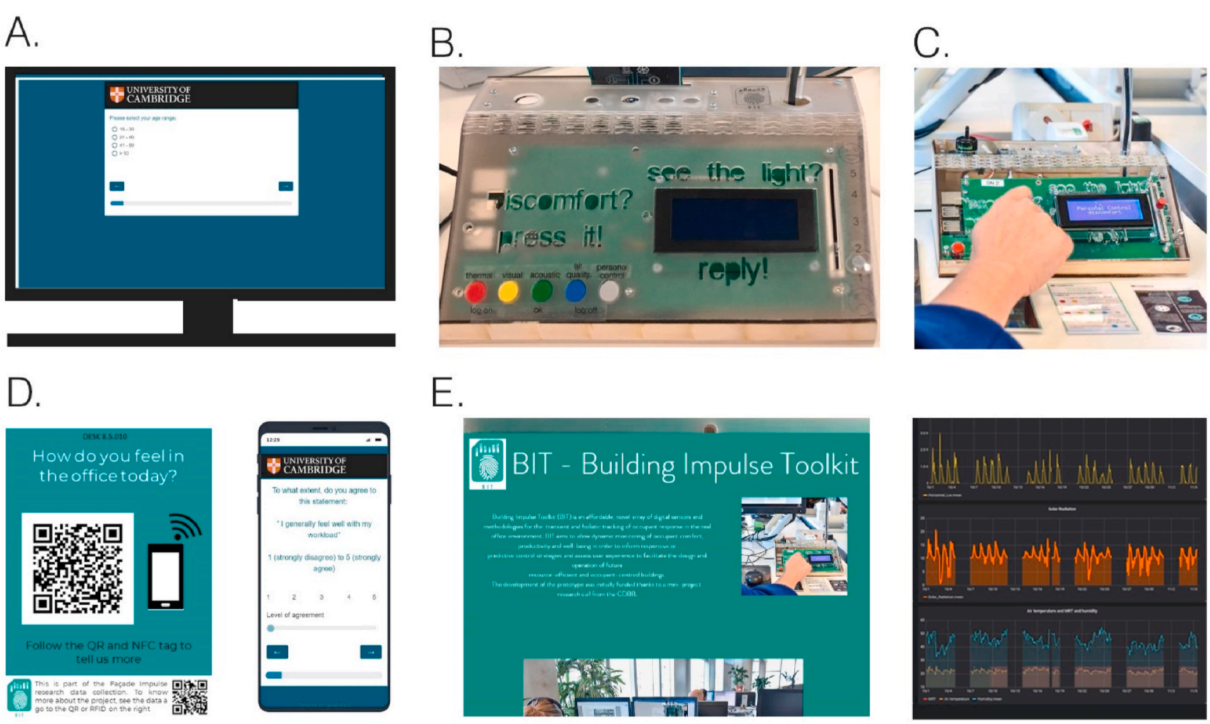

Fig. 5. BIT interfaces for direct occupant feedback: a) web-based survey (every 6 months), b) and c). BIT Station, d) Mobile app, e) Web-based visualisation interface.

these trials, several solution were tested as reported in a previous work [26]. The polling station format of BIT Station was selected over an alternative electronic survey with pop-up notifications because a pilot study with 16 volunteers at the University of Cambridge showed that the polling station was rated better for level of intrusiveness and the ease of use [26].

3.2. Interfaces for monitoring occupant interaction with the façade

Occupant interaction with the façade is captured every 15 min by BIT Glare, which uses a supervised learning algorithm to classify luminance images and recognise when blinds have been lowered or raised. After analysis, the images are deleted and only the status of the blind is recorded. The values are then stored in the cloud storage system. Similarly to previous work by Konis [11] the occlusion index is computed to evaluate in real time the overall occlusion of the façade. The occlusion index (OI) is defined as the percentage of the glazing in the façade that is obscured by shading devices. OI is computed for each façade bay and the overall façade by the cloud server, weighting the OI of each bay according to its surface projection.

4. IoT system architecture and ethical considerations

The overall architecture of BIT is shown in Fig. 6. In summary BIT Station captures: noise level, air temperature, humidity, CO_2 levels, horizontal illuminance, global horizontal solar radiation, globe temperature. While BIT Glare captures the vertical illuminance from single eye-level viewpoint and luminance.

Data is collected and post-processed by each BIT component and sent via a Wi-Fi connection using MQTT or SSH either to the timeseries database InfluxDB [118] either in the cloud or into a dedicated internal server depending on which server is available in the office space. Whenever, occupants press a discomfort button, BIT station records a measurement of the relevant environmental variable or sends a command for measurements to be taken to BIT Glare (if the visual discomfort button is pressed) via Message Queuing Telemetry Transport (MQTT).

One of the benefits of IoT technologies using open-source software is the possibility of integrating new data collection methods with existing monitoring platforms, such as those from the BMS. As shown in Fig. 6, BIT integrates multiple data collection methods: 1) data collection by direct in-situ measurements, 2) data monitored by the BMS and 3) external weather-station data that is available online.

4.1. Ethical considerations

All methods that collect data on occupant perception and behaviour in buildings must carefully assess the ethical implications, protect the benefits of the occupants in buildings and comply with the existing regulations on personal data protection, such as the EU GDPR [119]. This is especially true with IoT toolkits given that [120]: (i) they have the potential to be embedded in ordinary furniture and therefore remain unnoticed by occupants; (ii) they continuously monitor data in buildings and have the potential to integrate data from multiple locations and sources; (iii) communication of data happens without explicit prompting of the occupant. BIT was designed to be compliant with the ethical considerations that have arisen from a preliminary application and in particular:

1. Consent to participation. Firstly, the toolkit is installed after all the occupants in the relevant space have provided explicit and informed consent to participate in the environmental monitoring programme and, where relevant, to the occupant satisfaction data collection. In addition, the web-app interface for direct occupant feedback always asks for participant consent before proceeding, and participants need to explicitly log into the polling station before providing any data/feedback. Consent/log-in on every spate day the app/polling station is accessed.
2. Information on data collection and handling. Before expressing consent, occupants provided with detailed information on the data collection, handling, and usage process by receiving a written account on the data collection process. In addition, explanatory cards with a summary of this information are permanently located on the polling stations together with the information on how to use them, while infographics and signs are installed in the office environment to ensure that all occupants are aware of the toolkit.
3. Clearly identification of the toolkit. No attempt has been made to conceal BIT into office furniture or equipment. Indeed BIT has been designed to be clearly visible and identifiable. Labels indicate on each sensor identify the type of data collected.

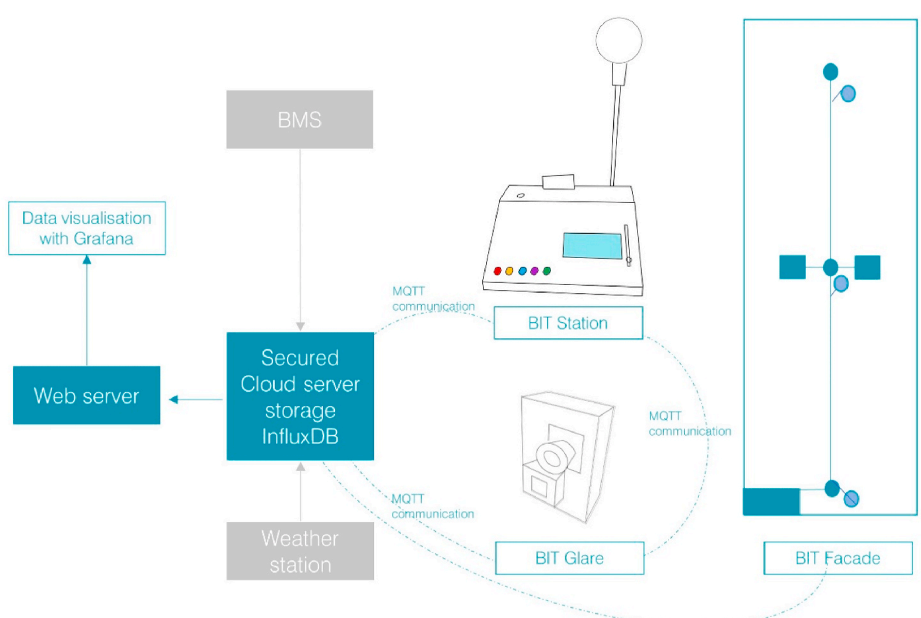

Fig. 6. Overall system architecture of BIT.

4. Occupants can power off BIT toolkit on their desk at any time and decide to withdraw from the monitoring.
5. Privacy protection. In both interfaces for occupant response, BIT Station and the web-app, the data is always anonymised with the use of random identification codes and no information is retained that could be used to retrospectively identify of the volunteer. The only sensitive information that is collected by the initial survey is gender and age, this latter is large categorical age groups. BIT Glare, which is also used to monitor occupant interaction, does not track the identity of the user and the luminance maps do not provide any information on the surrounding environment except for the levels of luminance on the window or the artificial lighting. Furthermore, images are not stored but DGP values per time-step are computed in real-time by the local device and the luminance map image is automatically deleted.
6. Data access. Data is always accessible to the occupants involved in the monitoring through visualisation dashboards, but not available to other occupants. Any data regarding occupant response is only visualised in aggregated manner to prevent identification of users by indirect means.
7. Data protection. The Data transfer and storage is protected in secured databases.
8. Data usage. In the test case presented in this paper, the data is only available to the researcher, who has obtained ethical approval to evaluate the interaction, comfort and discomfort of occupants in the space.

For future applications in real buildings, where data access and the purpose of the data collection could vary from the usage presented in this paper, for instance to inform occupant-centric controls, ethical implications will have to be carefully addressed and considered on a case-by-case basis. For instance, data access needs to be restricted only to certain users such as occupants involved in the monitoring and should not be made available to third parties which could use this data against a building occupant such as employers. This can be achieved by developing secure access environments that restrict access, prevent data download and only allow data to be analysed in safe online environments [121] and in the consented manner. Lastly, additional sophisticated methods for de-identifying occupants might be required and therefore privacy risk analyses and the application of ad-hoc privacy protection methods should be considered [121].

5. Deployment and validation in a real world office

5.1. Description of the test case

The BIT toolkit was deployed in an occupied mechanically ventilated office in central London. The curtain wall façade of the office has high-performance double-glazing units with internal manual venetian blinds and a window to wall ratio of 66%. This test case was chosen because it provides an example of office space with a glass façade without openable vents, but where occupants can interact with the façade for shading purposes. The characteristics of the façade are shown in Table 3. The office floor is 21×18 m^2. Fig. 7a shows the floor plan and the BIT toolkit setup. The office is composed of two spaces that are separated by a wide aisle. One space has a North-East facing façade and the other has a South-West facing façade. BIT Station and BIT Glare devices were placed at 1.5 m, 3.5 m and 6 m from the façades, respectively. Fig. 7b shows the installation of the toolkit on one desk and in one façade bay. BIT Façade devices were mounted along the façade bays in both orientations. In order to capture the effect of different seasons, monitoring was performed over period of nine months, from June 2019 to beginning of March 2020.

Table 3
Characteristics of the façade of the case study.

Façade characteristics	6 mm Solar Control Coating 50/25–15 mm cavity – 44.2
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)

5.2. Participants

18 out of 45 occupants volunteered for the experiment. The 18 participants (9 female and 9 male) were recruited by email invitation. Fifty percent of the participants were aged between 18 and 30, 33% were between 31 and 49 years and 17% were 50 years or older. Given the sample size and in order to minimise potential bias, the polling stations were placed on the desks were only hot-desking was allowed and therefore participants were not assigned to fixed desk positions, but they were asked to randomly choose different desks every day.

5.3. Procedure

The study was approved by the Ethical Committee of the Department of Engineering at the University of Cambridge. The following procedural steps were undertaken:

1. Volunteers provide consent to participation, fill the preliminary online survey and receive the identification code.
2. A handover session is organised to answer questions and explain the functioning of the toolkit. Infographics are also distributed on the functioning of the toolkit and the data handling process.
3. During the initial two weeks, volunteers get used to the toolkit and the data collected is discarded to avoid potential bias due to lack of habituation.
4. The actual monitoring phase starts. Participants are asked to log-on to the polling station with their identification code upon arrival and to log-off when leaving. Participants are asked to randomly choose their desk for the day. From December 2019 onwards, the QR Codes and RFID tags, linked to web-based mobile-app, are also installed.

5.4. O#1: Capturing the transient effect of façades on the IEQ at different distances from the façade

Fig. 8a shows the average values of vertical transmitted illuminance on both façades monitored by BIT Façade. The holiday season (20 December to 6 January) is not reported. Likewise, Fig. 8b shows the average surface temperature of the internal surface of the façade for both orientations. These carpet plots show a large variability of visual and thermal environmental parameters at the façade level. A similar level of data granularity was also captured at the occupant position. Fig. 9 shows the average hourly value of key environmental parameters on the façade and at the occupant position (1.5, 3.5 and 6 m from the façade). From comparison between changes in façade environmental parameters and occupant-location IEQ is possible to see the effect of the facade. While locations further from the façade (3.5 and 6 m) tend to have similar magnitudes and trends, positions closer to the façade (1.5 m) are on average more influenced by the façade in both the visual and thermal domain. In summer, for the occupant closer to the façade, the adjusted Operative Temperature (T_{op}*) (columns A and B, Row 3 in Fig. 9), and therefore the effect of solar radiation, is on average higher than at locations further from the façade, especially in peak hours where this is visible both at the façade and the occupant level. In Winter, due to the deeper sun penetration, the position closer to the façade is not always the most affected by the solar radiation (columns C and D, Row 3 in Fig. 9). Similar results are seen for the vertical illuminance (Row 5 in Fig. 9).

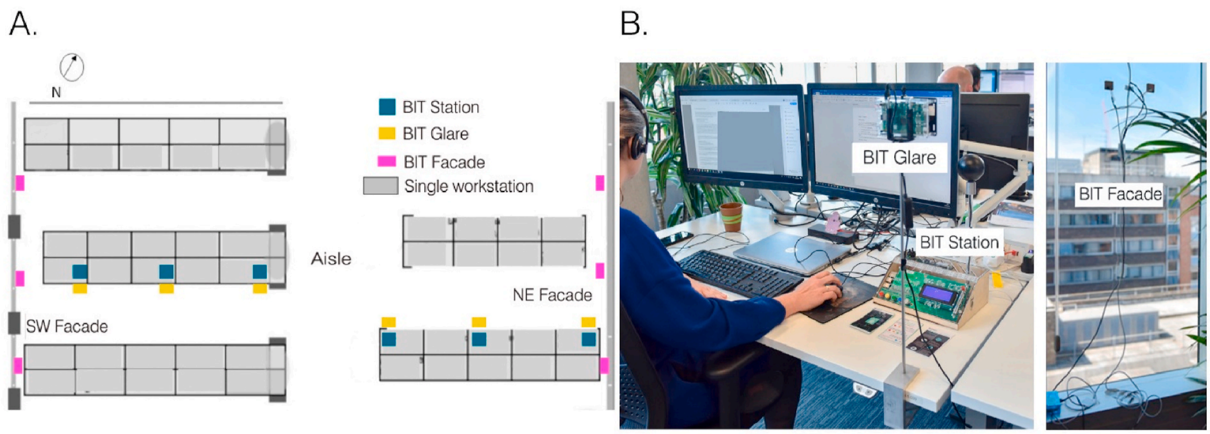

Fig. 7. a) Plan view of the case study with location of the BIT devices; b) Example of the installation of the toolkit on one of the desks and in one façade bay, after [26].

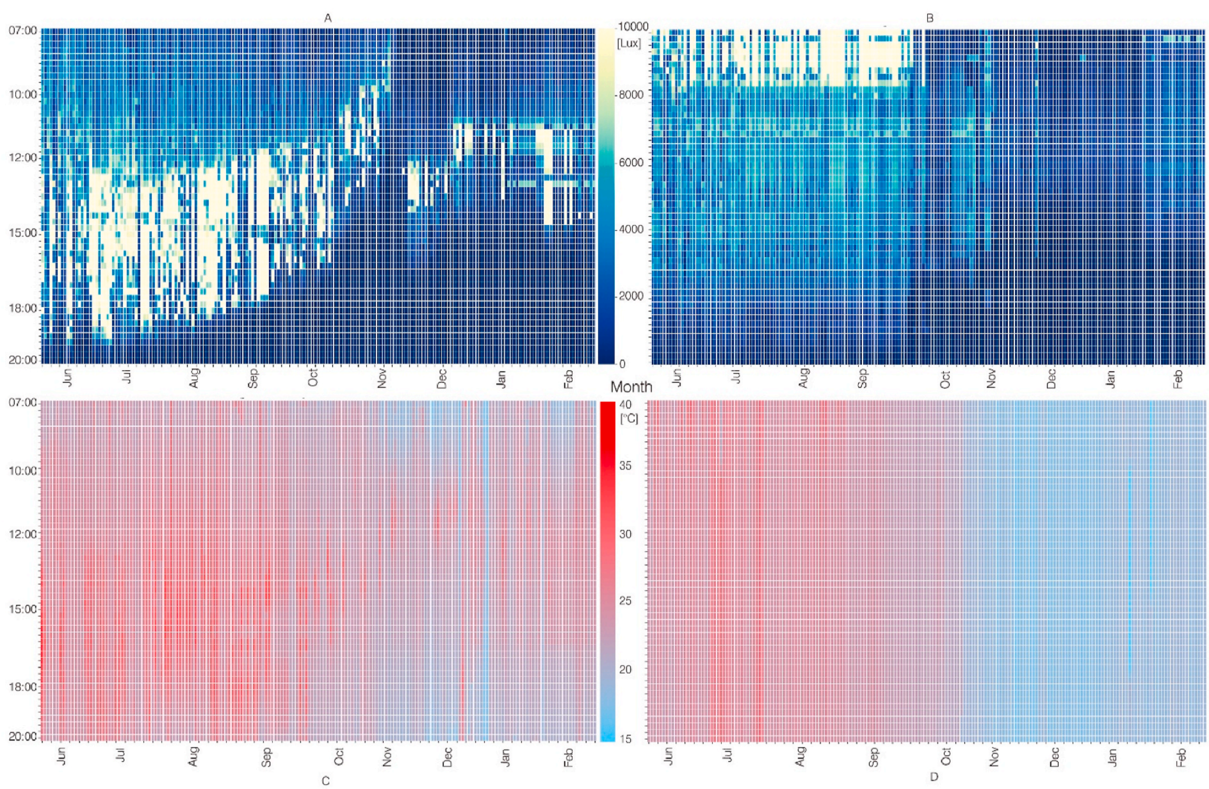

Fig. 8. Carpet plots showing measurements at façade: (A) Average Vertical Illuminance transmitted at the South-West façade and (B) North-East façade; (C) Average Surface Temperature on South-West façade and (D) North-East façade.

5.5. O#2.1 Capturing occupant environmental discomfort in time and at different locations from the façades and identifying façade-related causes of discomfort

Volunteers interacted with the BIT Station for a limited number of times, since only 6 desks were equipped with the toolkit. As a consequence, only 6 out of 18 volunteers could interact with the BIT Station at the same time. In addition, the desks were not available every day for the experiment. In several occasions, volunteers could not participate either because they were not in the office for a sufficient period of time (for instance after an hour of work in the office, they left for work meetings) or the desks were occupied by people who had only consented to the environmental and blind usage monitoring but were not involved in the discomfort data collection.

The number of days when volunteers were using the toolkit was recorded by means of volunteer log-ins. In total, considering both façade orientations, 278 responses were collected, with 148 responses collected at south-west and 130 at north-east. The toolkit was able therefore to collect in average one daily discomfort event, as shown in Fig. 10a. Very rarely, the toolkit was able to monitor a larger number of discomfort events per day, therefore further assessment on the comparison of actual number of discomfort events and calculated discomfort metrics should be performed to understand that this was due to the absence of discomfort or user disengagement with the toolkit. When higher frequency of discomfort events was captured by the toolkit, this was linked to specific comfort domains (visual, air quality and personal control).

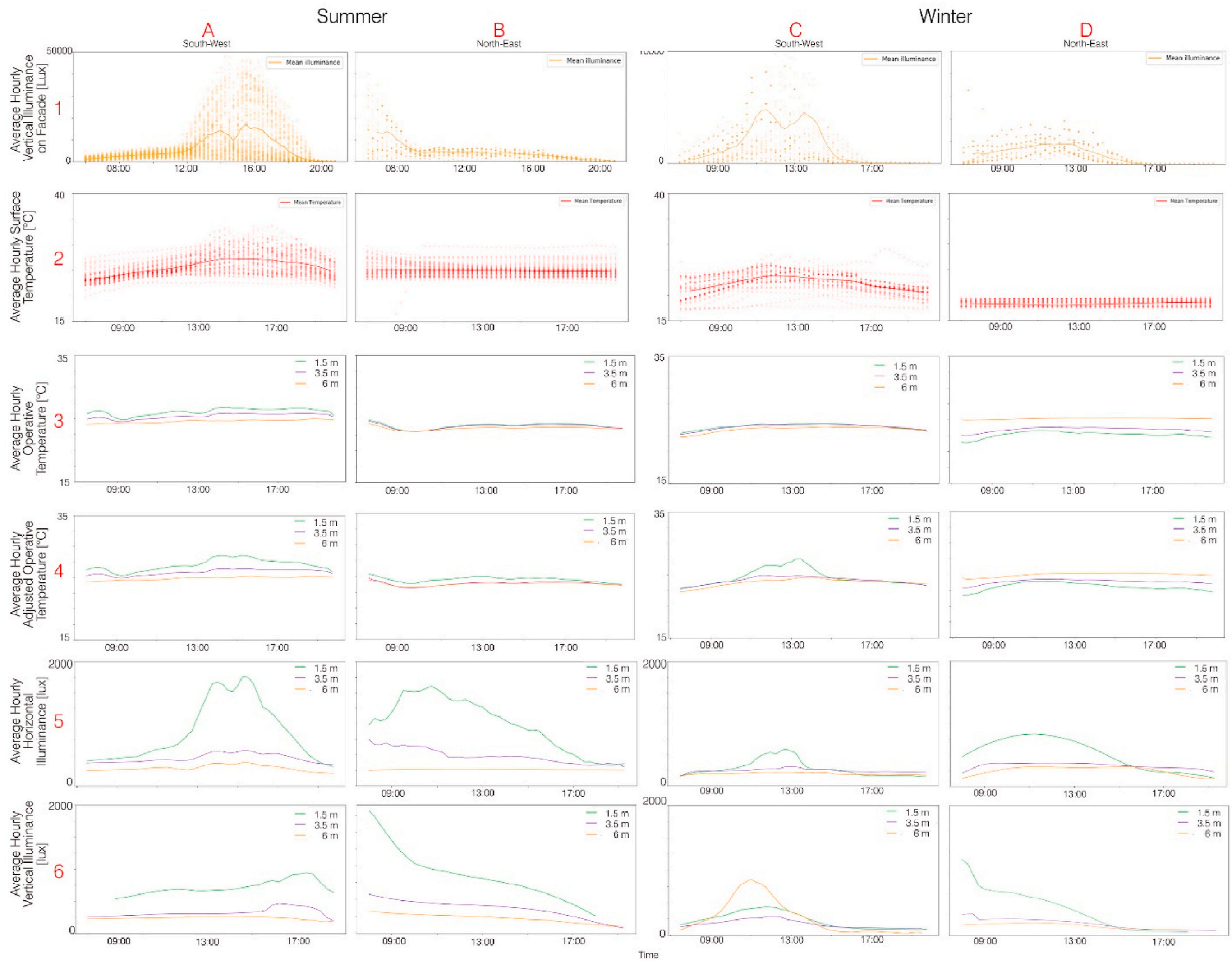

Fig. 9. Hourly average environmental parameters on façade and occupant position at 1.5, 3.5 and 6 m from the façade.

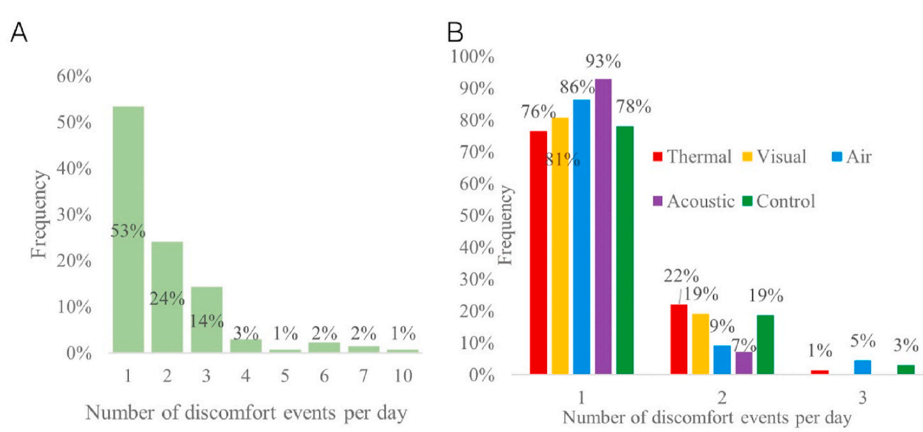

Fig. 10. a) Distribution of discomfort events per day; b) Distribution of discomfort events per day and domain.

Fig. 10b shows the distribution of discomfort events per comfort domain. Acoustic discomfort was perceived primarily only once a day, while other comfort domains were recorded with greater frequency, in particular air quality discomfort, followed by thermal, visual and personal control dissatisfaction. Days with non-discomfort events are not reported since they could be biased by a lower occupant engagement with the data collection system.

For 17% of the instances in which discomfort was expressed, it was perceived simultaneously in more than one domain. Fig. 11 shows the frequency distribution of multi-domain discomfort events. Among the multi-domain discomfort combinations, thermal and visual are the most frequent, followed by air quality and personal control, ahead of thermal

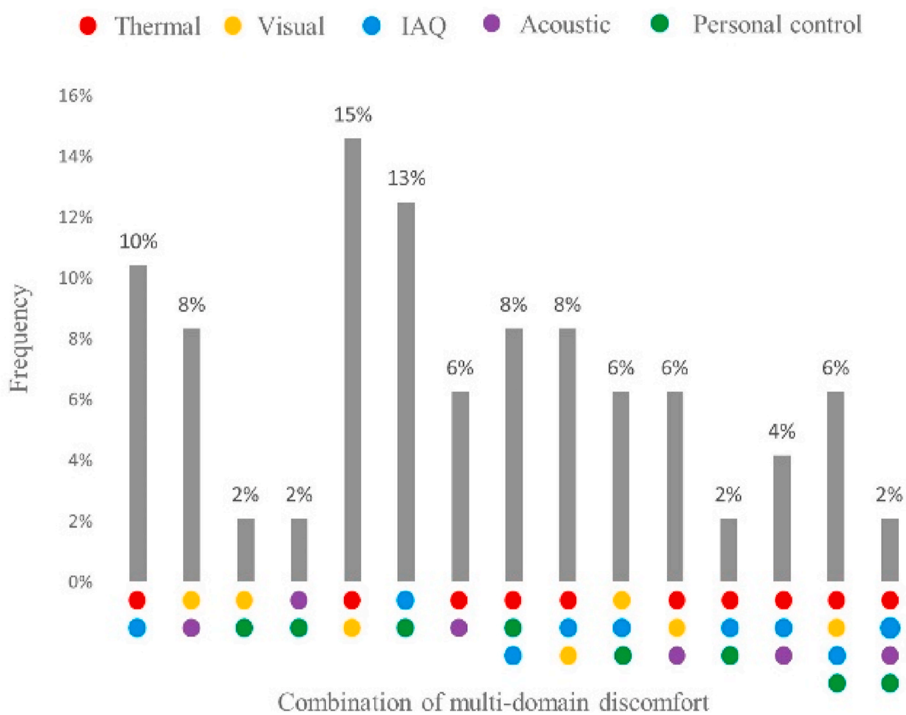

Fig. 11. Distribution of multi-domain discomfort events over the monitoring time.

and air quality. Thermal comfort was also the most commonly associated with other discomfort events, followed by personal control, air quality and visual. 63% percent of the overall multi-domain interactions occurred at the 1.5 m distance from the façade. This agrees with previous research that highlighted the significant role of the façade as a cause of multi-domain comfort [6]. Personal control dissatisfaction close to the façade was always associated with other discomfort events, in particularly with air quality discomfort and thermal discomfort. This may indicate that controls at the façade are inadequate (e.g. absence of openable vents, inadequate blind controls etc.).

Fig. 12 shows the frequency of discomfort events over the whole monitoring period and per season. Thermal discomfort was the most common form of discomfort for both orientations, followed by acoustic, visual, air quality and personal control dissatisfaction.

Frequency of discomfort is distributed differently depending on the distance from the façade, the season and the orientation (Fig. 12b). When the volunteers were located at the south-west orientation and in summer, they often expressed thermal and visual discomfort in proximity with the façade. This can be explained by the short penetration depth of the solar radiation in summer. Conversely in winter, volunteers locationed further from the façade, such as those at 6 m distance perceived more frequent thermal and visual discomfort as the sun penetration depth is higher. Acoustic discomfort increased with the distance from the façade and this can be explained by the fact that a larger distance from the façade corresponds to a larger exposure to background noise from the entire floorplate.

The frequency of discomfort distribution is strongly influenced by the orientation. Occupants were more dissatisfied with the perceived levels of personal control in south-west orientations than in north-east orientations and this can be explained by the less prominent role of the façade, since the solar radiation and illuminance were lower. As expected, the south-west façade had a larger effect on the IEQ. This was reflected by the larger frequency of discomfort expressed by occupant located closer to this façade.

5.6. *O#2.2: Capturing transient levels of occupant satisfaction with the environment and their relation to the façade*

209 responses were collected across 9 months of monitoring from 18 different volunteers. Each volunteer responded to the satisfaction at least once per façade-location distance, both in winter and in summer.

After the summer period, the mean satisfaction levels and S.E.M.

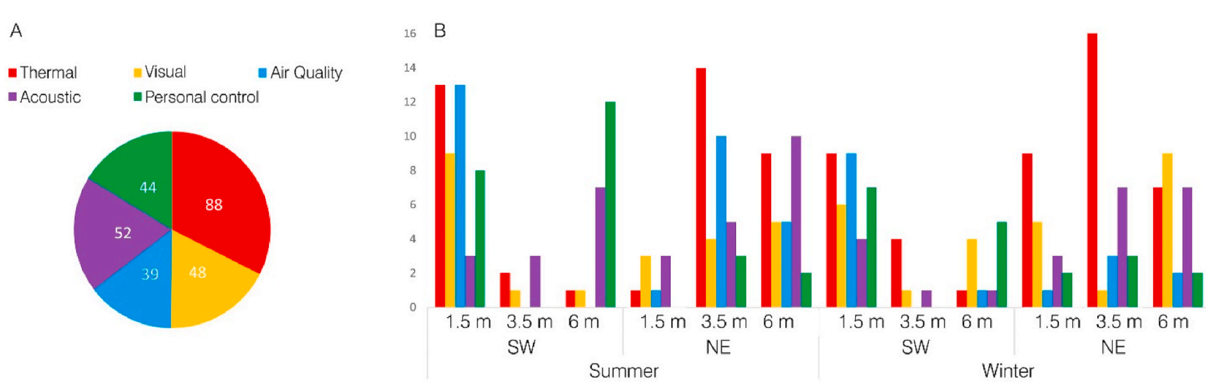

Fig. 12. a) Frequency of discomfort events over the whole period of monitoring, b) frequency of discomfort by season and distance from the façade.

from the survey were compared to the mean results from the polling station, collected over the summer period. Results are shown in Fig. 13. Except for the acoustic domain, the mean values reported only small differences and therefore show consistency between each data-collection method.

The responses were distributed equally across seasons and orientations, so the effects of season and orientation can be considered balanced. Since the toolkit was used to collect repeated measures per each volunteer and distance-location, linear mixed model was used to analyse the data. From visual inspection of residual plots, no deviations from homoscedasticity or normality were identified in accordance with the linear mixed model assumptions. The R package "lmer" was used to perform the analysis [122]. The independent variables were also tested for multi-collinearity with the Variance Inflation Factors (VIF) and the "R" package "Caret" [123]. All the independent variables did not show collinearity since the VIF was less than 2 and therefore below the threshold of 10.

In the model, the distance from the façade was included as fixed effect on the levels of environmental satisfaction, perceived levels of productivity, ease of concentration and appreciation of the office space. In addition, the fixed and interaction effect of perceived levels of happiness, rest, workload and fitness were also included. All these independent variables were included in the interaction term, while the ID of the volunteers was included as random factor. The main effect of the level of single-domain environmental satisfaction was also included to assess their combined effect on the perceived ease of concentration, level of productivity and appreciation of the work environment. Cross-modal effects between different domains of environmental satisfaction were also investigated, including the level of environmental satisfactions with other domains as fixed and interaction term in the model. When not significant, the interaction terms were excluded from the model. When significant, the R package emmeans [124] was used to perform post-hoc comparisons, applying the multiplicity adjustment Tukey's HSD to control for false discovery rate.

As shown in Fig. 14, when volunteers where sitting close to the façade, their level of satisfaction was significantly higher for daylight levels, thermal environment. However, closer to the façade they were significantly less satisfied with glare and IAQ. Occupants appreciation for their office space was significant higher closer to the façade.

On average volunteers close to the façade expressed levels of perceived productivity similar to those further away from the façade, but they did express a higher non-significant level of concentration. The perceived level of productivity was found to be significantly dependent on happiness ($p < 0.001$), workload ($p < 0.001$) and level of rest ($p < 0.01$). A significant interaction between happiness, workload and level of fitness on perceived productivity was also found, but larger datasets would be needed for further clarification of the interaction effect. Acoustic satisfaction was significantly dependent on satisfaction with

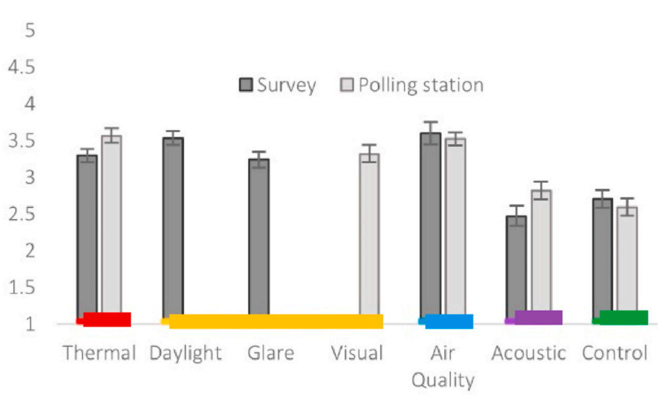

Fig. 13. Mean level of agreement and S.E.M. from the initial survey and the polling station responses during the summer period (N = 18).

the workload ($p < 0.001$). Glare was significantly dependent on perceived level of fitness ($p < 0.05$) and distance from the façade ($p < 0.001$). Thermal was significantly dependent on happiness ($p < 0.05$).

Satisfaction with daylight ($p < 0.05$), IAQ and personal control ($p < 0.05$) were found significant on the thermal satisfaction. Thermal satisfaction was also significantly correlated with daylight satisfaction ($p < 0.1$), as shown by previous research [125]. Personal control was significantly correlated with visual satisfaction ($p < 0.001$), while satisfaction with IAQ ($p < 0.01$) and personal control ($p < 0.1$) affected satisfaction with glare.

5.7. O#2.3. Capturing occupant response in a non-disruptive manner

User engagement with BIT was monitored by a count of the number of times per day occupants provided feedback on their environmental satisfaction. The number of times occupants pressed the discomfort buttons was excluded since it could be biased by the non-presence of discomfort events, when occupants would not press any buttons regardless of their active engagement. Fig. 15 shows the cumulative user engagement over time (users were not all participating on the same day and some of the days none was participating to the experiment). The preliminary and interim meetings between the authors and the volunteers helped to boost user engagement. For instance, Fig. 15, shows that the general meetings with volunteers were followed by a surge in the number of interactions per day. The installation of RFID tags and QR codes also helped to increase user engagement. A survey was distributed at the end of the monitoring period to evaluate if the volunteers deemed the toolkit to be disruptive. Results are shown in Fig. 16. Overall, the toolkit was received positively because on average: 1) Volunteers agreed that using the polling station did not distract them from their work (Average level of agreement = 3.76) and found the mobile app more distracting (Average level of agreement = 2.61); 2) Volunteers preferred the analogue interface or the combination of both analogue and digital interfaces and none preferred the mobile apps alone; 3) Volunteers agreed that BIT sensors devices were not obtrusive (average level of agreement = 3.53); 4) Volunteers liked giving feedback on their environment but were less convinced that giving feedback was useful, which indicates that providing more information or insights on their environment in response to their feedback would have helped to increase user engagement, as shown in previous research [126].

5.8. O#3. Tracking high frequency occupant interaction with the façade

The use of blinds was monitored by BIT Glare and the built-in analytics described in Section 3.3. Three states of blind position were defined: 0% when façade was unobstructed, 50% when blinds were at their half-way position and 100% when blinds were fully deployed and the view of the glazing completely obstructed. Fig. 17 shows the average occlusion index for the south-west and north-east façade during the working hours (from 8am to 8pm) and days (weekends and holidays excluded). Occupant interaction with the façade is captured at 15 min intervals. As shown in Table 4, on average between the 9% and the 39% of the whole façade surface was shaded by blinds at any given time, depending on the season and the orientation. Overall, the 9-months of monitoring, occupants interacted with the façade for less than the 15% of the time, especially at the south-west facade in summer, when blinds were left down for 39% of the time. This confirms previous work showing that occupants forget to operate the façade during their working day, missing opportunities to increase daylight levels. The tracking of occupant interaction at 15 min intervals, revealed that the occupant interaction with blinds varies according to the time of the day, as shown in Table 5 for the South-West orientation.

6. Conclusion

This paper describes BIT, a novel IoT solution for capturing the effect

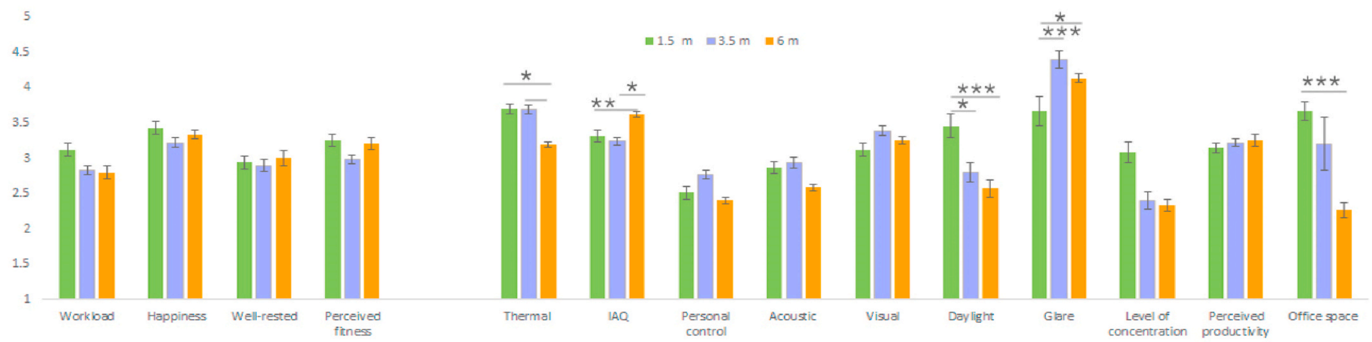

Fig. 14. Occupant agreement with the level of environmental satisfaction and other psychological factors (N = 18). Level of significance are indicated as: * = $p < 0.05$, ** = $p < 0.01$ and *** = $p < 0.001$.

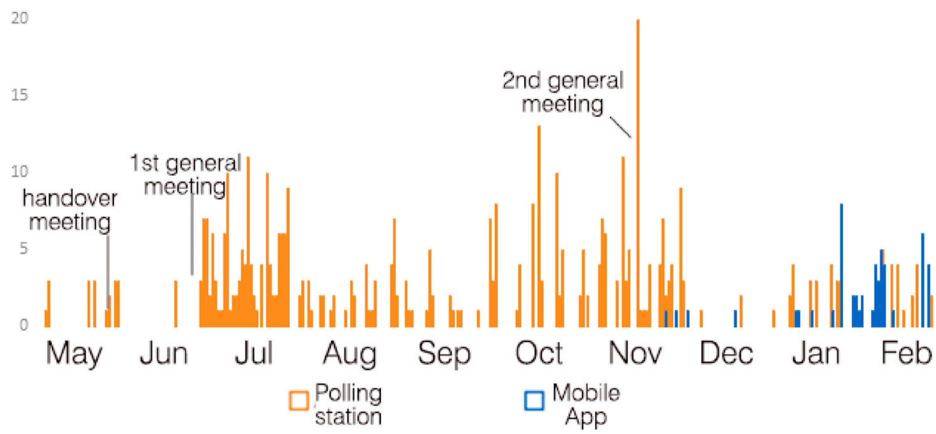

Fig. 15. Number of volunteer interactions per day.

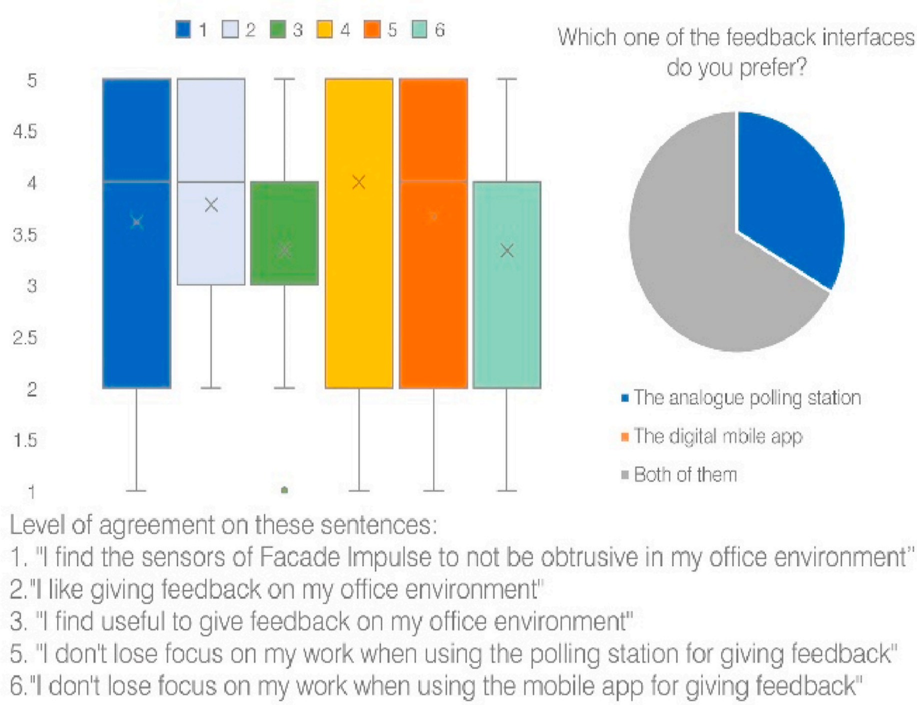

Fig. 16. Level of agreement on user acceptance of the toolkit (N = 18).

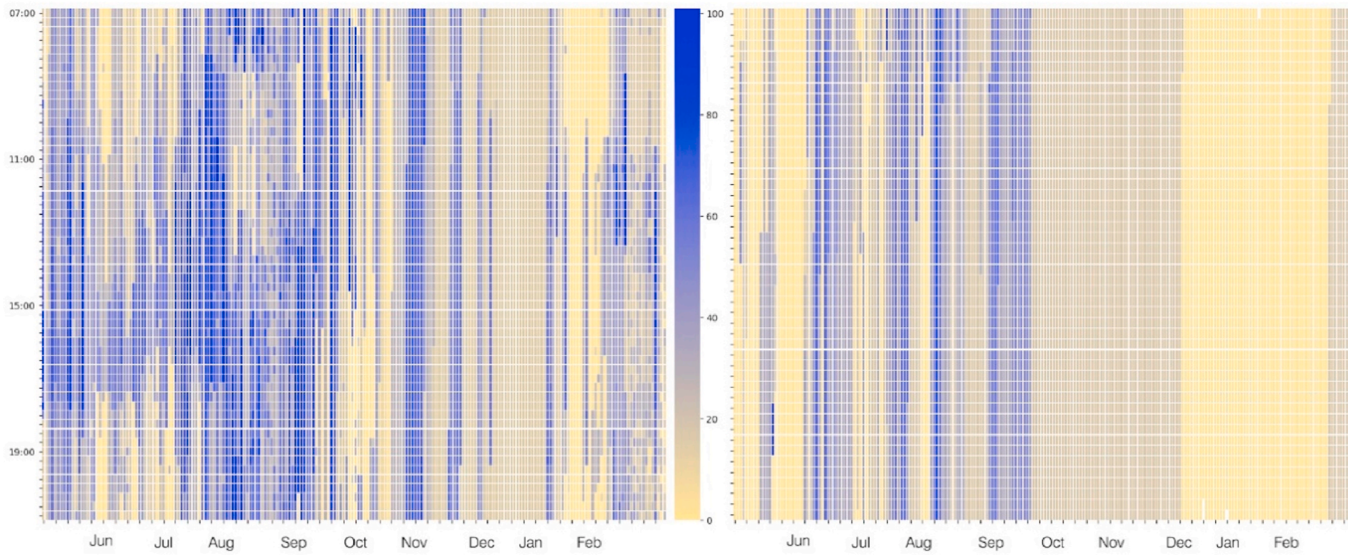

Fig. 17. Occlusion index of the south-west façade (left) and north-east façade (right).

Table 4
Frequency analysis of user interaction with façade.

Orientation	Season	Days	Average surface of façade shaded	Time OI ≤ 50	Time OI > 50	Time blinds were operated	Time blinds were left unchanged
SW	Summer	84	39.5%	67%	33%	13%	87%
SW	Winter	81	23.76%	81%	19%	6%	94%
NE	Summer	84	30.22%	87%	23%	2%	98%
NE	Winter	81	9.2%	100%	0%	0.1%	99.9%

Table 5
Frequency with which occupants interact with blinds in relation to time of the day.

Orientation	Time of the day	Time blinds were lowered	Time blinds were raised	Time blinds are left unchanged
SW	8–12	4.7%	3.5%	91.8%
SW	12–16	3%	5%	92%
SW	16–20	5.4%	3.5%	91.1%

of façades on IEQ and occupants. BIT and the associated data collection proved to be successful in capturing the transient and holistic effect of façades on IEQ (O#1), and it provided new insights on the variation of the effect of façades over time. The monitoring of discomfort events through the use of "discomfort buttons" (O#2.1) also proved to be successful for recording discomfort events on a daily frequency. However, user engagement and participation could have been higher, which would in turn have generated higher granularity of occupant response. Previous studies showed higher level of user participation [108], but over a shorter monitoring period. Furthermore, discomfort buttons offer only a binary choice (discomfort or not) and therefore need to be complemented with other interfaces such as questionnaires. The toolkit was also successful in capturing the occupants' transient levels of satisfaction (O#2.2). The results from the BIT Station were consistent with those obtained by the questionnaire for the summer. The toolkit was on average perceived as not disruptive and volunteers felt engaged with the data collection (O#2.3). Overall, volunteers preferred the polling station over than the mobile app, however the combination of both provided the best user engagement. Future work should test additional strategies for occupant engagement with the interface, such as weekly newsletter with insights from the IEQ monitoring and personalised reminders. Finally, the methodology and frequency for monitoring occupant interaction proved to be sufficient for gaining insights on occupant interaction with the façade (O#2.4). A larger sample size is required to make statistically significant conclusions on the effect of façades on occupant environmental satisfaction and discomfort. In this respect the deployment of BIT in more buildings could provide this data in a systematic and repeatable manner. The proposed methodology and case study provided in this paper is however deemed sufficient to validate the use of BIT for capturing the holistic and transient effect of façades and demonstrates that, despite the lower level of accuracy of the sensors, IoT solutions are an effective means of capturing continuous data for the operation of user-centred buildings.

Declaration of competing interest

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

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Appendix A. Calibration of the Globe temperature and measurement of the Adjusted Operative Temperature

The globe temperature of BIT has a diameter of 70 mm and a black matte rough surface. The MRT is calculated as indicated by the ISO 7726 [79], taking into account the different diameter and the condition of forced mechanical ventilation. Since the toolkit has been designed for mechanical ventilated spaces (façades without openable vents) and no air flow meter has been included, the air velocity to be considered for the calculation of the MRT will have to be decided in a case-by-case scenario. For the calibration, an air velocity of maximum 0.25 m/s was considered as the calibration room was a controlled space with a known air velocity pattern.Fig. A1 shows the comparison between the MRT and the Globe temperature of the off shelve 150 mm Globe sensor and BIT Globe. The error was estimated to be ±0.4 °C in the measurement of the MRT. Since the MRT takes into account only the long-wave radiation contribution, the use of the MRT adjusted with the short-wave contribution was also included, as defined by Arens et al. [33] and following previous studies [12].

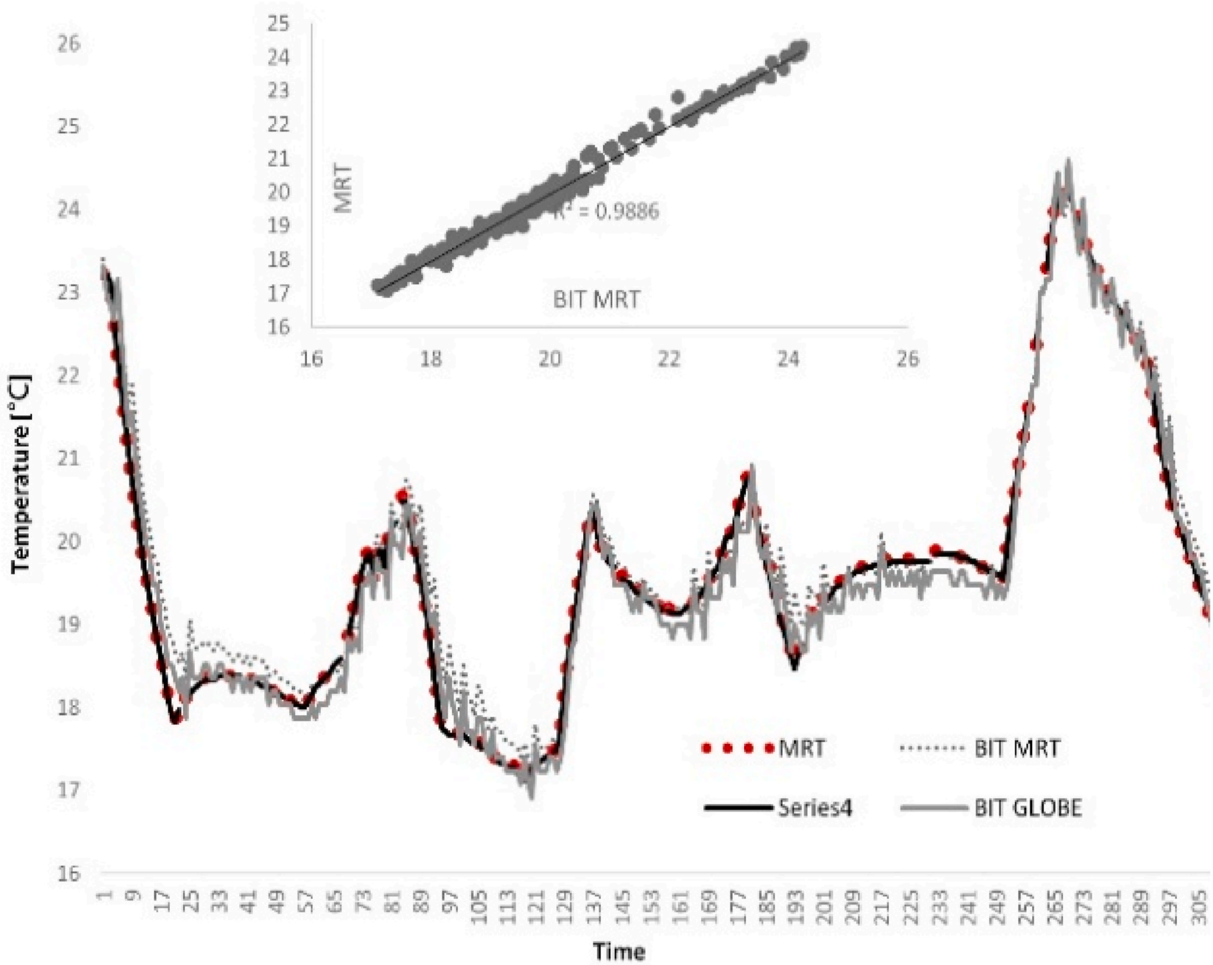

Fig. A1. Calibration and measure of the MRT with off-shelf sensor and BIT.

As described in equations (1)–(3), the effect of direct solar radiation E_{solar} on the occupant skin is computed as an equivalent increase of Effective Radiant Field (ERF) (Eq 1) and, subsequently, of MRT (Eq 2) and this is then added to the long-wave MRT (Eq 3) (Appendix C, ASHRAE 55–2017):

$$ERF = \frac{\alpha_{sw}}{\alpha_{lw}} E_{solar} \tag{1}$$

$$\Delta MRT = \frac{ERF}{(f_{eff}\ h_r)} \tag{2}$$

$$MRT^* = \Delta MRT + MRT \tag{3}$$

where f_{eff} is the fraction of the body surface exposed to radiation, α_{Lw} is the skin long-wave absorptivity and α_{sw} is the skin short-wave absorptivity. BIT cannot compute the solar radiation on the occupant skin but uses the horizontal solar radiation measured by the polling station on the desk to estimate the solar radiation on the occupant.

The Operative temperature T_{op} is calculated as follows Eq 4 [127]:

$$T_{op} = \frac{h_r\ MRT + \ h_c\ T_a}{h_r + h_c} \tag{4}$$

In addition, the “Adjusted” Operative temperature T_{op}^{*} is calculated from Refs. [12,33] in Eq 5:

$$T_{op}^{*} = \frac{h_r\, MRT^{*} + h_c\, T_a}{h_r + h_c} \tag{5}$$

Appendix B. BIT-Glare post-processing algorithm and comparison with conventional methods

The procedure suggested by Pierson et al. [93] was followed to calibrate and measure the characteristics of the Raspberry Pi camera, such as actual field of view and the camera response curve. The algorithm is shown in Fig. B1. Once the vignetting correction algorithm and the response curve of the camera are known, the Low Dynamic Range Images (LDRI) are captured. This is done with the raspistill command and selecting a sensitivity of ISO 100. At this time, the vertical illuminance is also measured and stored. A customised Python script then checks the pixel values of the image and deletes any under or over exposed images. The High Dynamic Range Image is then created using HDRGen [92] and applying the previously calculated response curve. The picture is then cropped and resized according the actual field of view and, subsequently, corrected for vignetting as suggested by Pierson et al. [93]. The header of the HDR file is then corrected to make sure contains information on view and exposure. Lastly, the image is calibrated using the measured and calculated vertical illuminance (using the Radiance Evalglare -V command [128]). The correction factor is stored to allow verification at a later stage and, in case the correction factor is too large, to discard the image. Once the image is calibrated, the DGP is calculated with Radiance Evalglare and the image stored in falsecolour to show the luminance ranges.

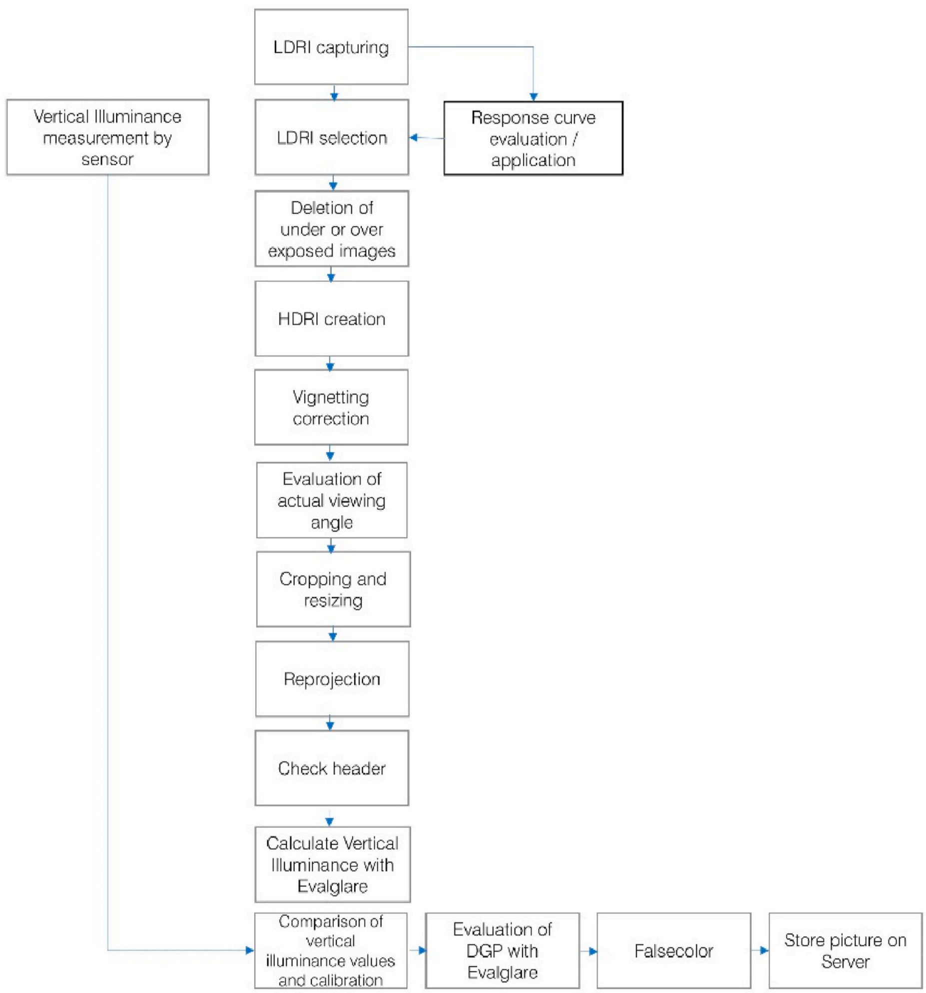

Fig. B1. BIT Glare algorithm to capture and evaluate the Vertical Illuminance and the DGP.

Calibrating the HDRI with the Vertical Illuminance measurement is known to be a less accurate method. Therefore, a test in daylit and artificially lit environments was performed to understand the accuracy of this system against conventional methods (DSLR system with luminance-spot calibration and vertical illuminance calibration). Several targets were positioned in the scene in order to compare the different methods. In the daylight scene, BIT Glare was only compared with the established method, which uses a DSLR Camera, the luminance-spot measurement for the calibration and the vertical illuminance sensor to just double check the functioning. Both tests were performed in an environment with 0.3 > DGP >0.20. Fig. B2 shows the results for an artificially lit environment and Fig. B3 shows the results for a daylit one. BIT Glare underestimates high luminance values in the scene and seems less accurate in capturing a wide range of luminance. When calculating the DGP, the error was estimated to be 10% in artificially lit environments and 4% in daylit environments. However, this could be due to the fact in both situation the glare was mainly induced by high levels of vertical illuminances on the eye rather than for stronger contrast in the scene. Consequently, more assessments in differently lit environments will be needed to verify the capabilities of BIT Glare.

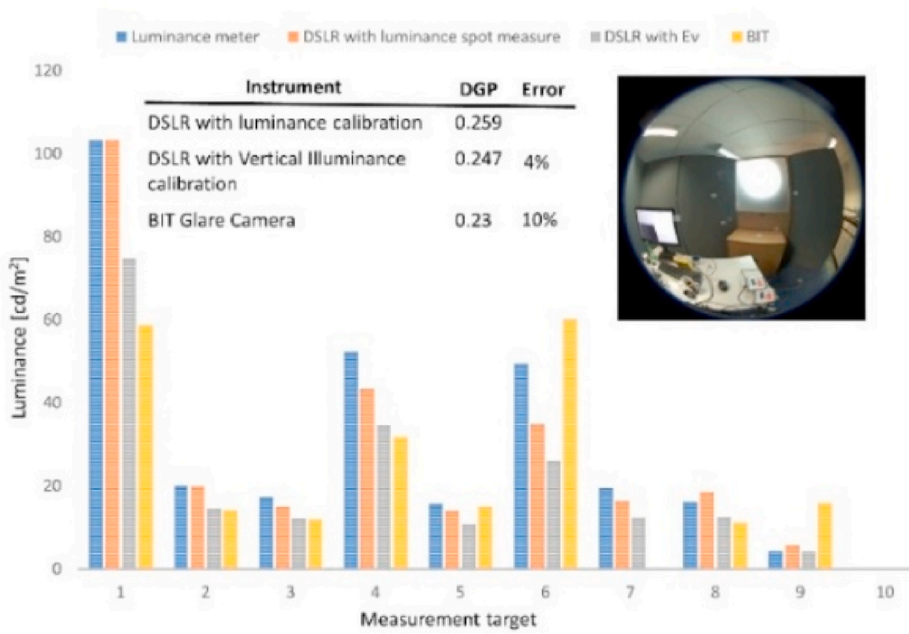

Fig. B2. Comparison between BIT Glare and conventional methods (DSLR with luminance calibration and DSLR with vertical illuminance calibration).

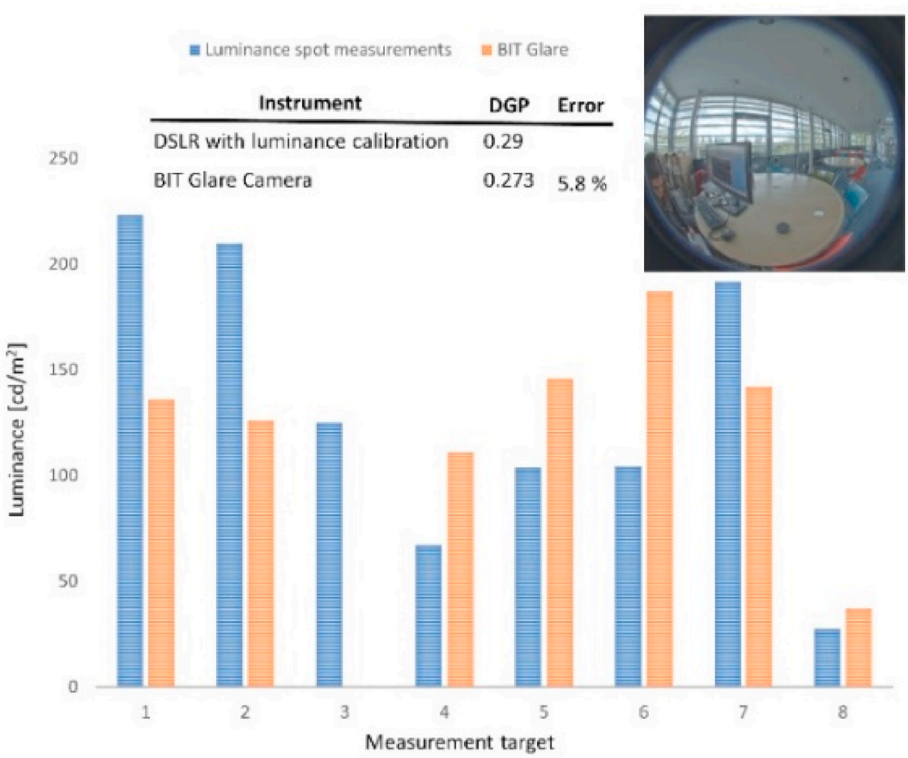

Fig. B3. Comparison between BIT Glare and conventional methods (DSLR with luminance calibration) in a daylit environment.

References

[1] UN, UNCC Race to zero [Online]. Available: https://unfccc.int/climate-action/race-to-zero-campaign. (Accessed 21 July 2020).
[2] UN, World Urbanization Prospects: the 2018 Revision, 2019.
[3] IEA, World Energy statistics and balances [Online]. Available: www.iea.org/statistics, 2019. (Accessed 20 July 2020).
[4] J. Kim, S. Schiavon, G. Brager, Personal comfort models – a new paradigm in thermal comfort for occupant-centric environmental control, Build. Environ. 132 (2018) 114–124.
[5] 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.
[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] J.K. Day, et al., A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort, Build. Environ. 178 (2020) 106920.
[8] M. Schweiker, et al., "Review of multi-domain approaches to indoor environmental perception and behaviour, Build. Environ. 176 (2020) 106804.
[9] H. Zhang, C. Huizenga, E. Arenas, D. Wang, Thermal sensation and comfort in transient non-uniform thermal environments, Eur. J. Appl. Physiol. 92 (6) (2004) 728–733.
[10] 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.
[11] K. Konis, Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in San Francisco, California, Build. Environ. 59 (2013) 662–677.
[12] 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: Proceedings of Building Simulation 2019: 16th Conference of IBPSA, 2020.
[13] K. Konis, S. Selkowitz, Effective daylighting with high-performance facades, in: Effective Daylighting with High-Performance Facades, Springer International Publishing, 2017, pp. 251–269.
[14] T. Parkinson, A. Parkinson, R. De Dear, Continuous IEQ Monitoring System : Context and Development, vol. 149, 2019, pp. 15–25.
[15] K. Weekly, et al., Building-in-briefcase: a rapidly-deployable environmental sensor suite for the smart building, Sensors 18 (2018) 1381.
[16] M. Kimmling, S. Hoffmann, Comfort monitoring - comprehensive and cost-effective with the sensor station CoMoS [Behaglichkeitsmonitoring – flächendeckend und kostengünstig mit der Sensorstation CoMoS], Bauphysik 41 (2019) 111–119.
[17] H.S. Alavi, H. Verma, M. Papinutto, D. Lalanne, Comfort: A coordinate of user experience in interactive built environments, in: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 2017.
[18] S. Petersen, S.M.L. Pedersen, Desktop polling station for real-time building occupant feedback, in: CLIMA 2016 - Proc. 12th REHVA World Congr, vol. 7, 2016, pp. 36–38. August.
[19] P. Jayathissa, M. Quintana, T. Sood, N. Nazarian, C. Miller, Is your clock-face cozie? A smartwatch methodology for the in-situ collection of occupant comfort data, J. Phys. Conf. Ser. 143 (2019).
[20] F. Salamone, et al., "Integrated method for personal thermal comfort assessment and optimization through users' feedback, IoT and machine learning: a case study, Sensors 18 (2018) 1602.
[21] E. Laftchiev, D. Nikovski, An IoT system to estimate personal thermal comfort, in: 2016 IEEE 3rd World Forum on Internet of Things, WF-IoT 2016, 2017.
[22] T. Parkinson, A. Parkinson, R. de Dear, Continuous IEQ monitoring system: performance specifications and thermal comfort classification, Build. Environ. 149 (2019) 241–252.
[23] K. Konis, M. Annavaram, The Occupant Mobile Gateway: a participatory sensing and machine-learning approach for occupant-aware energy management, Build. Environ. 118 (2017) 1–13.
[24] F. Jazizadeh, A. Ghahramani, B. Becerik-Gerber, T. Kichkaylo, M. Orosz, Human-building interaction framework for personalized thermal comfort-driven systems in office buildings, J. Comput. Civ. Eng. 28 (2014) 2–16.
[25] M. Arnesano, B. Bueno, A. Pracucci, S. Magnagni, O. Casadei, G.M. Revel, Sensors and control solutions for Smart-IoT façade modules, in: 2019 IEEE International Symposium on Measurements and Networking, M and N 2019 - Proceedings, 2019.
[26] 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).
[27] E. Upton, H. Gareth, Raspberry Pi User Guide, 2014.
[28] CEN, Energy Performance of Buildings - Ventilation for Buildings EN 16798:2019, 2019.
[29] E. Arens, et al., Performance Measurement Protocols for Commercial Buildings, 2009.
[30] J. Carmody, S. Selkowitz, E. Lee, D. Arasteh, T. Willmert, Window Systems for High Performance Buildings, Norton, First. New York, 2004.
[31] DallaDS18B20 Temperature Sensors Semiconductor, DS18B20 Temperature Sensor, Dallas Semicond. datasheets, 2002.
[32] M. Integrated, MAX31856 [Online]. Available: https://www.maximintegrated.com/en/products/sensors/MAX31856.html. (Accessed 20 July 2020).
[33] 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.
[34] D.L. King, D.R. Myers, Silicon-photodiode pyranometers: Operational characteristics, historical experiences, and new calibration procedures, in: Conference Record of the IEEE Photovoltaic Specialists Conference, 1997.
[35] ISO, Solar Energy — Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation ISO 9060:2018, 2018.
[36] D.R. Myers, K.A. Emery, T.L. Stoffel, Uncertainty estimates for global solar irradiance measurements used to evaluate PV device performance, Sol. Cell. 27 (1989) 455–464.
[37] M. Sengupta, P. Gotseff, T. Stoffel, Evaluation of photodiode and thermopile pyranometers for photovoltaic applications, in: 27th Eur. Photovolt. Sol. Energy Conf. Exhib, 2012.
[38] S. Lab, SI1145 [Online]. Available: https://www.silabs.com/documents/public/data-sheets/Si1145-46-47.pdf. (Accessed 20 July 2020).
[39] BOSCH, BME280 [Online]. Available: https://www.bosch-sensortec.com/products/environmental-sensors/humidity-sensors-bme280/. (Accessed 20 July 2020).
[40] L. Facility, Globe temperature pt100 [Online]. Available: https://www.labfacility.com/radiation-pendulum-temperature-sensor.html. (Accessed 20 July 2020).
[41] ANSI/ASHRAE, ANSI/ASHRAE 55:2017 Thermal Environmental Conditions for Human Occupancy, Ashrae, 2017.
[42] 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.
[43] ASHRAE, ANSI/ASHRAE Addendum D to ANSI/ASHRAE Standard 55-2013, Ashrae Stand., 2015.
[44] ISO, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics ISO 15251, 2007.
[45] CEN, Thermal Performance of Curtain Walling. Calculation of Thermal Transmittance EN ISO 12631:2017, 2017.
[46] CEN, Glass in Building. Determination of Thermal Transmittance (U Value). Calculation Method EN 673: 2011, 2011.
[47] CEN, Glass in Building - Determination of Thermal Transmittance (U Value) - Guarded Hot Plate Method EN 674:2011, 2011.
[48] CEN, EN 675:2011 Glass in Building. Determination of Thermal Transmittance (U Value). Heat Flow Meter Method, 2011.
[49] CEN, Glass in Building. Determination of Thermal Transmittance (U Value). Heat Flow Meter Method BS EN ISO 10077:2017, 2017.
[50] A./NFRC, ANSI/NFRC 200-2017: Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence, 2017.
[51] CEN, Glass in Building. Determination of Luminous and Solar Characteristics of Glazing EN 410: 2011, 2011.
[52] ISO, Glass in Building — Determination of Light Transmittance, Solar Direct Transmittance, Total Solar Energy Transmittance, Ultraviolet Transmittance and Related Glazing Factors ISO 9050:2003, 2003.
[53] CEN, Solar Protection Devices Combined with Glazing. Calculation of Total Solar Energy Transmittance and Light Transmittance EN 13363:2005, 2005.
[54] EN, Thermal Performance of Building Components - Dynamic Thermal Characteristics - Calculation Methods EN 13786:2017, 2017.
[55] CEN, Thermal Performance of Buildings. Determination of Air Permeability of Buildings. Fan Pressurization Method EN 13829:2001, 2001.
[56] ASTM, ASTM E3158 -18 Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building, 2018.
[57] ASTM, ASTM E1827 - 11(2017) Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door, 2017.
[58] CEN, Curtain Walling -Product Standard EN 13830:2015, 2015.
[59] CEN, Daylight in Buildings EN 17037:2019, 2019.
[60] CEN, Light and Lighting. Lighting of Work Places. Indoor Work Places EN 12464-1:2011, 2011.
[61] ANSI, RP-1-12 Americal National Standard Practice for Office Lighting, 2012.
[62] A. Dix, Human-computer interaction, Encycl. Database Syst. (2016) 1327–1331.
[63] CEN, Solar Protection Devices Combined with Glazing. Calculation of Total Solar Energy Transmittance and Light Transmittance EN 14501:2005, 2005.
[64] IES, ANSI, Office Lighting ANSI/IES RP-1-12, 2013.
[65] ANSI, Ventilation for Acceptable Indoor Air Quality ANSI/ASHRAE Standard 62.1-2010, Ashrae, 2007.
[66] WHO/Europe, WHO Guidelines for Indoor Air Quality: Selected Pollutants, 2010.
[67] World Health Organization, Air Quality Guidelines. Global Update 2005, 2006.
[68] CEN, Assessment of Release of Dangerous Substances - Determination of Emissions into Indoor Air EN 16516:2017, 2017.
[69] ISO, Acoustics — Description, Measurement and Assessment of Environmental Noise ISO 1996:2016, 2016.
[70] ANSI S12.2:2008, Criteria for Evaluating Room Noise, 2008.
[71] ISO, Acoustics - Rating of Sound Insulation in Buildings and of Building Elements – Part 1: Airborne Sound Insulation 717-1, 2013.
[72] CEN, Building Acoustics. Estimation of Acoustic Performance of Buildings from the Performance of Elements EN 12354:2017, 2017.
[73] American National Standards Institute Inc, ANSI S1.43-1997. Specifications for Integrating-Averaging Sound Level Meters, 2007.
[74] ISO, Mechanical Vibration and Shock. Evaluation of Human Exposure to Whole-Body Vibration. Vibration in Buildings ISO 2631:2003, 2013.
[75] ISO, Bases for Design of Structures. Serviceability of Buildings and Walkways against Vibrations ISO 10137:2007, 2007.
[76] E. Parliament, Regulation (EU) No. 305/2011 of the European Parliament and of the Council of 9 March 2011 Laying Down Harmonised Conditions for the Marketing of Construction Products and Repealing Council Directive 89/106/EEC, vol. 88, 2011, pp. 5–43.
[77] ISO, Mechanical Vibration and Shock - Ibration and Shock in Buildings with Sensitive Equipment ISO/TS 10811-2000, 2000.
[78] BS, Guide to Evaluation of Human Exposure to Vibration in Buildings BS 6472: 2008, 2008.
[79] ISO, Ergonomics of the Thermal Environment — Instruments for Measuring Physical Quantities ISO 7726, 1998.
[80] ISO and CIE, Characterization of the Performance of Illuminance Meters ISO/CIE 19476:2014, 2014.
[81] A. Nabil, J. Mardaljevic, Useful daylight illuminances: a replacement for daylight factors, Energy Build. 38 (7) (2006) 905–913.

[82] CEN, Indoor Air. Sampling Strategy for Carbon Dioxide (CO2) BS EN ISO 16000-26:2012, 2012.
[83] EPA, A Standardised EPA Protocol for Characterizing Indoor Air Quality in Large Office Buildings, 2003.
[84] C. Huizenga, H. Zhang, P. Mattelaer, T. Yu, E. Arens, P. Lyons, Window Performance for Human Thermal Comfort, February. 2006.
[85] T. Instrument, OPT3001 [Online]. Available: https://www.ti.com/lit/ds/symlink/opt3001.pdf?ts=1595516097224&ref_url=https%253A%252F%252Fwww.google.com%252F. (Accessed 20 July 2020).
[86] J. Mardaljevic, R. Kelly Waskett, R. Painter, Neutral daylight illumination with variable transmission glass: Theory and validation, Light. Res. Technol. 48 (2015) 267–285.
[87] J. Mardaljevic, L. Heschong, E. Lee, Daylight metrics and energy savings, Light. Res. Technol. 41 (2009) 261–283.
[88] W.K.E. Osterhaus, Discomfort glare assessment and prevention for daylight applications in office environments, Sol. Energy 79 (2005) 140–158.
[89] G.R. Newsham, C. Arsenault, A camera as a sensor for lighting and shading control, Light. Res. Technol. 41 (2009) 143–163.
[90] J.F. Nicol, M. Wilson, A critique of European Standard EN 15251: strengths, weaknesses and lessons for future standards, Build. Res. Inf. 39 (2) (2011) 183–193.
[91] T. Kruisselbrink, M. Aries, A. Rosemann, A practical device for measuring the luminance distribution, Int. J. Sustain. Light. 19 (2017).
[92] G. Ward, HDRgen [Online]. Available: http://www.anyhere.com/. (Accessed 20 July 2020).
[93] 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.
[94] J. Wienold, Daylight Glare in Offices, 2010.
[95] P. Wargocki, Improving Indoor Air Quality Improves the, Int. Cent. Indoor Environ. Energy, Dep. Civ. Eng. Tech. Univ. Denmark, Kgs. Lyngby, Denmark, 2002, pp. 1–7.
[96] W.J. Fisk, A.H. Rosenfeld, Estimates of improved productivity and health from better indoor environments, Indoor Air 7 (3) (1997) 158–172.
[97] A. Steinemann, P. Wargocki, B. Rismanchi, Ten questions concerning green buildings and indoor air quality, Build. Environ. 112 (2017) 351–359.
[98] W. Wei, P. Wargocki, J. Zirngibl, J. Bendžalová, C. Mandin, Review of parameters used to assess the quality of the indoor environment in Green Building certification schemes for offices and hotels, Energy Build. 209 (2020) 109683.
[99] EPA, Emission standards for adhesives and sealants [Online]. Available: https://www.epa.gov/sites/production/files/2017-08/documents/va_9_vac_5_chapter_45_article_6_revised_10-1-13.pdf. (Accessed 20 July 2020).
[100] COZIR LP [Online]. Available: https://www.gassensing.co.uk/product/cozir-lp-co2-sensor/. (Accessed 20 July 2020).
[101] 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.
[102] J. Kim, R. de Dear, Workspace satisfaction: the privacy-communication trade-off inopen-plan offices, J. Environ. Psychol. (2013) 18–26.
[103] P. Li, T.M. Froese, G. Brager, Post-occupancy evaluation: state-of-the-art analysis and state-of-the-practice review, Build. Environ. 133 (December 2017) (2018) 187–202.
[104] J. Kim, et al., Occupant comfort and behavior: high-resolution data from a 6-month field study of personal comfort systems with 37 real office workers, Build. Environ. 148 (2019) 348–360.
[105] S.R. Porter, M.E. Whitcomb, W.H. Weitzer, Multiple surveys of students and survey fatigue, N. Dir. Inst. Res. 121 (2004) 63–73.
[106] A.H. Lam, Y. Yuan, D. Wang, An occupant-participatory approach for thermal comfort enhancement and energy conservation in buildings, in: Proc. 5th Int. Conf. Futur. Energy Syst. - E-Energy '14, 2014, pp. 133–143.
[107] F. Jazizadeh, F.M. Marin, B. Becerik-Gerber, A thermal preference scale for personalized comfort profile identification via participatory sensing, Build. Environ. 68 (2013) 140–149.
[108] K.S. Konis, Leveraging ubiquitous computing as a platform for collecting real-time occupant feedback in buildings, Intell. Build. Int. 5 (3) (2013) 150–161.
[109] N. Lassen, F. Goia, S. Schiavon, J. Pantelic, Field investigations of a smiley-face polling station for recording occupant satisfaction with indoor climate, Build. Environ. 185 (2020) 107266.
[110] J. Berquist, M.M. Ouf, W. O'Brien, A method to conduct longitudinal studies on indoor environmental quality and perceived occupant comfort, Build. Environ. 150 (2019) 88–98.
[111] I. Pigliautile, S. Casaccia, N. Morresi, M. Arnesano, A.L. Pisello, G.M. Revel, "Assessing occupants' personal attributes in relation to human perception of environmental comfort: measurement procedure and data analysis, Build. Environ. 177 (2020) 106901.
[112] X. Cheng, B. Yang, T. Olofsson, G. Liu, H. Li, A pilot study of online non-invasive measuring technology based on video magnification to determine skin temperature, Build. Environ. 121 (2017) 1–10.
[113] F. Jazizadeh, W. Jung, Personalized thermal comfort inference using RGB video images for distributed HVAC control, Appl. Energy 220 (March) (2018) 829–841.
[114] M. Allen, M. Overend, Can a building read your mind ? Results from a small trial in facial action unit detection, J. Phys. Conf. Ser. CISBAT 1343 (2019) 2019.
[115] J.Y. Park, T. Dougherty, H. Fritz, Z. Nagy, LightLearn: An adaptive and occupant centered controller for lighting based on reinforcement learning, Build. Environ. 147 (January 2019) (2019) 397–414.
[116] S. Schiavon, K.H. Lee, Dynamic predictive clothing insulation models based on outdoor air and indoor operative temperatures, Build. Environ. 59 (2013) 250–260.
[117] G. Labs, Grafana [Online]. Available: https://grafana.com/. (Accessed 20 July 2020).
[118] influxdata, InfluxDB [Online]. Available: https://www.influxdata.com/. (Accessed 20 July 2020).
[119] EU Commission, 2018 Reform of EU Data Protection Rules, European Commission, 2018.
[120] European Commission Ethics Subgroup IoT Expert Group, "IoT Privacy, Data Protection, Security".
[121] M.B. Kjærgaard, et al., Current practices and infrastructure for open data based research on occupant-centric design and operation of buildings, Build. Environ. 177 (2020), 106848.
[122] A. Kuznetsova, P.B. Brockhoff, R.H.B. Christensen, lmerTest package: tests in linear mixed effects models, J. Stat. Software 82 (2017).
[123] M. Kuhn, Caret Package, J. Stat. Software 28 (5) (2008).
[124] R. Lenth, H. Singmann, J. Love, P. Buerkner, M. Herve, Package ' Emmeans, 2020. R package version 1.15-15.
[125] G. Chinazzo, J. Wienold, M. Andersen, Daylight affects human thermal perception, Sci. Rep. 9 (2019) 13690.
[126] B.W. Meerbeek, C. de Bakker, Y.A.W. de Kort, E.J. van Loenen, T. Bergman, Automated blinds with light feedback to increase occupant satisfaction and energy saving, Build. Environ. 103 (2016) 70–85.
[127] R. and A.-C. E. American Society of Heating, 2017 ASHRAE Handbook: Fundamentals, ASHRAE Handb. Fundam., 2017.
[128] 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.