WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

A real-world empirical investigation of indoor environment and workplace productivity in a naturally-ventilated office environment

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Abstract: Most studies on indoor environments and productivity in buildings have been conducted in controlled, static conditions often not representative of the real world, and have used self-reported assessments of productivity. This paper uses a case study-based, real-world approach to empirically investigate the relationship between the indoor environment and workplace productivity in a naturally-ventilated office environment in central London. A range of environmental parameters (indoor temperature, relative humidity (RH) and CO_2) were monitored continuously, alongside outdoor temperatures and RHs for six months covering both heating and non-heating periods. Transverse (BUS survey) and longitudinal surveys (Online survey) recorded occupant perceptions of their working environments, thermal comfort and *self-reported* productivity, while *performance tasks* were designed to *objectively* measure productivity over time in various environmental conditions.

Statistical analysis of the data shows that mean indoor temperatures were more strongly correlated with mean outdoor temperatures in the non-heating season (May-July) when compared to the heating season (Feb-Apr), probably due to opening of windows. Indoor RH was found to be low (<30%) while CO_2 levels were high in the heating season (peaks >2500ppm, higher diurnal ranges, higher daily averages). Results from online surveys showed that productivity was reported to decrease when there was an increase in mean indoor temperature and CO_2 levels. Negative but weak correlations were found between the performance task scores and CO_2 levels. Insights from the study can be used to optimise indoor office environments to improve staff productivity.

Keywords: productivity, office, indoor environment, survey, comfort

1. Introduction

Workplace productivity describes how well resources are used to achieve a goal (British Council for Offices, 2017). Research suggests that productivity benefits of 2-3% could be gained by improving the working environment (*ibid.*). When the majority of an organisation's costs relate to its staff, the importance of improving productivity becomes clear. Conversely, poor health and sickness cost UK employers more than £9 billion a year through absenteeism alone (ONS 2014), while presenteeism costs associated with low productivity could be even greater. Some poor health outcomes have been associated with spending prolonged periods of time in office environments with ill effects including musculoskeletal complications (Coggon et al., 2013), cardiovascular disease (Smith et al., 2016), and sick building syndrome (Shahzad et al., 2017). Improvements to office environments should both reduce the cost to employers and improve the health, wellbeing and productivity of employees.

Certain indoor environmental quality (IEQ) parameters in office buildings have been shown to influence workers' productivity (Alker et al., 2015, and references therein). However, there are currently no clearly defined parameters to guide the optimisation of indoor conditions in a range of office environments. The majority of the intervention and office-based studies that have shown increased productivity from improved indoor environment have focussed on individual indoor environment elements, e.g. temperature or ventilation rates (Niemelä et al. 2002; Seppänen et al. 2006; Park & Yoon 2011). However, these do not reflect the dynamic real office settings which experience varying temperature, relative humidity (RH), ventilation rates, and air pollutants over the course of a day. Interpreting data collected in office environments has additional challenges, such as isolating the effects of temperature from air quality; daylighting from outside views; and beneficial background noise versus distracting noise which impacts on workflow and concentration. In addition, office design, layout, and biophilia have all been shown to influence productivity and interact with indoor environment variables controlled by building services (Browning, 2016).

This paper empirically investigates the relationship between indoor environment and productivity in a naturally-ventilated office building in Central London (UK), over six months covering both heating and non-heating periods. A range of indoor environment parameters (temperature, relative humidity (RH) and CO_2 levels) were monitored using data loggers, along with outdoor temperature and RH. *Occupant surveys* were used to estimate self-reported productivity, thermal comfort and perception of working environment, while *performance tasks* were used to objectively assess the productivity of staff. The research study is part of an EPSRC funded *Whole Life Performance Plus* (WLP+) project that seeks to develop a dynamic approach for improving workplace productivity by optimising the indoor environmental conditions.

2. Evidence to date

CEN standard EN15251 acknowledges that the indoor environment affects occupant productivity, health and comfort (CEN, 2007). Recommended limits were therefore set for optimum performance. Negative factors in relation to productivity were often more obvious than positive factors: an environment that is too hot, too cold or too noisy can be uncomfortable or distracting to work in, and finding the optimal level of indoor environment parameters where productivity begins to increase, was found to be more challenging. This is why recent studies, outlined in Table 1, have been seeking to develop an understanding of the relationship between indoor environment and workplace productivity. However, most of these were conducted in climate chambers that create artificial environments.

The effect of temperature on health and comfort has been widely researched and it is broadly recognised as an important indoor environment factor. The recommended limits for Category II mechanically ventilated office buildings are 20-26°C, implying that between 21-25°C there are no direct risk to occupants' health and comfort. For naturally ventilated buildings, comfort indoor temperature is dependent on outdoor temperature and has a much wider comfort band. It is found that indoor temperature significantly influences workers' productivity in the recommended ventilation rate (Tham, 2004) and in a quiet environment (Witterseh et al, 2004). Fang et al. (2004) identified a link between temperature, RH and performance at different ventilation rates (with participants allowed to adjust clothing levels to maintain thermal comfort). At 10l/s/person, difficulty in thinking and other SBS symptoms was highest in 26°C and lowest in 20°C, although no significant effects of indoor environment on the tasks performed could be demonstrated. Lan et al (2011) took 12 participants in the same clothing level, in neutral and warm thermal conditions, and found that performance in all tasks (with the exception of text typing) decreased in warmer conditions. With text typing, although more characters were typed at higher temperature, more errors were also made. The results from the study imply that optimum thermal comfort and optimum productivity may not occur at the same temperatures – a finding supported by others (Al Horr et al., 2016). Seppänen et al's (2006) meta-analysis suggests the temperature range for optimum performance is close to the optimum range for comfort, particularly for mechanically ventilated buildings in winter. In free-running buildings there will be a bigger difference between optimal temperatures for comfort and performance. A 2% decrease in productivity for going 1°C beyond the optimal range will have significant cost implications for the organisation.

An indoor CO_2 concentration upper limit of 1500ppm is specified for office spaces in order to maintain comfort air quality. In studies by Allen et al. (2015), Satish et al. (2012) and Kajtar et al. (2003), performance was found to decrease as CO_2 concentration was increased. These studies indicate every-day CO_2 levels within the current recommended standards can have significant negative impacts on worker performance.

Table 1. Summary of selected, recent studies (intervention and observational) that investigate the links between indoor environment parameters on workplace performance.

Study	Study type and location	Procedure	Results
Tham (2004)	Intervention study in a mechanically ventilated call centre in Singapore (n=56)	Investigated the effect of temperature and ventilation rate.	Reduction in call talk time when ventilation rate was increased. Increase in call talk time when temperature was reduced.
Fang et al (2004)	Intervention study in a mechanically ventilated office in Denmark (n=30)	Participants exposed to different combinations of temperature, RH and ventilation rates.	Increase in SBS symptoms and difficulty in thinking in higher temperature. No significant effect of temperature and humidity on performance
Vimalanathan and Babu (2014)	Intervention study in a climate chamber India (n=10)	Participants exposed to three different thermal conditions and three different light conditions.	Temperature and light account for significant variation in performance.
Lan et al (2011)	Intervention study in a mechanically ventilated office in Denmark (n=12)	Participants exposed to two different thermal conditions (22°C and 30°C).	Performance in eight out of nine tasks (typical of office work) decreased in high temperature.
Seppänen et al (2006)	Review of studies	Meta-analysis conducted on published studies which have investigated the influence of temperature on performance.	Between 21-25°C there is no effect on performance. Updated analysis showed that the temperature range for maximum performance was 21-24°C. Linear model gives a 2% decrease in performance per 1°C increase in temperatures above 25°C.
Satish et al (2012)	Intervention study in a climate chamber in the USA (n=22)	Participants were exposed to different CO_2 concentrations.	Relative to 600ppm, there were moderate to large decrease in decision making performance at 1000ppm and 2500ppm

More recently Innovate UK's national research programme on building performance evaluation (BPE) undertook case study investigations of 50 low energy non-domestic buildings located across the UK, measuring the performance of building fabric, energy consumption, environmental conditions and occupant satisfaction. Meta-analysis of the surveys showed that occupant surveys in 12 out of the 21 workspaces reported an increase in perceived productivity due to the environmental conditions perceived by the occupants (Gupta et al, 2016). The meta-study found that when occupants were satisfied with the indoor temperature, noise, lighting and building related features, perceived productivity increased, while on the other hand, when indoor air was perceived as stuffy and smelly, perceived productivity decreased.

It is evident that there is growing recognition of some kind of a link between indoor environment and perceived productivity in workplaces. This paper seeks to empirically quantify this link between indoor environment, thermal comfort, and perceived and measured productivity, in a central London office environment.

3. Methods and overview of the case study

The methodology adopted in the study has a three-pronged approach: (1) *Physical monitoring of indoor and outdoor environment using data loggers* (2) *Occupant survey (transverse and longitudinal)* and (3) *Performance tasks (productivity tests).* These methods were implemented over a period of six months from 1 February 2017 to 31 July 2017. Figure 1 illustrates the methodological approach adopted in the project.

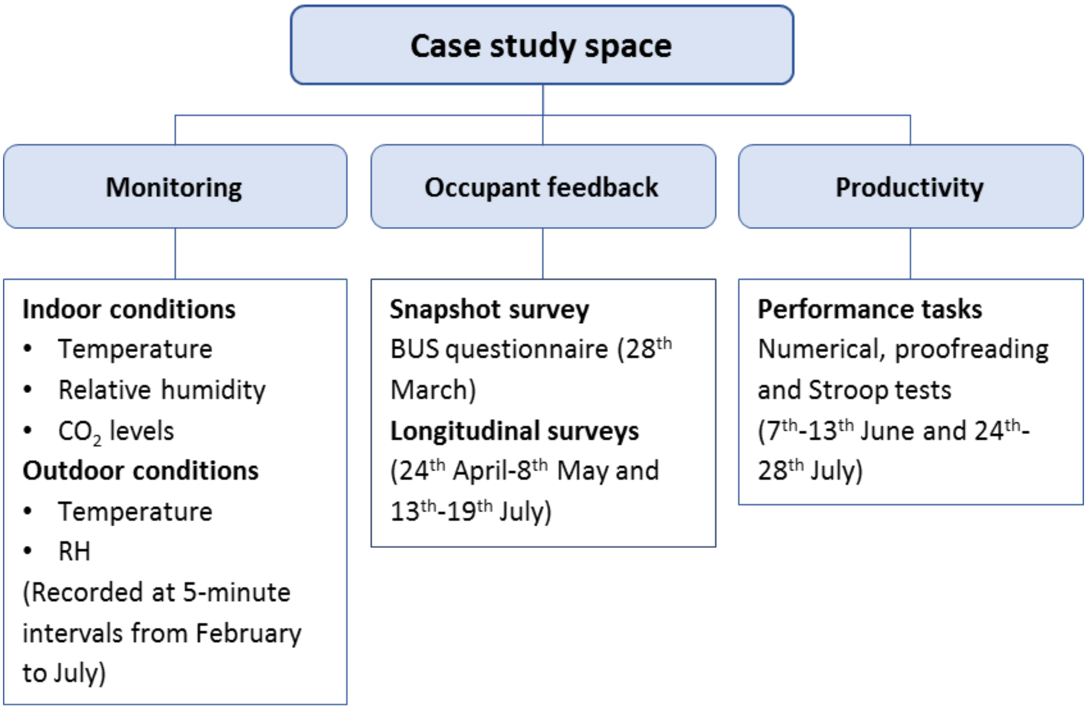


Figure 1. Methodological framework showing duration of physical monitoring, surveys and performance tasks.

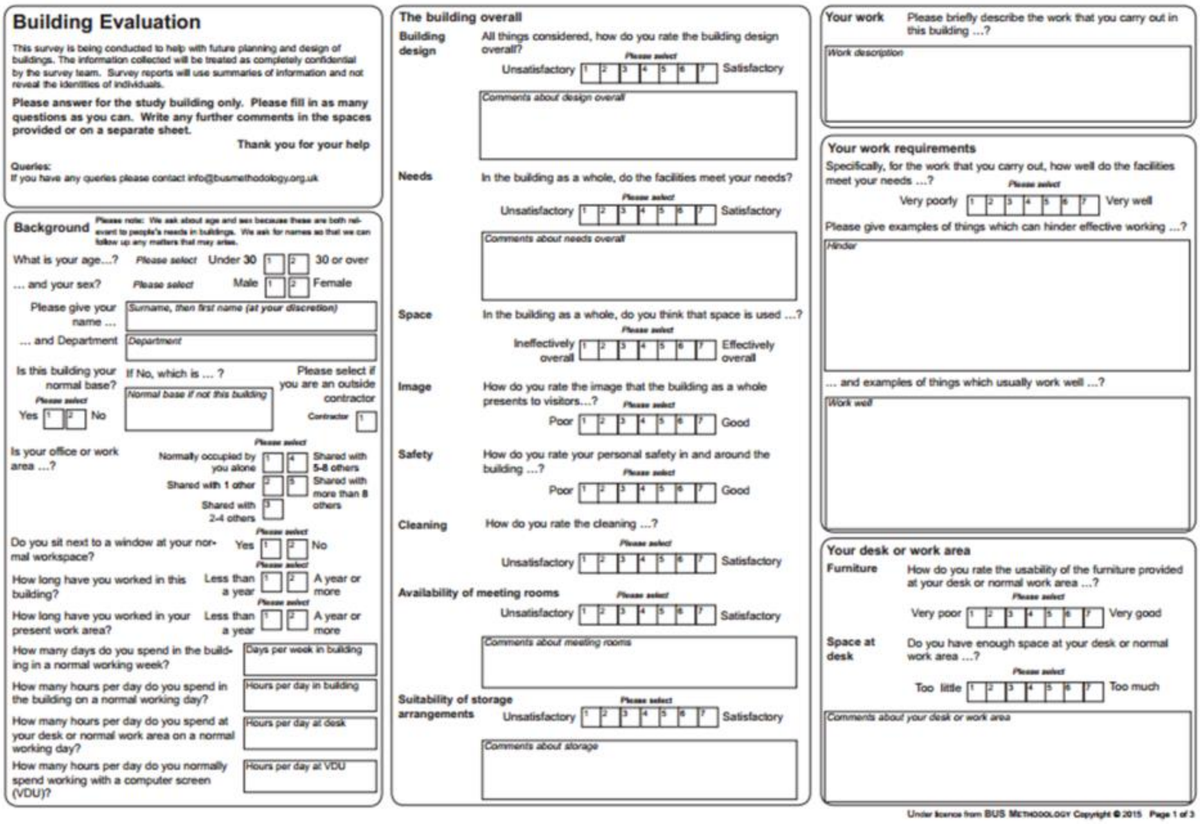
Indoor environmental parameters (temperature, RH and CO_2 levels) and outdoor environmental parameters (temperature and RH) were recorded at five-minute intervals and assessed in daily and hourly profiles for the occupied period. Data logging devices were chosen for physical monitoring due to their appropriate range, good level of accuracy and resolution. Hobo U12's (temperature/RH) and Tinytag TGE-0011's (CO_2) were used internally, and Hobo U23 Pro v2's (temperature/RH) were used externally (specifications given in Table 2). Readings were taken at 5-minute intervals and data manually collected from the loggers on a monthly basis.

Table 2. Specification, resolution and accuracy of data loggers

Device	Parameter	Range	Accuracy	Resolution
Hobo U12	Temperature	-20° to 70°C	±0.35°C	0.03°C
	RH	5% to 95%	±2.5%	0.05%
Tinytag TGE-0011	CO_2	0-5000ppm	± (50ppm +3% of reading)	0.1ppm
Hobo U23 Pro v2	Temperature	-40° to 70°C	±0.21°C	0.02°C
	RH	0-100%	±2.5%	0.03%

Occupant surveys and performance tasks were time stamped so that perceived environment, self-reported (perceived) and measured productivity could be assessed against actual environmental conditions.

The Building User Survey (BUS) provided a snapshot record of occupant perception of their working environment during summer and winter (BUS Methodology, 2018). BUS is a well-established way of benchmarking levels of occupant satisfaction within buildings against a large database of results for similar buildings. The survey uses a structured questionnaire containing 45 questions to record feedback on aspects including thermal comfort and ventilation, lighting and noise, personal control over the environment and change in perceived productivity. The BUS survey was conducted as a paper-based questionnaire in March 2017.



Building Evaluation

This survey is being conducted to help with future planning and design of buildings. The information collected will be treated as completely confidential by the survey team. Survey reports will use summaries of information and not reveal the identities of individuals.

Please answer for the study building only. Please fill in as many questions as you can. Write any further comments in the spaces provided or on a separate sheet.

Thank you for your help

Queries:
If you have any queries please contact info@busmethodology.org.uk

Background Please note: We ask about age and sex because these are both relevant to people's needs in buildings. We ask for names so that we can follow up any matters that may arise.

What is your age...? *Please select* Under 30 ☐1 ☐2 30 or over

... and your sex? *Please select* Male ☐1 ☐2 Female

Please give your name ... *Surname, then first name (at your discretion)*

... and Department *Department*

Is this building your normal base? *Please select* Yes ☐1 ☐2 No

If No, which is .... ? *Normal base if not this building*

Please select if you are an outside contractor — Contractor ☐1

Is your office or work area ...? *Please select*
Normally occupied by you alone ☐1
Shared with 1 other ☐2
Shared with 2-4 others ☐3
Shared with 5-8 others ☐4
Shared with more than 8 others ☐5

Do you sit next to a window at your normal workspace? *Please select* Yes ☐1 ☐2 No

How long have you worked in this building? *Please select* Less than a year ☐1 ☐2 A year or more

How long have you worked in your present work area? *Please select* Less than a year ☐1 ☐2 A year or more

How many days do you spend in the building in a normal working week? *Days per week in building*

How many hours per day do you spend in the building on a normal working day? *Hours per day in building*

How many hours per day do you spend at your desk or normal work area on a normal working day? *Hours per day at desk*

How many hours per day do you normally spend working with a computer screen (VDU)? *Hours per day at VDU*

The building overall

Building design All things considered, how do you rate the building design overall? *Please select* Unsatisfactory ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Satisfactory
Comments about design overall

Needs In the building as a whole, do the facilities meet your needs? *Please select* Unsatisfactory ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Satisfactory
Comments about needs overall

Space In the building as a whole, do you think that space is used ...? *Please select* Ineffectively overall ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Effectively overall

Image How do you rate the image that the building as a whole presents to visitors...? *Please select* Poor ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Good

Safety How do you rate your personal safety in and around the building ...? *Please select* Poor ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Good

Cleaning How do you rate the cleaning ...? *Please select* Unsatisfactory ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Satisfactory

Availability of meeting rooms *Please select* Unsatisfactory ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Satisfactory
Comments about meeting rooms

Suitability of storage arrangements *Please select* Unsatisfactory ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Satisfactory
Comments about storage

Your work Please briefly describe the work that you carry out in this building ...?
Work description

Your work requirements

Specifically, for the work that you carry out, how well do the facilities meet your needs ...? *Please select* Very poorly ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Very well

Please give examples of things which can hinder effective working ...?
Hinder

... and examples of things which usually work well ...?
Work well

Your desk or work area

Furniture How do you rate the usability of the furniture provided at your desk or normal work area ...? *Please select* Very poor ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Very good

Space at desk Do you have enough space at your desk or normal work area ...? *Please select* Too little ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Too much

Comments about your desk or work area

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Figure 2. Sample section from the BUS survey, including scalable responses and comment boxes.

An online questionnaire was used to record longitudinal feedback from occupants. The questionnaire contains six questions on perceived environment (thermal sensation and preference votes, air quality, noise, lighting, overall comfort) and one question on change in perceived productivity due to the environmental conditions. The commonly used sevenpoint Bedford scale[1] for thermal comfort was used to record perceived thermal comfort, and rating scales (1-7; 1: unsatisfactory and 7: satisfactory) identical to those used in the BUS survey were used for air quality, noise, lighting and overall comfort. Occupants were also asked to rate their change in perceived productivity on a scale from -20% or more to +20% or more with 5% increments. The questionnaires were sent via email three times a day (morning, midday and afternoon) during three weeks from April-July 2017.

Simulated performance tasks were conducted in two rounds (of approximately two working weeks) during the non-heating season, to provide an assessment of task performance alongside the monitoring of indoor environmental conditions occurring at the time. Three different sets of performance tasks were selected from those used in previous research studies (Wargocki et al, 2000, 2002, Park and Yoon, 2011). The tasks were designed to represent typical office tasks and consisted of: *Numerical tests* (to solve simple mathematical questions), *Proof reading* (to identify spelling errors in a paragraph of text) and *Stroop test* (an interference test, differentiating between the colour of the text and the word). Both the *test score* and *time taken* to complete the task were recorded. Tasks were designed to take no more than 10 minutes each to complete, so as to increase participation and minimise disruption to daily work. They were sent via email twice-daily (morning and afternoon) from 7th-13th June 2017 and 24th-28th July 2017. This provided performance data for the non-heating season. Since the project began in February, it was not possible to conduct online survey and performance tasks in the heating season because of the time taken to establish access to, and engagement with, the building's occupants.

Repeating surveys and tasks (multiple times per day and over at least a one-week period) ensured that a range of indoor environment conditions were recorded which is typical of naturally ventilated buildings, and also reduces potential bias in participation.

3.1. Overview of the case study

The case study building is located in central London next to a busy road. It was built in 1938 and fully refurbished in 1995. It is primarily an owner-occupied office building. Heating and cooling is provided by fan coil units. The seventh floor of the case study building was selected as the case study working environment for this project. The floor is home to an open-plan administrative department (approximately 400m^2 with 78 workstations). Desks, carpets and other furnishing in all areas of this floor were upgraded (replaced) in 2015. Lights were controlled locally and the official operating hours during the working days (i.e. hours the space was controlled for heating and cooling) were from 08:30 to 17:30. The study space was divided into four monitoring zones as shown in Figure 3. The average daily occupancy from February to July is 48 (occupancy rate of 61.5%). (Note: occupancy data were available from February to the first half of July).

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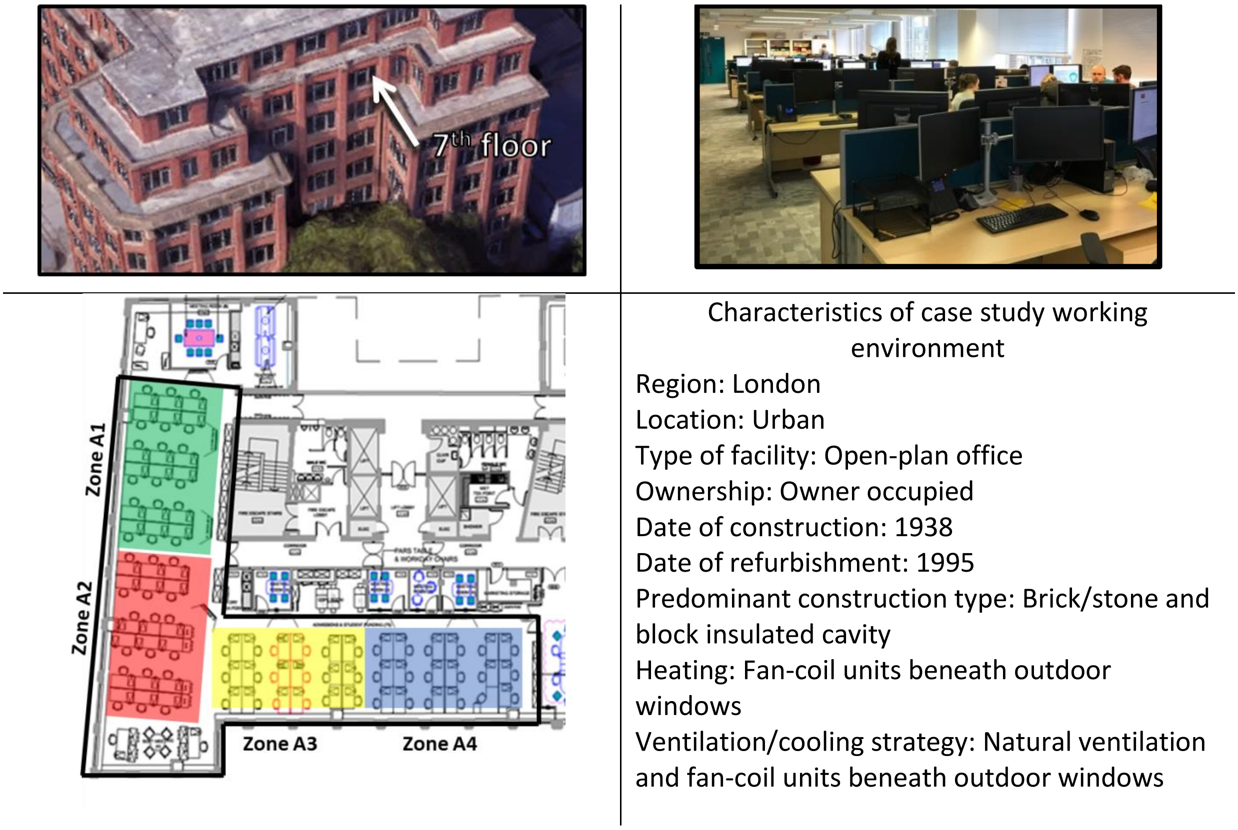
[1] Bedford Scale: 1 – Much too cool 2 – Too cool 3 – Comfortably cool 4 – Comfortable neither warm nor cool 5 – Comfortably warm 6 – Too warm 7 – Much too warm



Characteristics of case study working environment

Region: London
Location: Urban
Type of facility: Open-plan office
Ownership: Owner occupied
Date of construction: 1938
Date of refurbishment: 1995
Predominant construction type: Brick/stone and block insulated cavity
Heating: Fan-coil units beneath outdoor windows
Ventilation/cooling strategy: Natural ventilation and fan-coil units beneath outdoor windows

Figure 3. External view of building (top left), indoor view of zones A3 and A4 (top right), floorplan showing zones (bottom left) and descriptive characteristics of the case study working environment (bottom right).

4. Data analysis

4.1. Indoor environment (heating and non-heating periods)

A comparison of the distribution of indoor temperature during working-hours in both heating (February-April) and non-heating (May-July) seasons is shown in Figure 4. This shows significant overlap, but lower averages and a smaller range in the heating season.

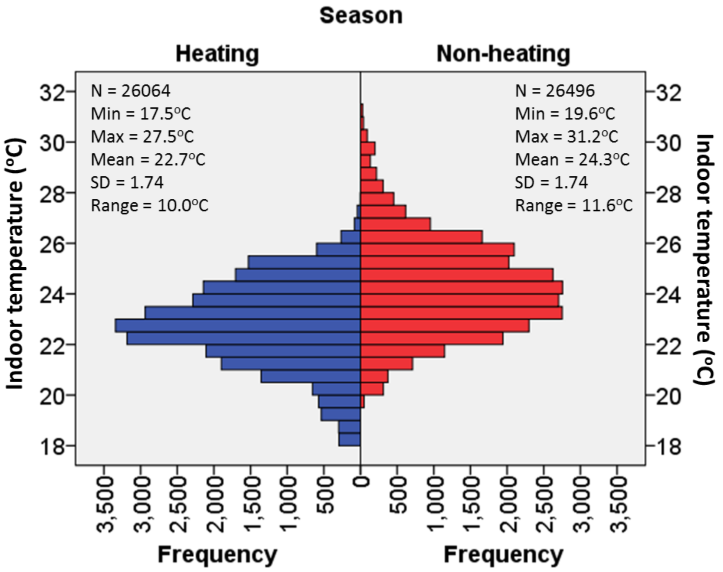


Figure 4. Comparison of working-hours indoor temperature distributions in the heating and non-heating seasons.

To gain a deeper understanding of the relationship between indoor and outdoor temperatures across the heating and non-heating seasons, Figure 5 shows scatter plots with linear trendlines and 95% confidence intervals plotted. The dashed line shows where indoor and outdoor temperatures were equal. In the heating season, temperatures were found to be higher internally than externally for more than 97% of the time. This dropped to 85% in the non-heating season. The link between outdoor and indoor temperatures is stronger in the non-heating season (Pearson correlation r=0.10 and r=0.53 in the heating and non-heating seasons respectively), when windows were more likely to be opened. There is also a narrower range of temperatures in the heating season compared to the non-heating season.

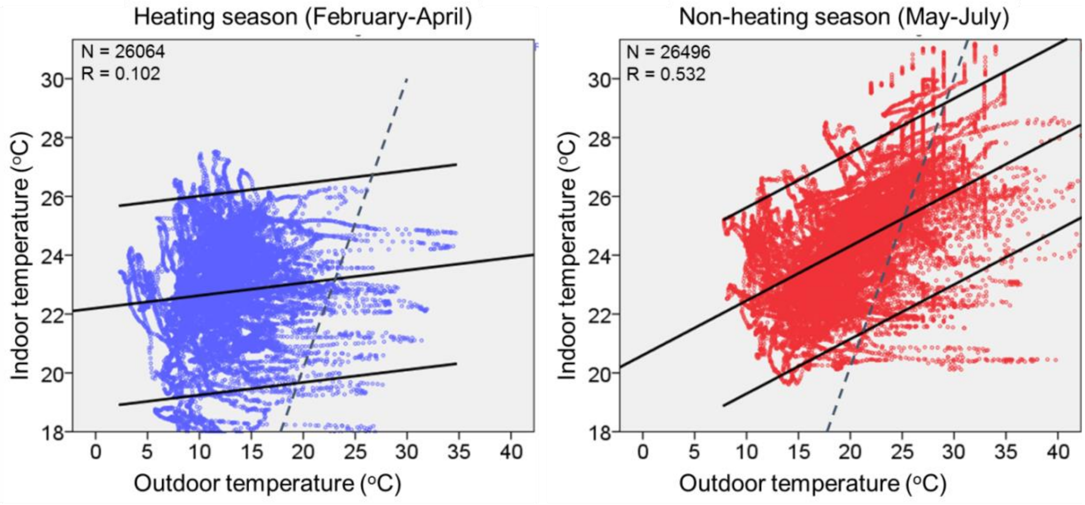


Figure 5. Relationship between outdoor and indoor temperatures in heating season (left) and non-heating season (right), showing linear trendlines and 95% confidence intervals. Dashed line shows when indoor and outdoor temps were equal.

Boxplots of indoor temperatures for each month in Figure 6 indicate the median, upper and lower quartiles for readings taken at 5-minute intervals. Mean outdoor temperatures and occupancy are also shown. Peak outdoor temperatures in June correspond with longer upper whiskers on the boxplot and more outliers above this. Taking February as a sample month for the heating period, and July as a sample month for the non-heating period, mean indoor temperatures in July were approximately 1.5°C higher compared to February.

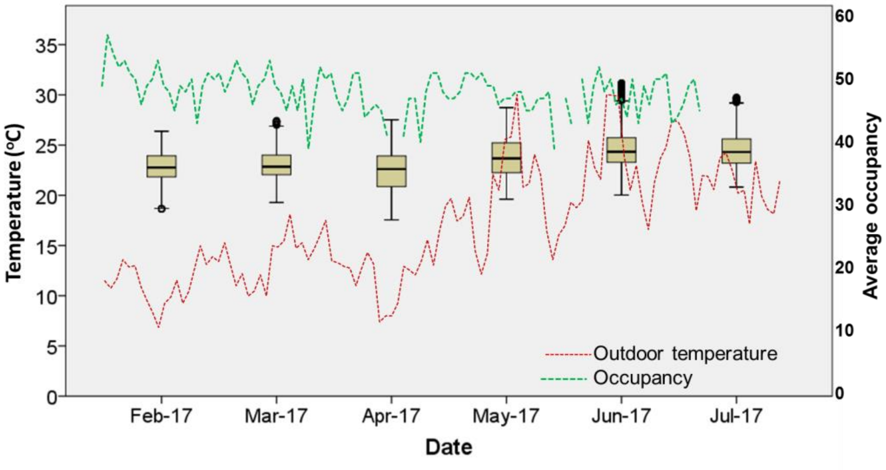


Figure 6. Distribution of temperatures each month, showing median and interquartile range, outdoor temperature and occupancy.

Investigating further into hourly temperature profiles for February and July, Figure 7 shows mean hourly temperatures averaged overall all four zones. During occupied hours, indoor temperature is found to increase by an average of 2.7°C in February and 1.7°C in July.

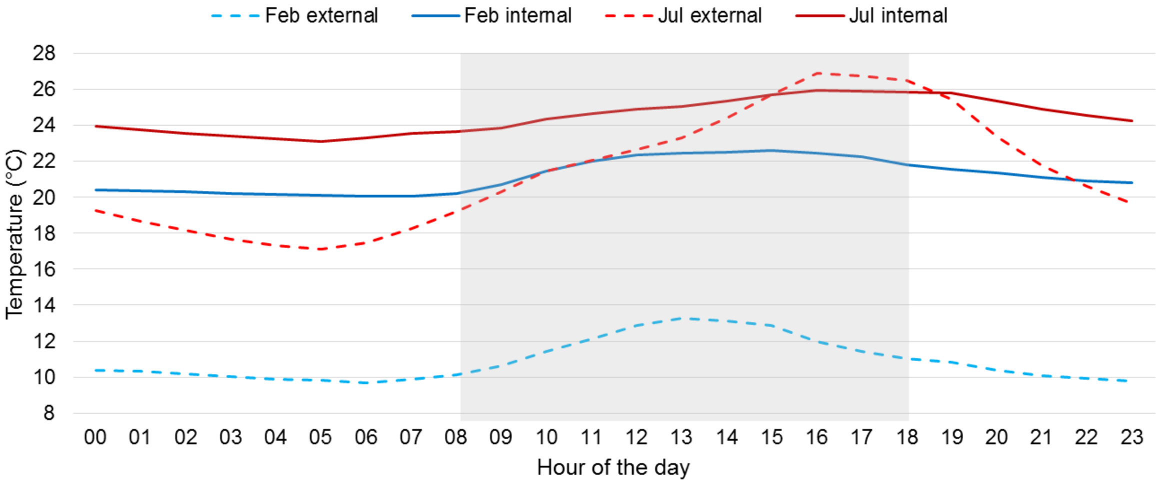


Figure 7. Hourly temperature profiles in February and July.

Recommended temperatures for thermal comfort in UK in offices is 21-23°C in the heating season and 22-24°C in the non-heating season (CIBSE, 2015). In both February and July, indoor temperatures in the case study working environment were within the recommended ranges for less than 15% of the occupied hours, and exceeded these ranges for over 80% of occupied hours. Analysis of thermal sensation and preference votes later in the paper will help to corroborate this.

Average indoor humidity (Figure 8) is found to be at the lower limits of the recommended 40-70% range (between 40-50% for over half of the occupied hours) in the heating season as the space was continuously heated.

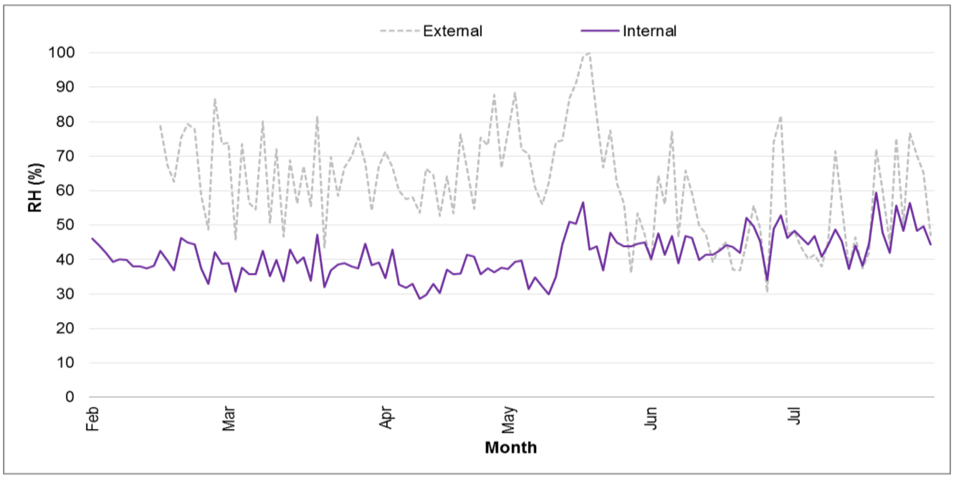
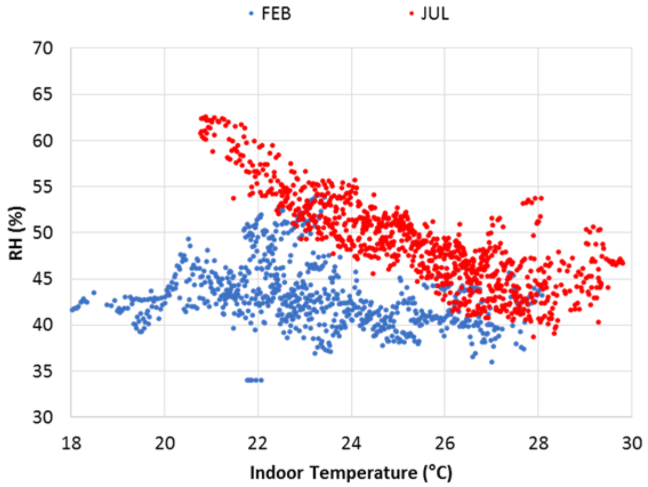


Figure 8. Daily average outdoor and indoor relative humidity (RH).

This is further confirmed when indoor RH is plotted with concurrent measurements of indoor temperature (Figure 9). Drier conditions (lower RH values) were observed in February compared to July, even at the same temperature. In July, relative humidity was within the recommended range (40-70%) for most of the occupied hours possibly due to no space heating and windows opening.



Descriptive statistics

	Feb (N=790)		Jul (N=893)	
	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)
Min	18.0	33.9	20.8	38.7
Max	28.1	54.1	29.8	62.5
Mean	23.2	43.1	25.4	48.9
SD	2.22	3.48	2.15	4.91

Figure 9. Scatter plots and descriptive statistics of indoor temperature and RH during working hours in February and July.

The distribution of indoor CO_2 levels for the six months is shown in Figure 10. Maximum daily CO_2 concentrations exceed 2500ppm in February and April (when windows were found to be closed), while In July, maximum daily CO_2 concentrations were around 1500ppm. In all months, the distribution of CO_2 levels is positively skewed. Interestingly the interquartile range (difference between lower and upper quartiles) of CO_2 concentrations is much larger in the heating months (especially February) compared to the non-heating months, indicating wider fluctuations in CO_2 concentrations over the course of a day. This is confirmed by the daily profiles of CO_2 concentrations wherein the profile in February shows a much greater variation over the course of a day (Figure 11). For both months, as expected, CO_2 levels start to increase from around 08:00 and decrease from 17:00, coinciding with when members of staff arrive at the start of the work day and when they leave at the end. Furthermore, in February CO_2 concentrations above 1500ppm occurred for almost 30% of the occupied hours, predominantly during the afternoons, while in July, occurrences of concentrations above 1500ppm were much lower – less than 1% of occupied hours. Open windows in the summer were likely to be the main cause of these significantly lower levels.

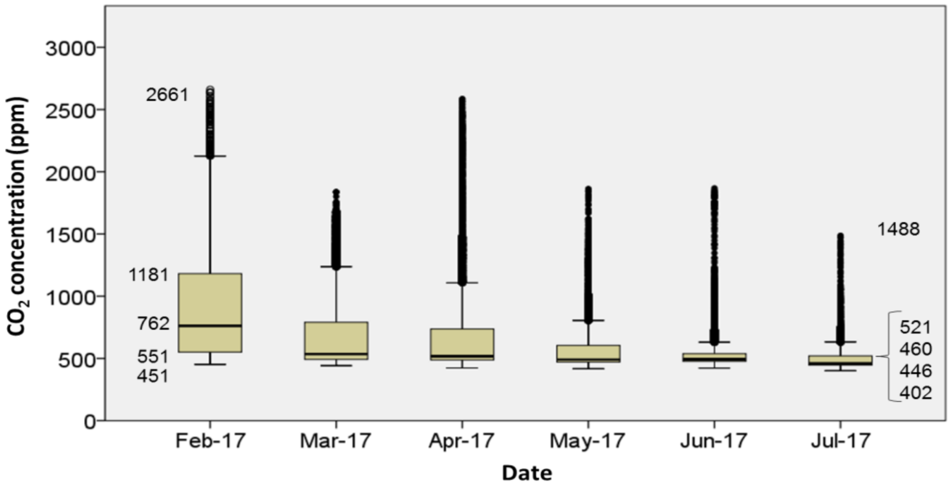


Figure 10. Distribution of CO_2 levels showing max/upper quartile/median/lower quartile/min for February and July.

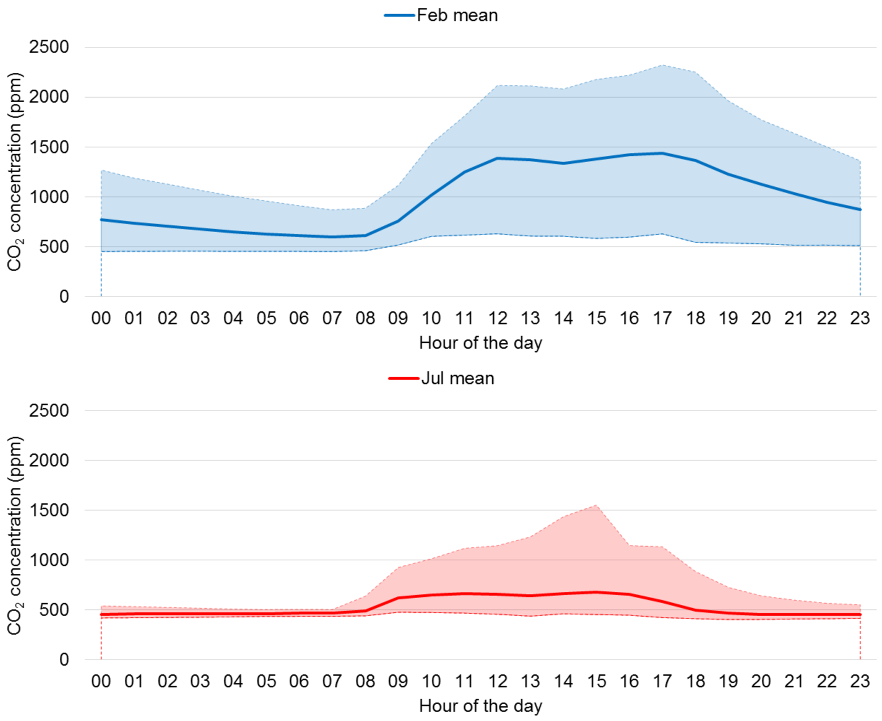


Figure 11. Hourly CO_2 profiles in February (top) and July (bottom), showing average maximum and minimum for each hour.

The wide range in CO_2 levels is again evident throughout February when the daily minimum/mean/maximum CO_2 concentrations were plotted alongside daily occupancy (Figure 12). In February, there is some suggestion that CO_2 levels may be related to occupancy with, for example, drops in both aspects around 10th and 20th February, and a rise in both from 24th-28th February. In July the link between occupancy and CO_2 concentration is less evident – the added factor of window openings is likely to negate any effect of occupancy levels.

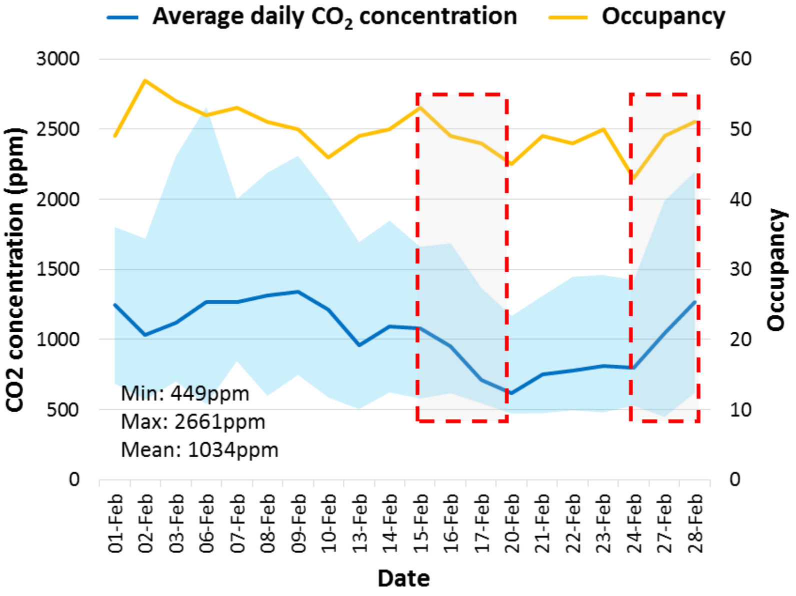


Figure 12. Daily indoor CO_2 profiles (min, mean, max) and daily occupancy in February 2017, with interesting periods highlighted.

4.2. Transverse survey of occupant perception of indoor environment and productivity

The BUS occupant survey was conducted as transverse survey on 28 March 2017. Questionnaires were handed out to occupants between 10:00 and 11:00. Completed questionnaires were collected between 16:00 and 16:30 on the same day. About 62 questionnaires were completed from 78 workspaces, representing a 79% response rate. Analysis of the responses showed a balance between gender and age groups. Over 50% of the respondents have been working in their work area for at least one year, implying they have experienced both heating and non-heating seasons in the building. Table 3 presents the mean average scores (scale of 1-7) of key environmental variables and change in perceived productivity. Scores were highlighted *red* (1.0-3.4), *amber* (3.5-4.5) and *green* (4.6-7.0). Responses regarding the building (design, space, cleanliness etc.) were broadly positive, all averaging a score of 4.8 or above.

Table 3. Average scores from respondents from the BUS survey (scale of 1-7)

Study variables	**Average response**
Temperature and air quality conditions in winter	
Temperature: Uncomfortable/Comfortable	**4.5**
Temperature: Too hot/Too cold	**4.5**
Air quality: Still/Draughty	**3.2**
Air quality: Dry/Humid	**3.3**
Conditions overall	**4.4**
Temperature and air quality conditions in summer	
Temperature: Uncomfortable/Comfortable	**3.2**
Temperature: Too hot/Too cold	**2.6**
Air quality: Still/Draughty	**2.9**
Air quality: Dry/Humid	**4.2**
Conditions overall	**3.4**
Noise conditions	
Unsatisfactory/Satisfactory	**4.4**
Lighting conditions	
Unsatisfactory/Satisfactory	**4.8**
Personal control	
Heating: No control/Full control	**1.2**
Cooling: No control/Full control	**1.2**
Ventilation: No control/Full control	**1.1**
Satisfaction with response to request change	**3.2**
Comfort and health	
Overall comfort: Unsatisfactory/Satisfactory	**4.7**
Change in productivity (perceived)	
Decreased/Increased	**-5.8%**

It is realised that occupants were generally satisfied with their working environment (especially noise and lighting conditions), although there was less satisfaction with the thermal and air quality conditions. For both summer and winter, occupants reported that temperature varied during the day and the air was still and stuffy. Occupants found the air dry (average score 3.2) in the winter, and more humid (average score 4.6) in the summer, as also confirmed by the measured humidity levels recorded in the case study space (Figure 9). The lowest scores given were for personal control of the environment: occupants reported that they have very little control over heating and cooling, and they were not satisfied with the speed of response to requests to change the environmental conditions. Interestingly, overall comfort in the building was rated as satisfactory, yet perceived productivity was found to decrease by 5.8% due to the environmental conditions.

Variables associated with the perceived environment were correlated with a change in perceived productivity to assess their relationship. Correlation coefficients are presented to indicate the direction and the strength of the relationship (Table 4). Spearman's rho test (a non-parametric test), is used here because the relationships being tested were not linearly related. A negative, albeit weak, correlation was found between indoor temperature variation and productivity (more varied temperatures correspond to a perceived reduction in productivity). A positive, but weak, correlation was found between air movement and perceived change in productivity (less air movement corresponding to a perceived reduction in productivity). Moderate correlations were also found for overall comfort, indicating that when occupants were more comfortable (due to the environmental conditions in the building), their perceived change in productivity is positive. This is further substantiated by the longitudinal survey responses and performance tasks discussed in the following sections. Since these were conducted in May, June and July, the cross-relation with physical monitoring data is during the non-heating (summer) period.

Table 4. Spearman's Rho correlation coefficients between perceived indoor environment and change in productivity.

Study variables	**Correlation (N=58)**
Perceived temperature and indoor air quality conditions in winter	
Temperature: Stable/Varies during the day	-0.34*
Air quality: Still/Draughty	0.24
Comfort and health	
Overall comfort: Unsatisfactory/Satisfactory	0.49*

*Correlation is significant at the 0.01 level (2-tailed)

4.3. Longitudinal survey of perceived productivity and comfort and measurement of indoor environment

Two rounds of online surveys were conducted in April-May 2017 (two weeks) and July 2017 (one week) to gather data on occupant perception of thermal comfort, indoor environment and productivity. A link to the questionnaire was sent via email to the occupants. The response rate dropped from 69% in Round 1 to 39% in Round 2. Since the surveys were time-stamped, the responses could be related to the concurrent measurement of the indoor environment.

The distribution of thermal sensation votes correlated with indoor temperatures in show in the figure below, with the trendline and 95% confidence intervals. As indoor temperature increases, thermal sensation votes move towards the warm end of the scale.

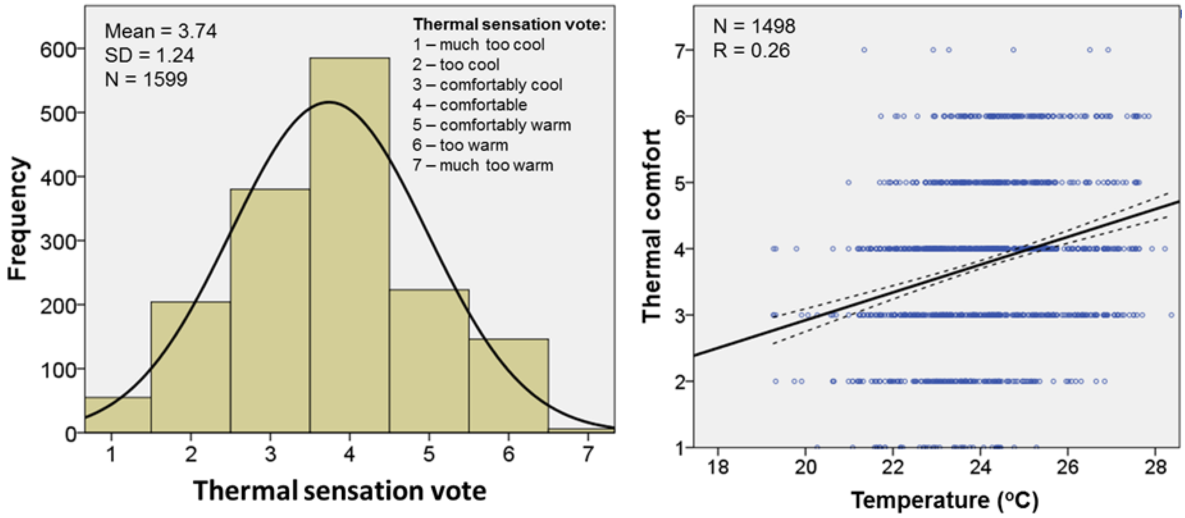


Figure 13. Thermal comfort vote distribution (left) and scatter of comfort vote and indoor temperature with linear regression line and error lines (right).

Figure 14 shows the distribution of air quality votes and correlation with CO_2 concentrations, with the trendline and 95% confidence intervals. Air quality votes were skewed towards the stuffy end of the spectrum, and the trendline indicates that occupants perceive the air quality as stuffier as CO_2 concentration increases. Interestingly the correlation coefficient is weaker (r= 0.11) than that of thermal sensation and indoor temperature (r= 0.26).

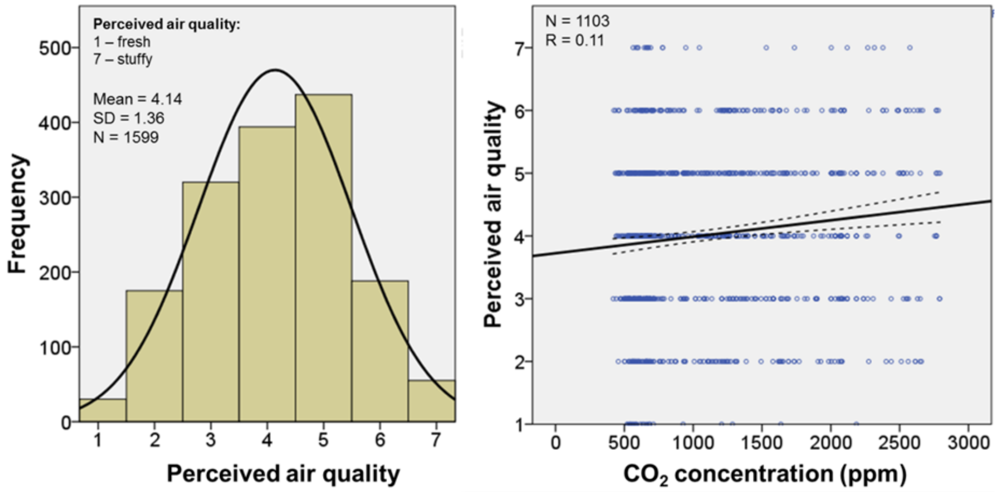


Figure 14. Air quality vote distribution (left) and scatter of air quality vote and CO_2 concentration with linear regression line and error lines (right).

Furthermore the measurements of indoor temperature and CO_2 concentrations were analysed when perceived change in productivity was negative, neutral (no change) and positive (Figure 15) during the three weeks of the longitudinal survey (April, May and July). The distribution of indoor temperatures changes slightly depending on the perceived change in productivity: the mean temperature is slightly higher (24.17^{o}C) when productivity is perceived to be reduced and slightly lower (23.97^{o}C) when productivity is perceived to be increased compared to the neutral 'no perceived change in productivity' (24.10^{o}C). For CO_2 concentration, there is a slight shift towards lower levels of CO_2 when change in productivity is perceived to be positive, although there is only a 5% difference in mean CO_2 concentrations between the negatively and positively perceived changes in productivity.

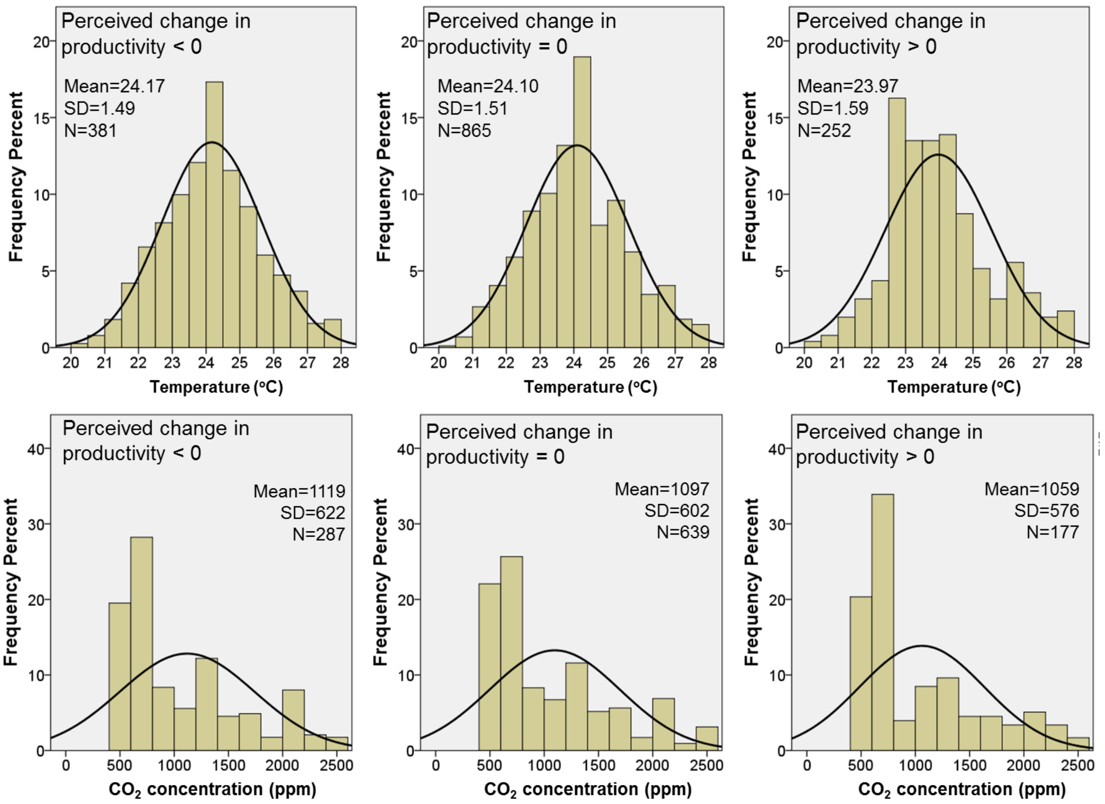


Figure 15. Distribution of indoor temperature (top) and CO_2 concentration (bottom), when change in perceived productivity was negative, neutral and positive during the three weeks in April, May and July 2017.

Overall thermal comfort vote and perceived change in productivity decreased during the course of the day (Figure 16) over the survey period of three weeks. While the occupants perceived their productivity to increase at the start of the day (+0.2%), by late afternoon, this had decreased to -1.6%.

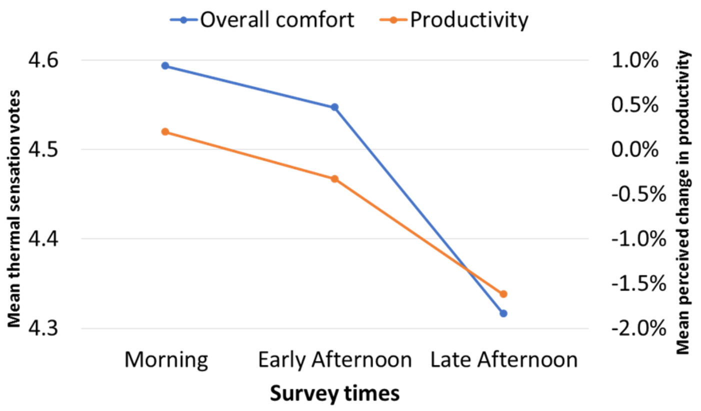


Figure 16. Average thermal comfort votes and perceived change in productivity.

Interestingly when cross-relations were investigated during the course of a day (Figure 17), changes in the thermal sensation and air quality votes strongly relate to changes in measured indoor temperatures and CO_2 levels. While the thermal sensation vote changes from being *comfortably cool* to *comfortably warm* during the course of the day as indoor temperature rises, indoor air quality which is perceived to be fresh in the morning moves towards the stuffy end of the scale in the late afternoon, as indoor CO_2 levels increase.

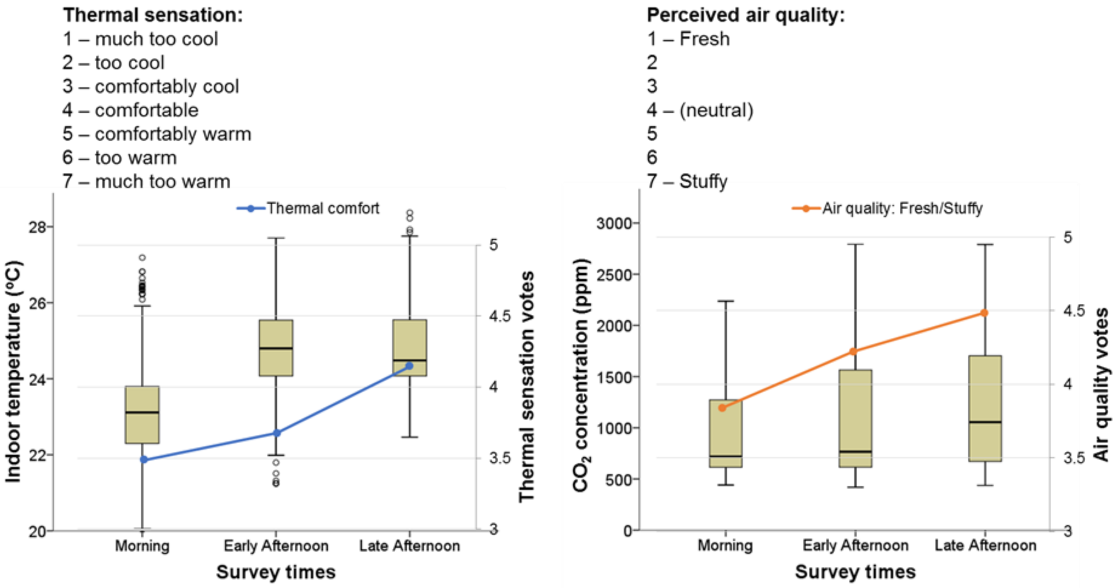


Figure 17. Change in daily mean thermal sensation vote and indoor temperature (left) and perceived air quality and CO_2 levels (right) in the non-heating period.

This was further reconfirmed in the mean thermal preference votes. Despite over half of the respondents not wanting a change in their thermal environment (Figure 18), there was a notable shift from morning to afternoon amongst respondents who wanted to be a bit warmer in the morning to a bit cooler in the afternoon. This could, in part, be explained by the influence of the working environment's west-facing orientation, which receives more direct solar gains in the afternoon.

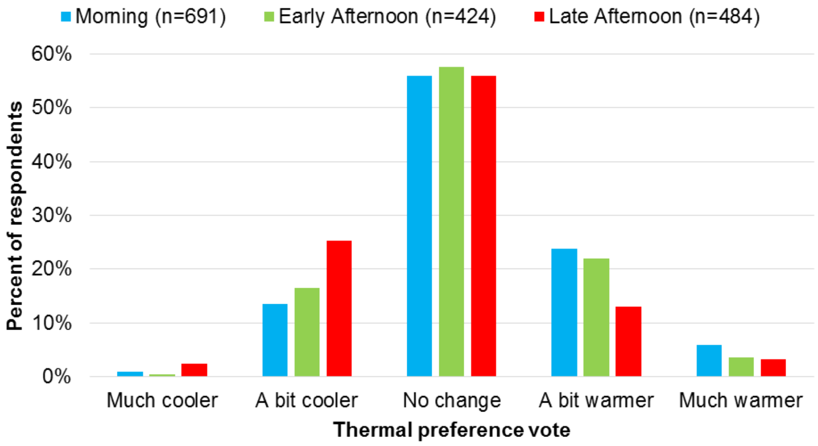


Figure 18. Thermal preference vote throughout the day.

4.4. Measuring productivity and indoor environment

Two rounds of performance tasks were conducted (lasting two working weeks) during the non-heating season to objectively measure the performance of staff. As with the online surveys, the performance tasks were time stamped and the indoor environment conditions at the time of completion were recorded. The response rate dropped from 39% in Round 1 to 32% in Round 2. Three different sets of performance tasks were selected which included - *Numerical tests* (to solve simple mathematical questions), *Proof reading* (to identify spelling errors in a paragraph of text) and *Stroop test* (an interference test, differentiating between the colour of the text and the word). The highest scores were recorded in the Stroop test, with participants scoring an average of 98%, while the lowest scores were recorded in the proof reading test. Interestingly in all three tests, there was little difference between the proportion of correct answers recorded in the morning and in the afternoon.

Figure 19 presents scatter plot of the proportion of correct answers in the proof-reading tasks compared to measured indoor CO_2 levels. It is realised that there is a negative but weak correlation between these two sets of data implying that lower scores correspond to higher levels of CO_2. Correlations between scores of other tests and indoor environmental parameters (temperature and RH) were even weaker, indicating that the indoor environment had little role to play in influencing the score of the performance tasks.

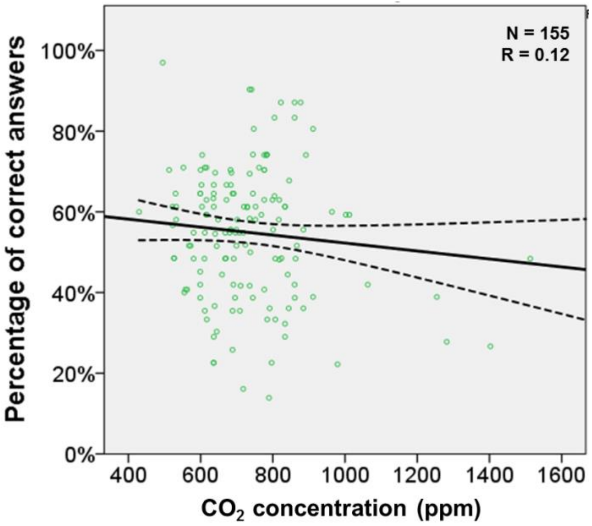


Figure 19. Scatter plot showing the relationship between proportion of correct answers in the proof-reading test and corresponding CO_2 concentration, with 95% confidence interval (dashed line).

Performance was also assessed in terms of time taken to complete the tasks. It took participants an average of 8.8, 9.0 and 2.4 minutes to complete the numeric test, the proof reading task, and the Stroop test respectively. The trendline in Figure 20 indicates that higher temperatures tend to lead to tests taking longer to complete, although again, correlations were very weak. It is worth noting that the times taken to complete the tests was measured from a start and end time rounded to the nearest minute, which, for such short time scales, gives a low degree of granularity in the data.

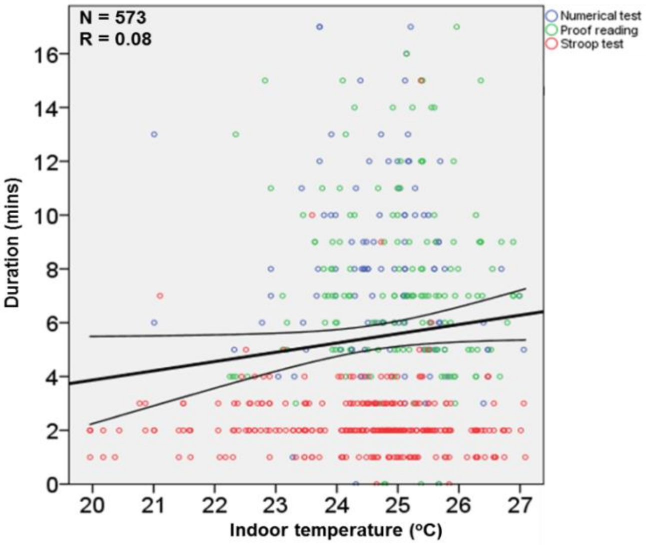


Figure 20. Scatter plot showing relationship between time taken to complete tasks and indoor temperature.

5. Discussion

In line with field studies of thermal comfort, mean indoor temperatures were found to strongly correlate with mean outdoor temperatures more in the non-heating season (May-July) than in the heating season (February-April). Although indoor temperatures have a wider range in the non-heating season (from 20°C to over 30°C) compared to the heating season (18-26°C), during the course of a typical working day, the increase in indoor temperature in the heating season is higher compared to the non-heating season (2.7°C compared to 1.7°C respectively). This is likely to be due to opening of windows in the non-heating season which helps in reducing diurnal temperature fluctuations. However there were constraints related to having window opening as a means of heat management (such as outdoor air pollution and outdoor noise), given the central London location of the case study.

Indoor RH is found to be lower in the heating season (typically in the mid-40's) when the heating serves to dry the air and the closed windows prevent outdoor humid air (typically around 80% in the heating season) entering the building. Conversely, CO_2 levels were higher in the heating season (higher peaks, higher diurnal ranges, higher averages) compared to the non-heating seasons. Reluctance to open windows in the heating season to vent CO_2 allows indoor CO_2 levels to increase throughout the working day.

The results from traverse and longitudinal surveys concur. The BUS survey indicated a negative correlation between temperature variability and perceived change in productivity, and a positive correlation between perceived overall comfort and perceived change in productivity. These findings were supported by the results of the longitudinal (online) surveys, which also identified a positive correlation between thermal comfort and perceived change in productivity. The online surveys found weak but significant correlations between indoor temperature and productivity (perceived increase in productivity corresponding to a lower mean temperature), and between indoor CO_2 concentration and productivity (perceived increase in productivity corresponding to a lower mean CO_2 concentration). Neutral responses for thermal sensation vote (comfortably cool/comfortable/ comfortably warm) covered a wide range of temperatures. This indicates there is no set temperature that is going to please everybody, which implies the role of adaptation. Likewise, a positive change in perceived productivity was recorded at a wide range of temperatures and CO_2 levels.

Interestingly, weak correlations were found between the outputs from the performance tasks and indoor environment. However, there was a negative (but weak) correlation found between proof-reading scores and CO_2 concentration (higher levels of CO_2 corresponding to lower scores) and a positive (weak) correlation found between proof-reading durations and indoor temperatures (higher temperatures corresponding to longer times taken to complete the tasks).

It is evident from the study that collecting empirical data of sufficient quality and quantity can be difficult when partnering with case study organisations. Data loggers can be set up and left to collect indoor environment data continuously with minimal interference to staff. However, measuring productivity is beset with challenges. Business output metrics, such as number of calls made or e-mails sent, proved to be very difficult to get access to despite being relevant to a study which has the potential to increase staff productivity. Likewise HR data, such as occupancy rates and absenteeism, were unavailable due to data protection and privacy issues. Self-reported productivity required occupants to take time to respond to surveys, while measured productivity required occupants to take even more time to respond to tasks. For empirical studies such as this, occupant engagement should be an integral part of research design, in order to ensure good response rates.

Establishing and maintaining good working relationships with the management and staff members is paramount. When staff members become disengaged or lose interest, response rates drop and the potential for disingenuous responses increases. Regular communication with participants, including some general feedback on their responses to date, can help keep their interest in the study although it requires resourcing in terms of time and manpower. Incentives for participants may help to improve response rates, but could also encourage 'straight-liners' and 'speeders' (those who respond with the same answer each time or too quickly to have given the questions any thought), leading to bad data. In short, secondary datasets (business output metrics and HR data) proved extremely difficult to access; primary datasets (surveys and tasks) proved difficult to gather.

It is also realised that optimising indoor environment to improve productivity is inherently more challenging than finding ways to worsen it. For instance, increasing indoor CO_2 levels above 2000ppm or setting indoor temperatures below 19^oC or above 28^oC, would likely lead to a decrease in productivity given the findings from longitudinal surveys, whereas finding the optimum threshold for indoor CO_2 or temperature to maximise productivity is much more challenging.

6. Conclusions

The study has provided interesting results through continuous physical monitoring and surveys of a case study working environment in central London, during the heating and non-heating periods. Despite the interesting findings, the study faced a number of challenges that are implicit in studies conducted in 'real world' settings (as opposed to studies conducted under tightly-controlled laboratory conditions). Isolating factors that can positively or negatively affect productivity is challenging. In reality, a wide range of factors, both scalable (such as indoor environment) and nominal (such as what someone had for breakfast or lunch) may influence productivity. Determining how much each factor plays a role in increasing or decreasing productivity is therefore challenging.

There are also ethical and data-protection issues that arise with collecting HR data such as occupancy and absenteeism. Data on business output metrics (used as proxy for productivity) were found difficult to obtain, even when anonymised. An organisation may, for many reasons, be reluctant to release these business output data to an external party.

Nevertheless, despite these challenges, this study has found empirical evidence that suggests indoor environment is related to workplace productivity. Therefore by managing the indoor environment effectively, there is potential to improve productivity, which is the next step in the WLP+ research project.

7. Acknowledgements

The authors would like to thank EPSRC (Grant ref: EP/N509000/1) and Innovate UK (Application number: 54815-413475) for funding the WLP+ research project under the *Building Whole-Life Performance* competition. The authors are grateful to LCMB (lead industry partner) and KINGS College (project partner) for their exceptional efforts with occupant engagement. The authors are also thankful to Jonida Murataj and Dr Adorkor Bruce-Konuah for their assistance in data collection.

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