Defining the link between indoor environment and workplace productivity in a modern UK office building

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Most studies on the link between indoor environments and productivity have been conducted in controlled, static conditions often unrepresentative of the real world. This paper uses a case-study-based, real-world approach to empirically investigate the link between indoor environment and workplace productivity in a mechanically-ventilated office environment in southern England. Evidence gathered during the baseline period was used to implement two interventions limiting peak temperature and CO_2 concentrations. Environmental parameters (temperature, relative humidity, CO_2) were monitored continuously. Transverse and longitudinal surveys recorded occupant perceptions of their working environment and self-reported productivity, while performance tasks provided proxy measures of worker performance in terms of cognitive ability, speed and accuracy.

Workplace productivity was perceived to decrease when occupants perceived thermal discomfort and stuffy air. Correlations with perceived changes in productivity were stronger for perceived rather than measured environmental conditions and for perceived air quality rather than either measured RH or CO_2 concentration. This implies that occupants' subjective feelings can impact their perceived productivity more than objective environmental conditions. Furthermore median task scores were 15% lower when conducted at CO_2 levels above 800ppm compared to below 800ppm. Insights from the study can help to optimise indoor office environments and improve workplace productivity.

Keywords: building performance, productivity, indoor environment, office, survey

1. Introduction

Workplace productivity has been defined as a measure of how well resources are used to achieve a goal (BCO 2017). It has become increasingly recognised as playing a significant role in the economic output of both individual companies and nations. In the

UK, research suggests that workplace productivity is as much as 16% lower than the G7 average (the G7 consisting of Canada, France, Germany, Italy, Japan, the UK and the USA, the group of countries with the largest and most advanced economies in the world) (ONS 2018) and that this deficit could be reduced by around 3% through improvements to the indoor environment (BCO 2017), which would be hugely significant in financial terms. When around 90% of an organisation's costs relate to its staff (Alker et al. 2014; UKGBC 2017), the importance of improving productivity becomes clear.

Negative impacts on productivity such as poor health and sickness cost UK employers upwards of £9 billion a year (ONS 2014), while costs associated with low productivity due to presenteeism (turning up for work when ill) could be even greater. Poor health outcomes including musculoskeletal complications (Coggon et al. 2013), cardiovascular disease (Smith et al. 2016), and sick building syndrome (Shahzad et al. 2016) have all been associated with spending prolonged periods of time in office environments. The health, wellbeing and productivity of employees could all be improved through improvements to office environments.

Certain indoor environmental quality (IEQ) parameters in office buildings have been shown to influence workers' productivity (Alker et al. 2014). There are currently, however, no clearly defined parameters to produce optimal indoor conditions in mechanically ventilated office environments. Intervention and office-based studies that have shown an increase in productivity from improved indoor environment have focussed on tightly controlled individual indoor environment elements which 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. Gathering and interpreting data collected in office environments has additional challenges, including isolating the effects of temperature from air quality; outside views from daylighting; and distracting noise versus beneficial background noise. Office design, layout and biophilia have also been shown to influence productivity and interaction with the indoor environment (Browning 2016).

This paper adopts a case study-based real-world approach to empirically investigate the link between indoor environment and workplace productivity using mixed methods (environmental monitoring, surveys and performance tasks) in a mechanically-ventilated office environment in southern England. A range of environmental parameters (indoor air temperature, RH and CO_2 levels alongside outdoor temperature and RH) were monitored continuously for nineteen months. A transverse Building Use Studies (BUS) survey (BUS 2019) was conducted in April 2017 to provide an overview of occupants' perception of their working environment. During the monitoring period, longitudinal online surveys recorded occupant perceptions of their working environment, thermal comfort and self-reported productivity, while performance tasks were designed to objectively measure productivity.

2. Evidence to date

The recommended temperature range for Category II mechanically ventilated office buildings is 22-25°C in summer and 21-23°C in winter (CIBSE 2015). These figures, based on research into the effects of temperature on health and comfort, imply that within these ranges there is no negative impact on occupant health and comfort. For naturally ventilated buildings, the indoor temperature is more strongly dependent on the outdoor temperature, whereas mechanically ventilated and air-conditioned buildings are designed to provide indoor conditions which are much more independent of outdoor conditions.

Studies on the relationship between indoor environment and occupant productivity, health and comfort have found negative factors such as high temperatures or high levels of CO_2 to be generally more obvious than positive factors (i.e. the optimum conditions to enable improvements in health and comfort or increases in productivity) (e.g. (Witterseh, Wyon, and Clausen 2004; Fang et al. 2004; Allen et al. 2015). Further studies have therefore sought to more fully understand these relationships. Summaries of selected studies investigating the influence of indoor environmental conditions on comfort and productivity are given in Table 1.

Table 1 Summary of selected, recent studies that investigated the links between IEQ parameters on workplace performance in mechanically ventilated offices and climate chambers.

Study	Study type and location	Procedure	Results
Al Horr et al. (2016)	Review of over 300 papers focussed on indoor environment, occupant comfort, productivity in green buildings	Reviewed existing literature to understand the relationship between indoor environmental and occupant productivity	IEQ factors influencing occupant productivity in offices covered 8 interacting categories: IAQ and ventilation; thermal comfort; lighting and daylighting; noise and acoustics; office layout; biophilia and views; look and feel; location and amenities
Allen et al (2015)	Intervention study, climate chamber, USA (n=24)	Participants exposed to different levels of CO_2, VOC and ventilation	Increasing CO_2 by 400 ppm and VOC by 0.5 mg/m^3 decreased cognitive function by 13-21%. Increasing ventilation rates improved cognitive function by 18%
Fang et al (2004)	Intervention study, mechanically ventilated office,	Participants exposed to different combinations of	Increase in SBS symptoms and difficulty in thinking

	Denmark (n=30)	temperature and RH (20°C / 40%; 23°C / 50%; 26°C / 60%) and ventilation rates (3.5 and 10 l/s/p)	at higher temperature. Performance not significantly affected by temperature or humidity
Federspiel et al (2004)	Observation study, mechanically ventilated call centre, USA	Average call handling time, temperature, RH and CO_2 recorded for almost three months	Call handling times increased as difference in indoor and outdoor CO_2 increased above 75ppm. Temperatures between 21.7 and 24.5°C had no effect on performance
Gupta et al (2016)	Meta-analysis of low-energy office buildings, UK (n=50)	Analysis of occupant surveys conducted in a variety of non-domestic workspaces	Perceived productivity increased due to perceived environmental conditions in over half of workspaces.
Kajtar et al (2003)	Intervention study, climate chamber, Hungary (n=10)	Participants exposed to different CO_2 levels (600, 1500, 3000 and 4000 ppm)	Significantly more misspelled words as CO_2 levels increased from 600 ppm to 3000 and 4000 ppm
Lan et al (2011)	Intervention study, mechanically ventilated office, Denmark (n=12)	Participants completed tasks at two different thermal conditions (22 and 30°C)	Performance in 8 out of 9 tasks decreased in high temperature. At 30°C in text typing, more characters were typed but more mistakes were made
Park and Yoon (2011)	Intervention study, climate chamber, South Korea (n=24)	Participants exposed to three different ventilation rates (5, 10, 20 l/s/p)	Increasing ventilation rate from 5 to 20 l/s/p improved calculation accuracy by 5% and typing and memorisation accuracy by 2.5%
Satish et al (2012)	Intervention study, climate chamber, USA (n=22)	Participants exposed to different CO_2 levels (600, 1000 and 2500 ppm)	Decision making performance decreased as CO_2 levels increased from 600 ppm to

			1000 and 2500 ppm
Seppänen et al. (2006)	Review of studies (11 field-based, 9 climate-chamber based)	Meta-analysis conducted on published studies which investigated the influence of temperature on performance	Temperature range for maximum performance found to be 21-24°C with a 2% decrease in performance per 1°C increase in temperature above 25°C
Tenabe et al. (2015)	Intervention study, climate chamber, Japan (n=11)	Participants exposed to 5 scenarios combining temperature (25.5 and 28.5°C), clothing (with and without suits), and cooling items (fan, air-con' shirt, mesh chair)	Actual air temperature correlated poorly with self-estimated performance, whereas perceived thermal satisfaction correlated well with self-estimated performance
Tham and Willem (2005)	Intervention study, mechanically ventilated call centre, Singapore (n=56)	Call times measured at different temperatures (22.5 and 24.5°C) and ventilation rates (5 and 10 l/s/p)	Increasing ventilation rate to 10 l/s/p reduced call talk time by 11%. Reducing temperature to 22.5°C increased call talk time by 15.5% (at 10 l/s/p)
Vimalanathan and Babu (2014)	Intervention study, climate chamber, India (n=10)	Participants exposed to different thermal conditions (17, 21 and 28°C) and light conditions (500, 700 and 1000 lux)	Temperature and light accounted for 39% and 20% variation in performance respectively. Optimum conditions (21°C and 1000 lux) improved worker productivity
Wargocki et al (1999)	Intervention study, mechanically ventilated office, Denmark (n=30)	Participants exposed to three different ventilation rates (3, 10, 30 l/s/p)	Overall performance increased by 1.7% for every two-fold increase in ventilation rate from 3-30 l/s/p
Witterseh et al (2004)	Intervention study, mechanically ventilated office, Denmark (n=30)	Participants completed tasks whilst exposed to 3 air temperatures (22°C, 26°C and	3% decrease in performance in calculation tasks at higher noise level. 56% more mistakes

		30°C) and 2 noise levels (35dBA and 55dBA)	in task at highest temperature

Indoor temperature was found to significantly influence occupant productivity in several studies (Witterseh, Wyon, and Clausen 2004; Lan et al. 2011; Tham and Willem 2005; Seppanen, Fisk, and Lei 2006). Climate chamber studies have also identified temperature as accounting for as much as 40% of the variation in task performance, with both high temperatures (28°C) and low temperatures (17°C) showing a negative correlation with performance (Vimalanathan and Babu 2014). Interestingly, another climate chamber study found only a poor correlation between measured air temperature and perceived performance, but a much stronger correlation between thermal comfort and perceived performance (Tanabe, Haneda, and Nishihara 2015). Several studies (Lan et al. 2011; Allen et al. 2015) found a discrepancy between the temperature ranges for optimal thermal comfort and optimum productivity, the temperature range identified as thermally comfortable being different to the range that produced the best productivity. CO_2 concentration (either measured directly in parts/million or indirectly as ventilation rates – litres/second/person) has also featured in several studies investigating occupant performance. Studies found that higher ventilation rates/lower CO_2 concentrations) correlated with a more productive workforce (Tham and Willem 2005; Wargocki et al. 1999; Park and Yoon 2011; Allen et al. 2015; Satish et al. 2012; Kajtar, Herczeg, and Lang 2003; Federspiel et al. 2004).

Meta-analysis of published studies investigating the links between indoor environment and occupant productivity revealed eight IEQ factors that influenced occupant productivity in an office environment (Al Horr et al. 2016). Alongside measurable parameters (indoor air quality and ventilation; thermal comfort; lighting and daylighting; noise and acoustics), were more subjective parameters (office layout;

biophilia and views; look and feel; location and amenities). There was significant interaction and crossover between these factors (e.g. levels of daylighting interacting with thermal comfort; lower temperatures leading to improved perception of air quality).

Meta-study of Building User Studies (BUS) surveys of 43 low-energy non-domestic buildings (1,170 respondents) in the UK has revealed that more than half of the buildings reported an increase in perceived productivity due to the environmental conditions perceived by the occupants (Gupta, Cudmore, and Bruce-Konuah 2016). The BUS methodology survey asks respondents questions about their experience of their workplace (BUS methodology, 2019). Statistical analysis of the BUS survey data from the sample of 1.1170 responses covering 43 buildings was undertaken. Particular focus was given to identifying which independent variables had the most significant links to perceived change in productivity (defined in the survey by the question, "Please estimate how you think your productivity at work is decreased or increased by the environmental conditions in the building", with responses on a scale from "-40% or more" to "+40% or more" in 10% increments).

It was found that several independent variables had statistically significant connections (correlations and covariance) with the occupants' perceived change in productivity (Table 2). The strongest correlations with perceived change in productivity came from "*Comfort*" ("All things considered, how do you rate the overall comfort of the building environment?" on a scale from 1 (unsatisfactory) to 7 (satisfactory), Spearman R = 0.52), "*Health*" ("Do you feel less or more healthy when you are in the building?" on a scale from 1 (less healthy) to 7 (more healthy), Spearman R = 0.44) and "*Conditions in winter*" ("How would you describe typical working conditions in your normal work area in winter?" on a scale from 1 (unsatisfactory overall) to 7 (satisfactory overall), Spearman R = 0.42). How well the buildings' facilities met the needs of the workers, lighting and control of heating all showed weaker but still statistically significant correlations with perceived change in productivity. Interestingly occupants who said that they had changed their behaviour because of conditions in the building were found to be statistically more likely to rate changes to their productivity more negatively.

Table 2 Spearman correlations between BUS independent variables and perceived change in productivity (N=1170).

Variable	Spearman's Rho correlation with perceived change in productivity (statistically significant at the 0.05 level)
Comfort	0.52
Health	0.44
Conditions in winter (overall)	0.42
Facilities	0.40
Lighting (natural)	0.24
Control (heating)	0.22

It is worth noting that although correlations and covariance do not necessarily equate to causation, findings from this meta-study provides useful insights into the potential relationship between perceived indoor environmental conditions and perceived change in productivity, something that will investigated further in this study. Such subjective data will be cross-related with objective data on indoor environment and worker performance to empirically investigate the link between perceived indoor environment and perceived productivity, as well as measured indoor environment and worker performance in terms of cognitive capability, speed and accuracy.

3. Methodology and case study

The methodology adopted in the study had a three-pronged approach:

- *Physical monitoring* of indoor and outdoor environment using data loggers, recording temperature, RH and CO_2 concentration at five-minute intervals from March 2017 to September 2018;

- *Occupant surveys* (transverse and longitudinal) as a measure of perceived productivity;

- *Performance tasks* (productivity tests) as a proxy measure of worker performance in terms of their cognitive capability, speed and accuracy.

Physical monitoring was implemented using data loggers located throughout the case study workspaces (Table 3). The workspaces were divided into 20 zones, each zone consisting of between six and sixteen workstations and approximately 40 to 90 square metres, with each one monitored. This provided granularity in the data and allowed occupant responses to be cross-related to concurrent indoor environmental conditions. Within the case study workspace, individuals may have had differing job descriptions, but all fell under the umbrella of computer/desk-based office work. Throughout the study, response rates for the surveys and tasks varied from one zone to the next. As responses were entirely voluntary, it was not possible to control this – respondents were a self-selecting group. However, repeating the surveys and tasks over many rounds helped to alleviate any potential bias in the responses.

Table 3 Specifications for the installed data loggers.

Data logger	Measure	Specifications
Yanzi Comfort by Spika 	*Temperature*	Range: -20°C to +60°C Accuracy: ±1°C
	RH	Range: 0% to 100%RH Accuracy: ±5% RH
	CO_2 concentration	Range: 400ppm to 5000ppm Accuracy: ±(50ppm +5% reading)
Yanzi Motion+ by Spika	Temperature	Range: -20°C to +60°C Accuracy: ±0.3°C (+5°C to +50°C)

	RH	Range: 0% to 100%RH Accuracy: ±5% RH
Hobo UX100-003  Dimensions: 37x85x15mm	Temperature	Range: -20°C to +70°C Accuracy: ±0.21°C (from 0°C to 50°C) Resolution: 0.024°C at 25°C
	RH	Range: 15% to 95% Accuracy: ±3.5% from 25% to 85% Resolution: 0.07% at 25%
HOBO U12-012  Dimensions: 58x74x22mm	Temperature	Range: -20°C - +70°C Accuracy: ±0.35°C from 0°C to 50°C Resolution: 0.03°C at 25°C
	RH	Range: 5% - 95% Accuracy: ±2.5% from 10% to 90% Resolution: 0.03%
Tinytag CO_2-TGE-0011  Dimensions: 85x100x26mm	CO_2 concentration	Range: 0 – 5000ppm Accuracy: < ±(50ppm or 3% of measured value) Resolution: 0.1ppm
HOBO MX2301  Dimensions: 102x38mm	Outdoor temperature	Range: -40°C to +70°C Accuracy: ±0.25°C from -40°C to 0°C, ±0.2°C from 0°C to 70°C Resolution: 0.04°C
	Outdoor RH	Range: 0% to 100% Accuracy: ±2.5% from 10% to 90% Resolution: 0.05%

The surveys and performance tasks were implemented over a baseline period from March to July 2017, with results used to inform the intervention designs that were implemented over two four-week periods, the first during October/November 2017 and the second during May/June 2018. Figure 1 outlines the methodological approach adopted in the project.

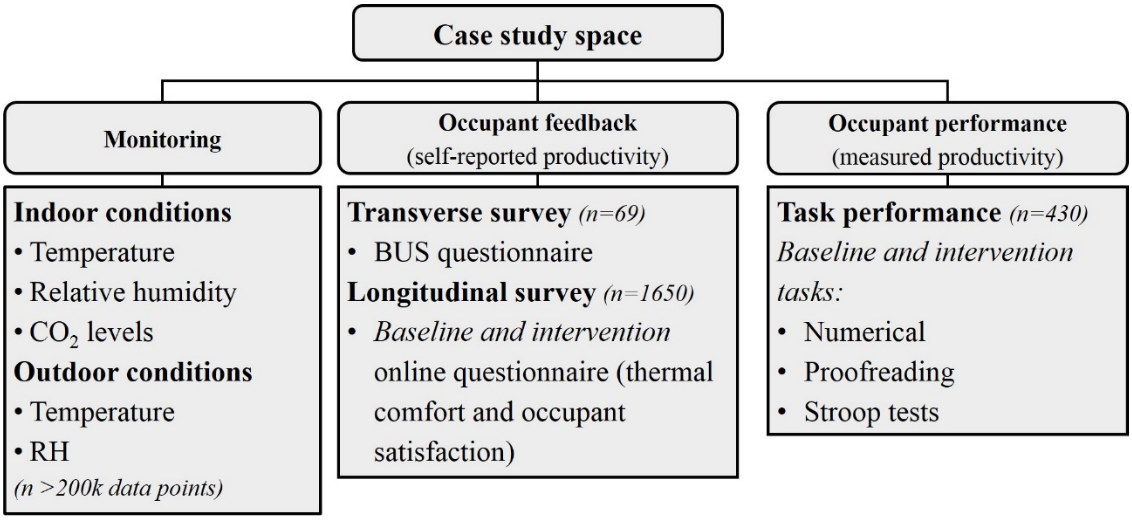


Figure 1 Methodology

The performance tasks were chosen to emulate the typical tasks occupants would undertake:

- 'Numerical' tasks consisted of 25 mentally-solvable arithmetic questions;
- 'Proofreading' tasks consisted of 4 short paragraphs of text in which respondents had to identify spelling errors;
- 'Stroop' test: an interference test where respondents had to differentiate between the colour and text of 50 words.

Screenshot examples of each of these test types are given in Figure 2. Throughout this study, the proofreading tests proved to be the most challenging of the three tests. This provided a broader spread of test scores and test durations than either the numerical or Stroop tests, but was consequently the least popular of the three tests.

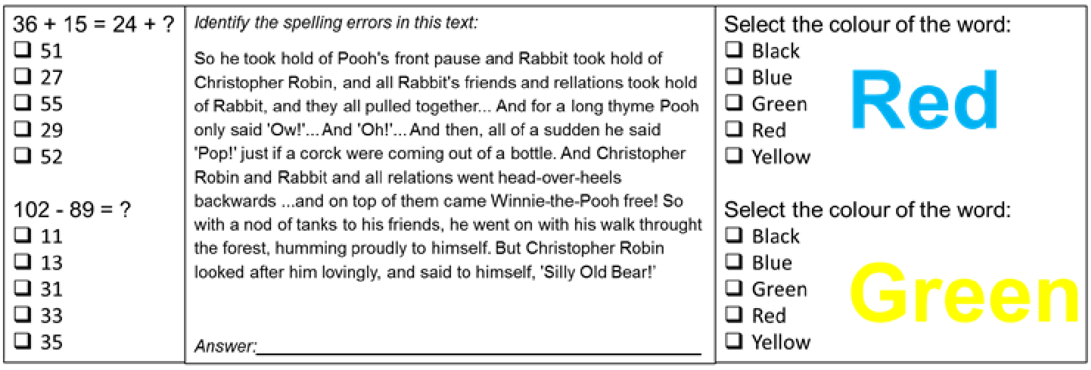
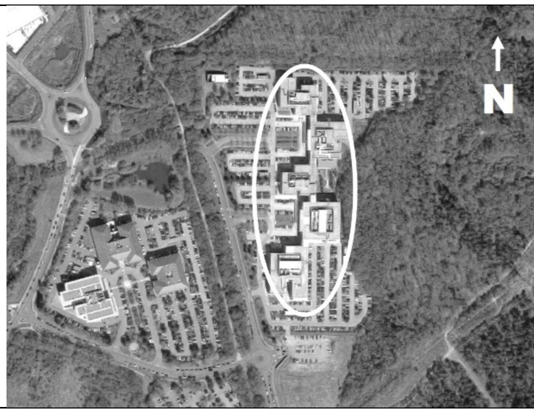


Figure 2 Screenshot samples of the numerical test (left), proofreading test (centre) and Stroop test (right).

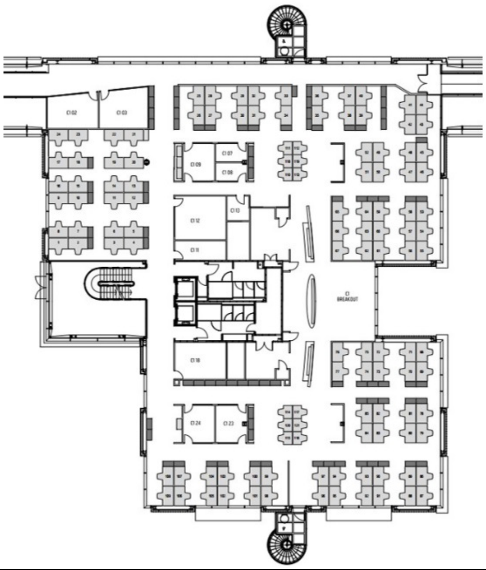
Case study building

The case study building, located in a business park in southern England, is a modern office building typical of those found in the UK (Korolija et al. 2013) and which will become the normal archetype within the next decade. Images, floorplans and descriptive characteristics of the building are provided in Table 4. Facilities are managed by an on-site external facilities management company using a BMS system, with mechanical ventilation and non-openable windows: Occupants are therefore not able to control their working environment directly but can contact the facilities management team to request changes. Two open-plan administrative office areas were selected for the study, approximately similar in size and occupancy. The gender mix of occupants in this workspace (approximately 57% male, 43% female), and the distribution of age groupings (approximately 10% under 30, 90% 30 and over based on the BUS questionnaire responses) was representative of a typical working office. Although there were 162 workstations within the case study offices, the mailing list for surveys and tasks consisted of 220 occupants, and the occupancy rate within the case study offices was approximately 80% during the monitored period.

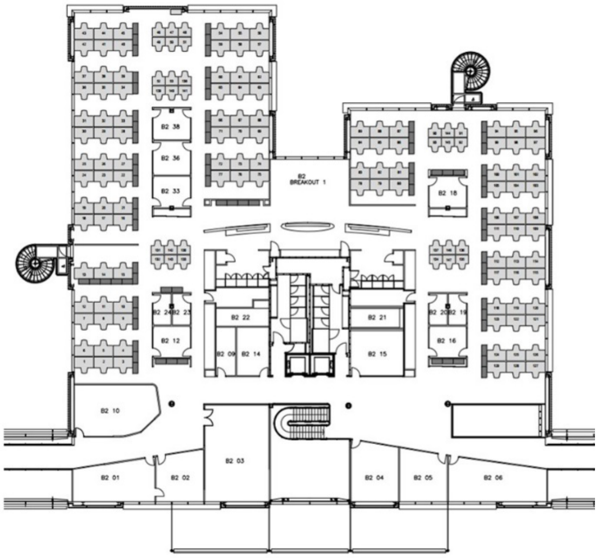
Table 4 External view of building (top left), satellite image of building (top right), floorplan of first and second floor case study areas (middle), descriptive characteristics of the case study building (bottom left) and of the case study offices (bottom right).



1st floor office area



2nd floor office area



Characteristics of case study building	Characteristics of case study offices
Location: Business park adjacent to woodland, southern England **Type of facility:** Open-plan office **Date of construction:** 2004-6 **Ownership:** Owner occupied **Facility management:** Subcontractor **Energy systems:** Mains gas and grid electricity **Heating and cooling:** Mechanically ventilated and heated throughout. **EPC Energy rating:** C and D **Operating hours (hours space is controlled for heating/cooling):** Weekdays, 07:00 –	**Floor area:** 1,900 m^2 approx. **No. of workstations:** 162**Main tasks:** Administration **Working arrangement:** Allocated desks and hot-desking. **Local control over windows:** No **IT equipment:** Desktops, laptops, telephones **Meeting rooms:** 24 **Working hours:** 08:30 – 18:30

18:00	

4. Indoor environment: temperature, relative humidity and CO_2 concentration

Physical monitoring showed that during occupied hours (08:30 – 18:30) indoor temperatures remained within a narrow band throughout the whole nineteen months of monitoring. During the heating seasons (March-April 2017 and October 2017-April 2018) indoor temperatures were below the recommended 21°C for less than 0.3% of occupied hours. Although indoor temperatures exceeded the recommended 23°C for over 81% of occupied hours, they only exceeded 24°C and 25°C for 24% and 1% of occupied hours respectively. During the non-heating seasons (May-September 2017 and May-September 2018) indoor temperatures were below the recommended 22°C for less than 0.4% of occupied hours. Indoor temperatures exceeded the recommended 24°C for 51% of occupied hours and 25°C for 7% of occupied hours.

The boxplot of indoor temperatures by month, with the monthly average outdoor temperatures (recorded on site using an outdoor logger) during working hours also shown is presented in Figure 3. The building's heating and cooling system was able to keep the indoor temperatures within a fairly narrow band.

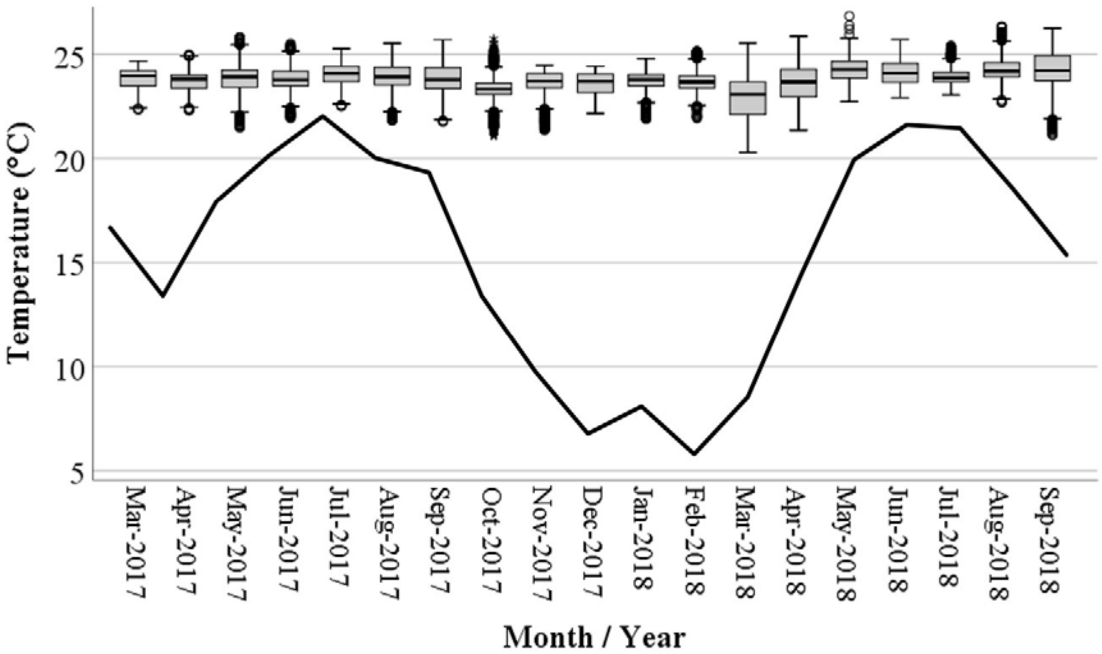


Figure 3 Boxplots of temperatures during working hours in the case-study working areas, with line showing monthly average outdoor temperatures during working hours.

The distinction between seasons is more apparent in Figure 4 where, although peak indoor temperatures were about the same, mean temperatures during working hours were around 0.5°C higher in the non-heating season.

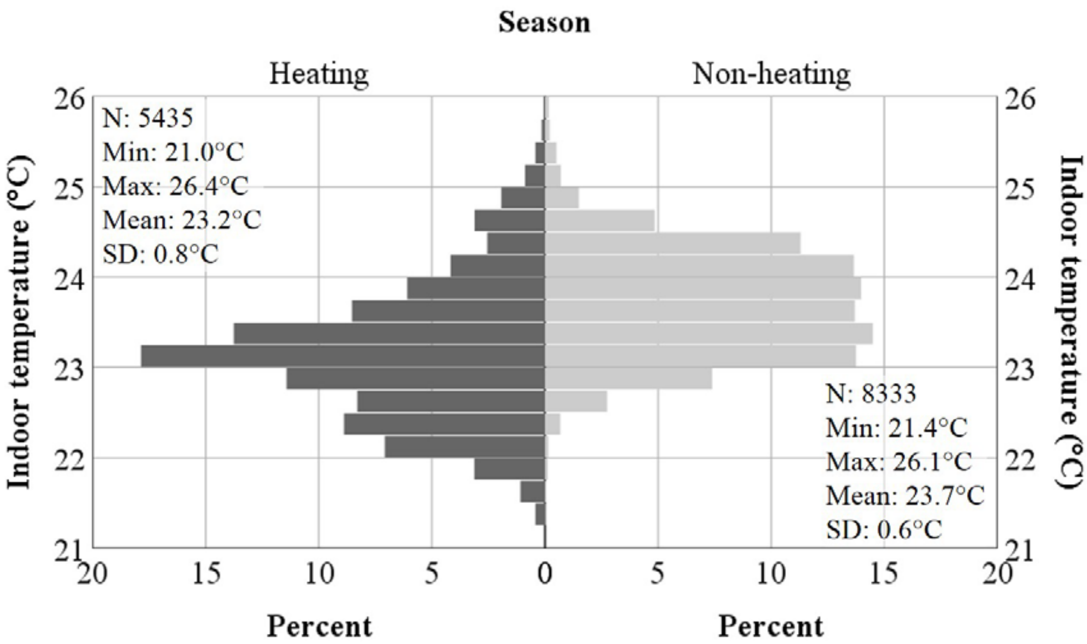


Figure 4 Population pyramid showing distribution of temperatures during working hours in the heating and non-heating seasons, with descriptive statistics also given.

The diurnal stability of the indoor temperatures is apparent in Figure 5, which shows the indoor and outdoor temperature profiles over a sample Monday-Friday week in the heating season (5th – 9th February 2018) and non-heating season (24th – 28th July 2017).

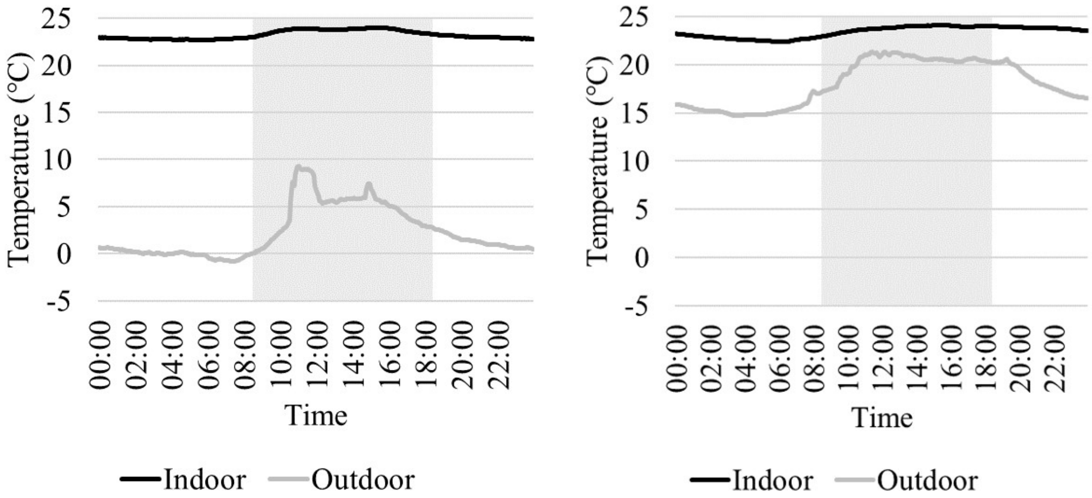


Figure 5 Indoor and outdoor temperature profiles averaged over 5 working days: 5th -9th Feb 2018 (left); 24th-28th Jul 2017 (right). Shaded area represents occupied working hours.

In contrast to indoor temperature, indoor RH levels showed much more variation over the course of the monitored period. Figure 6 shows the boxplot of indoor RH during working hours by month, with the monthly average outdoor RH during working hours also shown. The recommended RH range in offices is 40-70% (CIBSE 2015). During the heating seasons (March-April 2017 and October 2017-April 2018), indoor RH was below 40% for 66% of occupied hours, and below 30% for 25% of occupied hours.

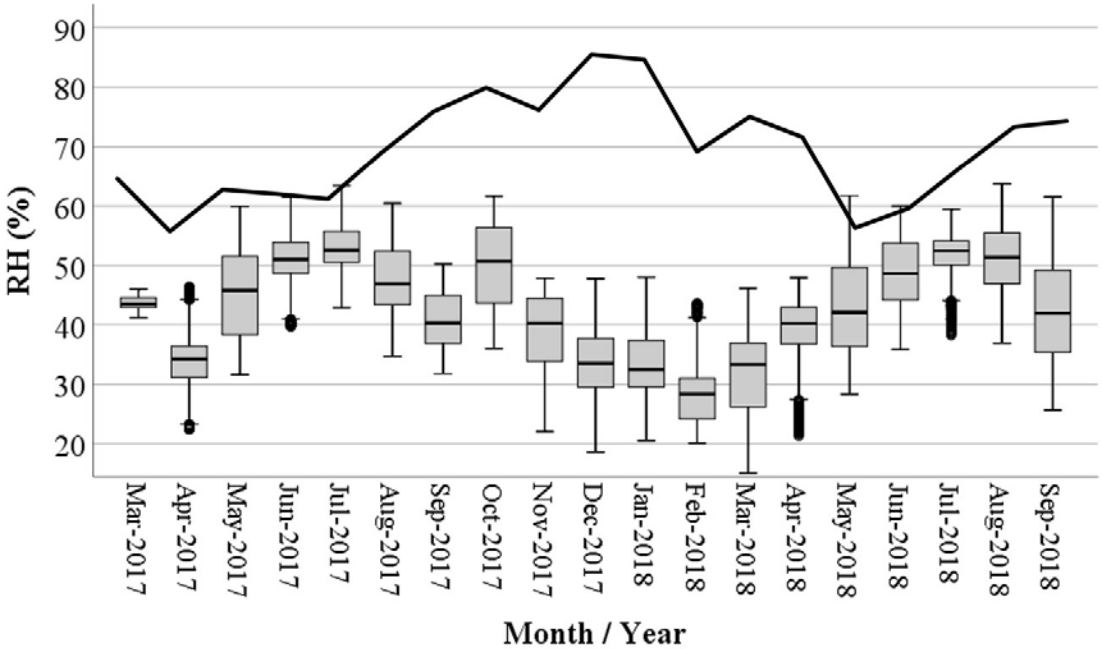


Figure 6 Boxplots of RH during working hours in the case-study working areas, with line showing monthly average outdoor RH during working hours.

In contrast, during the non-heating seasons (May-September 2017 and May-September 2018), when outdoor RH is generally lower than during the heating season, indoor RH was below 40% for only 19% of occupied hours and below 30% for less than 1% of occupied hours (Figure 7).

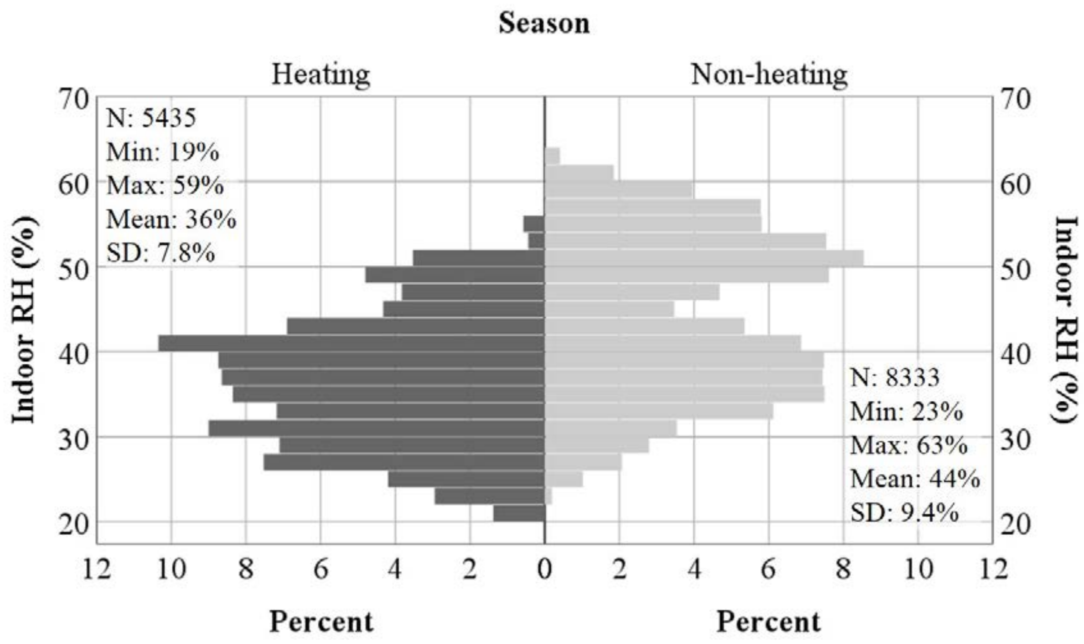


Figure 7 Population pyramid showing distribution of RH during working hours in the heating and non-heating seasons, with descriptive statistics also given.

The diurnal stability of indoor RH levels is apparent in Figure 8, which shows the indoor and outdoor temperature profiles over a sample Monday-Friday week in the heating season (5th – 9th February 2018) and non-heating season (24th – 28th July 2017).

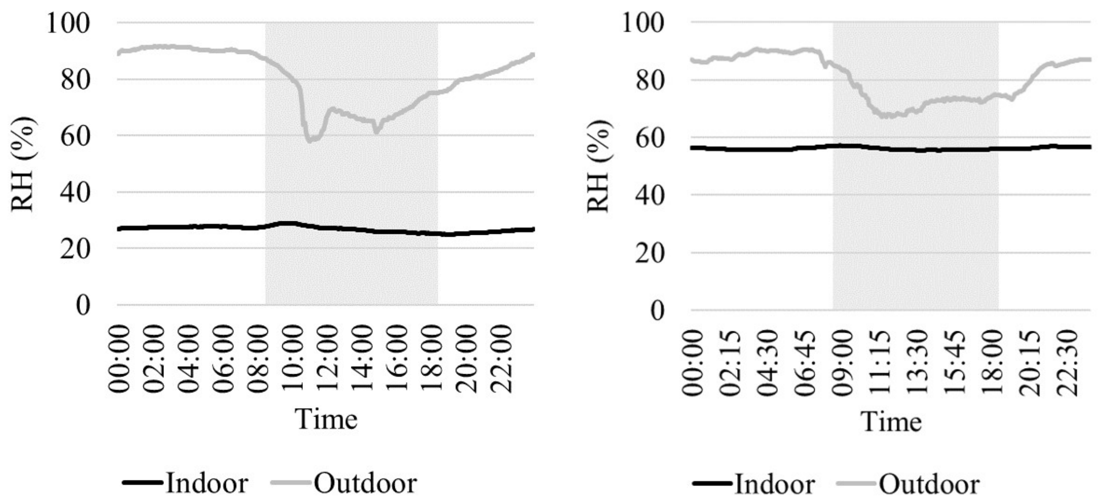


Figure 8 Indoor and outdoor RH profiles averaged over 5 working days: 5th -9th Feb 2018 (left); 24th-28th Jul 2017 (right). Shaded area represents occupied working hours.

Although the range of outdoor temperatures was much greater than indoor temperatures, both daily and seasonally, the correlation between the two was moderately strong (Pearson correlations p = 0.50 and 0.48 during the heating and non-heating seasons respectively, both significant at the 0.01 level) (Figure 9). The correlation between outdoor and indoor RH was very weak during the heating season (Pearson correlation p = 0.10) but moderate during the non-heating season (p = 0.54), both statistically significant at the 0.01 level.

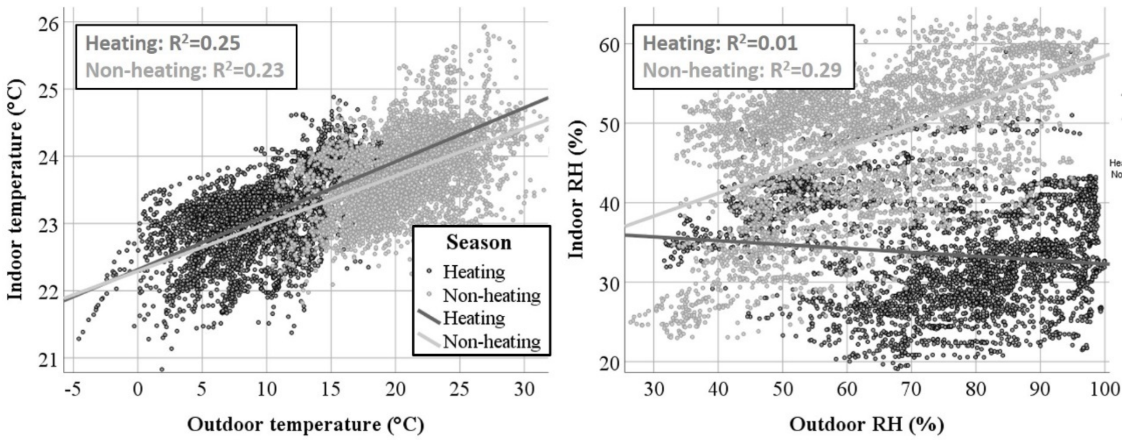


Figure 9 Scatterplots of concurrent outdoor and indoor temperatures (left) and outdoor and indoor RH (right), showing linear trend lines for both the heating and non-heating seasons.

CO_2 concentration varied throughout the year but remained below 1000 ppm (recommended limit in UK offices – CIBSE, 2015) for 92% and 99% of occupied hours during the heating and non-heating seasons respectively (Figure 10).

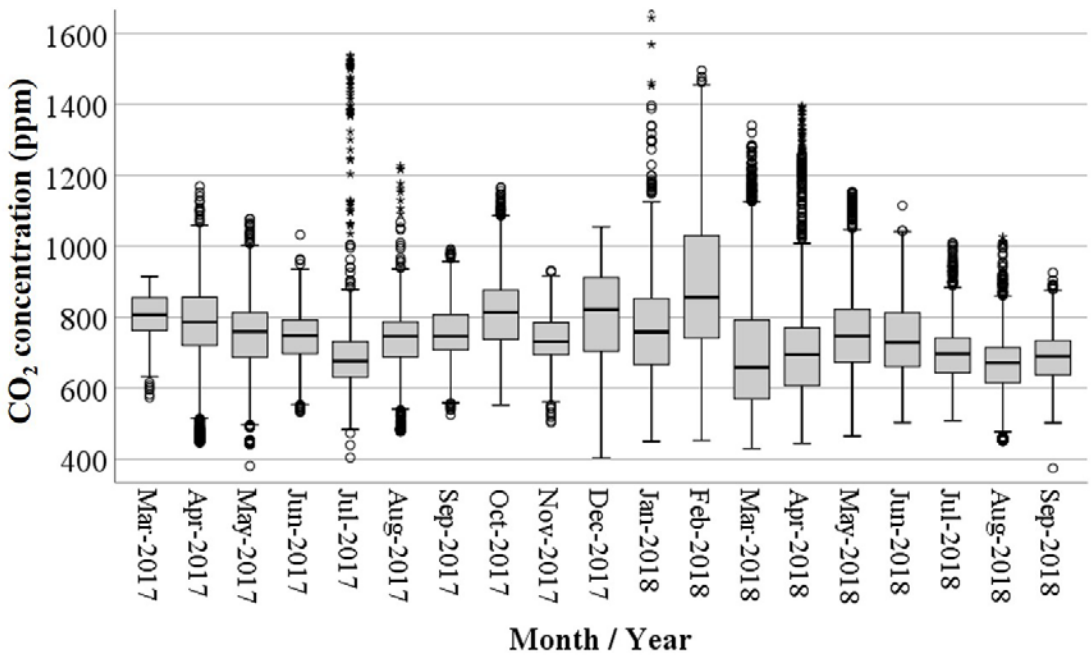


Figure 10 Boxplots of CO_2 concentration during working hours in the case-study working areas.

Spikes in CO_2 concentration were rare and brief. Although peak CO_2 concentrations were greater during the heating season, the mean CO_2 concentration was more than 60 ppm greater during the non-heating season (Figure 11).

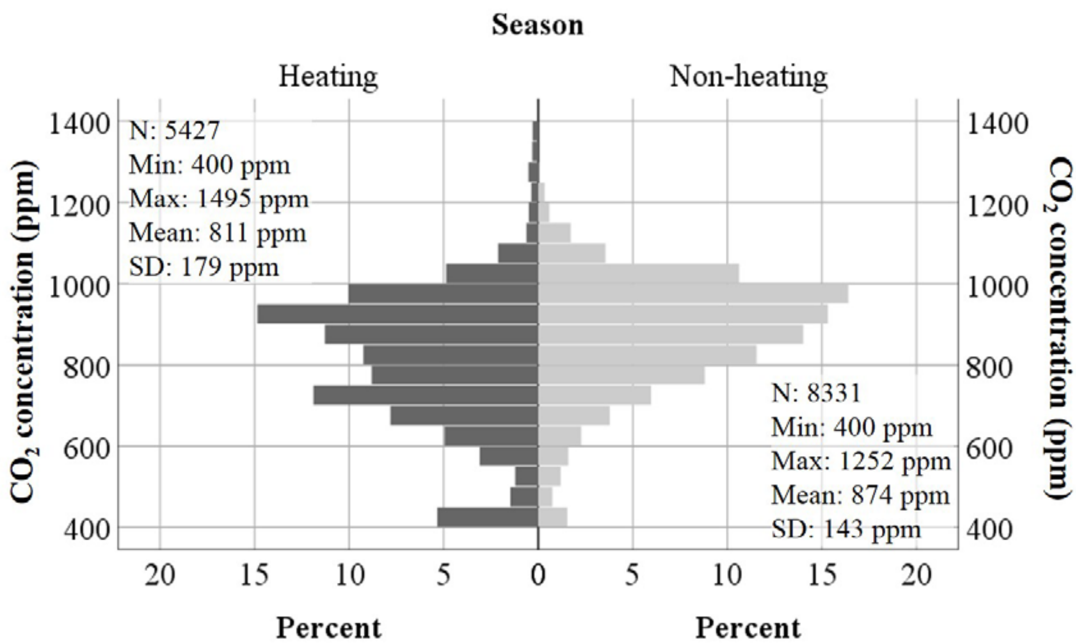


Figure 11 Population pyramid showing distribution of CO_2 concentrations during working hours in the heating and non-heating seasons, with descriptive statistics also given.

In contrast to the typical diurnal temperature and RH profiles, CO_2 levels varied significantly (Figure 12). Over the course of a typical weekday, CO_2 concentrations tended to rise steeply at the start of the working day, increasing from ambient levels in the 400-500 ppm range until late morning (11:00 – 12:00) when they would plateau and remain stable until the end of the working day when they would decrease back to ambient levels in the evening. The spike in CO_2 concentration seen in the heating season profile (Figure 12, left) was an anomaly caused by particularly high readings on the morning of 5th February 2018.

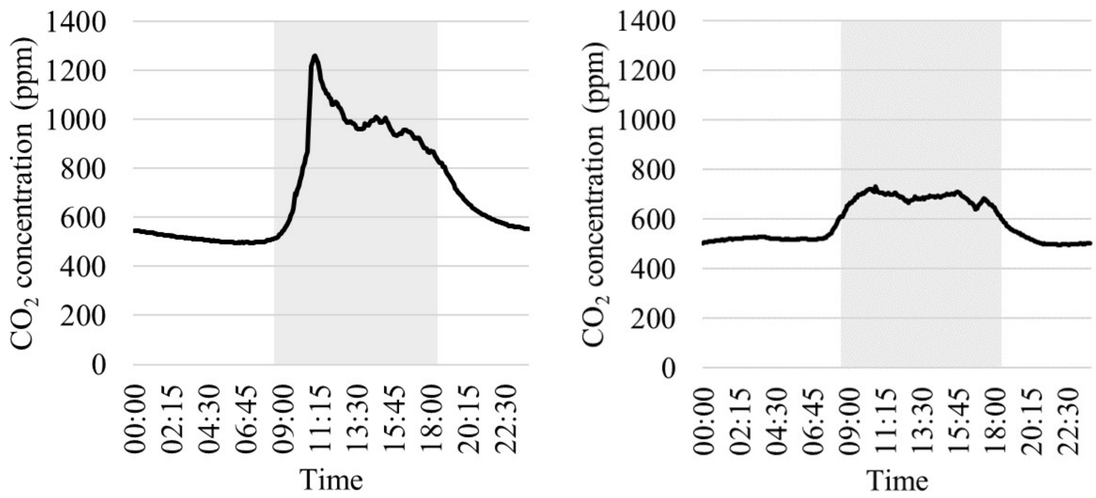


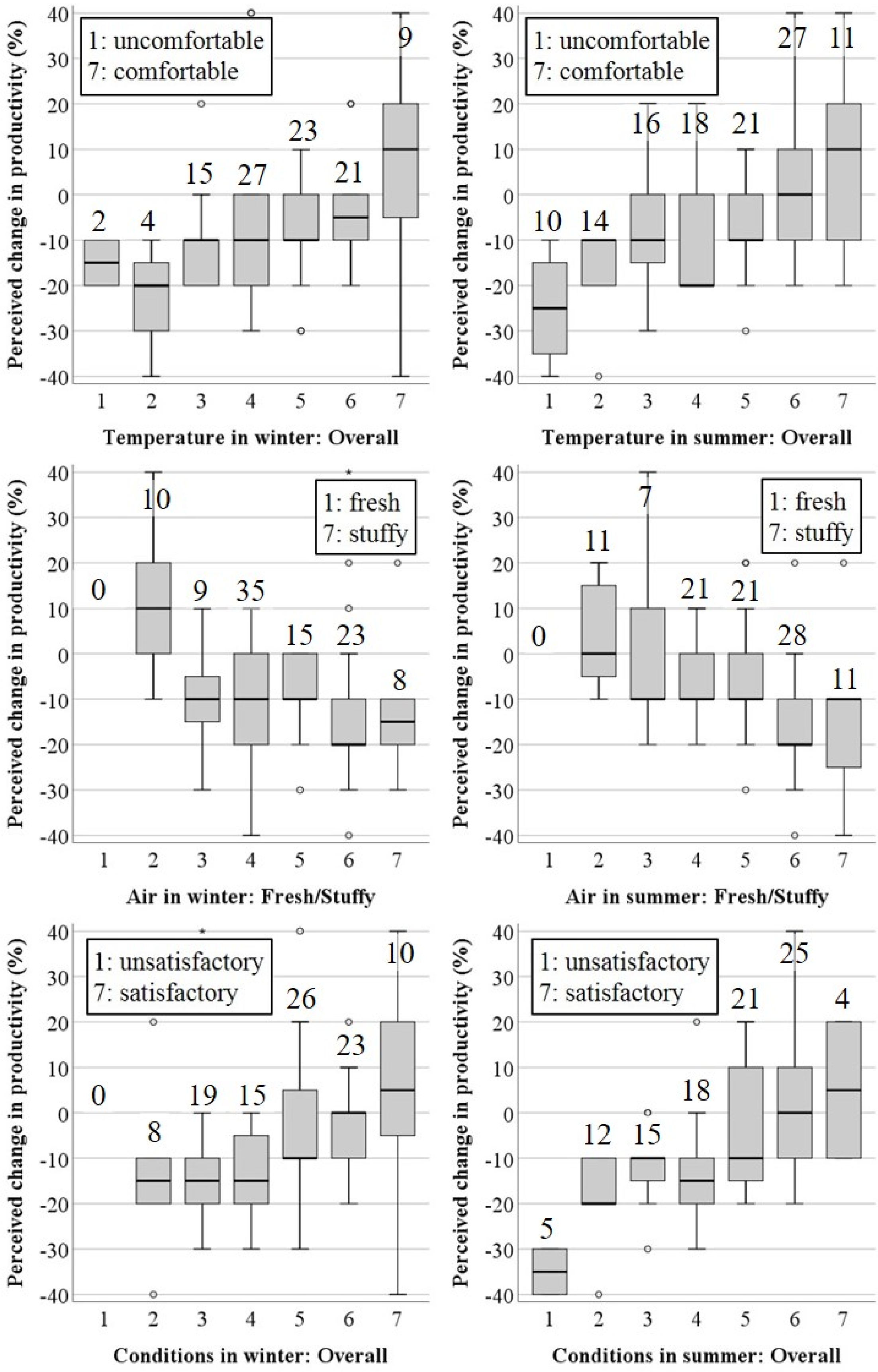
Figure 12 CO_2 concentration profiles averaged over 5 working days: 5th -9th Feb 2018 (left); 24th-28th Jul 2017 (right). Shaded area represents occupied working hours.

5. Baseline period

Perceived productivity and indoor environment

The BUS survey (n: 69) provided a transverse view of occupant perception of their working environment during summer and winter and self-reported change in productivity. Paper copies of the survey were handed out to all occupants of the case study working areas between 11:00 and 12:00 and collected between 16:00 and 17:00 the same day. The response rate was approximately 47%. Respondents were asked questions relating to their perception of the building in terms of space, comfort and amenities, their perception of temperatures and air in the summer and winter, and their perception of how the building affects their health and productivity. Specifically, occupants were asked, ‘Please estimate how you think your productivity at work is decreased or increased by the environmental conditions in the building?’, with responses on a scale from ‘-40% or less’ to ‘+40% or more’ in 10% increments. Overall, occupants estimated that their productivity *decreased* by a median average of

10% due to the indoor environmental conditions (mean = 6.1% decrease, mode = 10% decrease). Interestingly when occupants perceived the environment to be unfavourable (e.g. thermally uncomfortable, stuffy air or unsatisfactory overall), their perceived productivity decreased (Figure 13). Notably, other indoor environmental parameters (such as whether the temperature was stable or varied, whether the air was still or draughty or whether the air was dry or humid) showed no statistically significant relationship to occupants' perception of their change in productivity.



1: uncomfortable
7: comfortable
Perceived change in productivity (%)
2 4 15 27 23 21 9
Temperature in winter: Overall
1: uncomfortable
7: comfortable
Perceived change in productivity (%)
10 14 16 18 21 27 11
Temperature in summer: Overall
1: fresh
7: stuffy
Perceived change in productivity (%)
0 10 9 35 15 23 8
Air in winter: Fresh/Stuffy
1: fresh
7: stuffy
Perceived change in productivity (%)
0 11 7 21 21 28 11
Air in summer: Fresh/Stuffy
1: unsatisfactory
7: satisfactory
Perceived change in productivity (%)
0 8 19 15 26 23 10
Conditions in winter: Overall
1: unsatisfactory
7: satisfactory
Perceived change in productivity (%)
5 12 15 18 21 25 4
Conditions in summer: Overall

Figure 13 Boxplots of selected BUS questionnaire responses plotted against perceived change in productivity (with distribution of responses shown by percentage).

The longitudinal survey was conducted from 11 to 24 May 2017 and from 11 to 17 July 2017, three times a day for fifteen days in total. A total of 950 responses were received, with approximately 100 of the 160 or so individuals participating in at least one survey. The mean number of responses from those who did respond was 6.6, with a maximum of 37 responses from one individual. The respondents were a self-selecting group as this allowed the maximum potential responses with the minimum potential disruption to their normal workload: respondents were able to respond whenever they wanted within a 2-3 hour window, but were under no obligation to do so as it was important at this stage and all stages of the project to keep the occupants 'on side'. A link to the questionnaire was sent via e-mail to the occupants three times a day (mid-morning, early afternoon and late afternoon). The responses were time stamped and respondents also indicated their location so concurrent indoor environmental measures could be identified. Respondents were asked to indicate their perceived thermal comfort (on a 7-point scale from 'much too cool' to 'much too warm'), their thermal preference (on a 5-point scale from ('much cooler' to 'much warmer'), perceived air quality (on a 7-point scale from 'fresh' to 'stuffy') and overall comfort (on a 7-point scale from 'uncomfortable' to 'comfortable'). The responses to each of these questions were close to normally distributed, with air quality skewed slightly toward stuffy rather than fresh and overall comfort skewed slightly towards comfortable rather than uncomfortable. Occupants were also asked about their productivity ('At present, please estimate how you think your productivity has decreased or increase by the environmental conditions in the building'). Responses were on a scale from '-20% or less' to '+20% or more' in 5% increments.

Plotting the occupants' responses to their perceptions of the environment against their perceived changes in productivity showed significant interrelationships (Figure 14). Around 73% of responses were in the thermally comfortable middle of the scale ('comfortably cool', 'comfortable…' and 'comfortably warm'), where occupants perceived their productivity to be neutral. When occupants felt cool (6% of responses) or warm (21% of responses), they perceived their productivity to be decreased (more so at the warm end of the scale than at the cool end). Notably, occupants perceived their productivity to be more positively affected when they were comfortably cool than neutrally comfortable or comfortably warm. (Within this and subsequent boxplots, where there is a line rather than a box, this indicates that the upper quartile, median and lower quartiles were all the same).

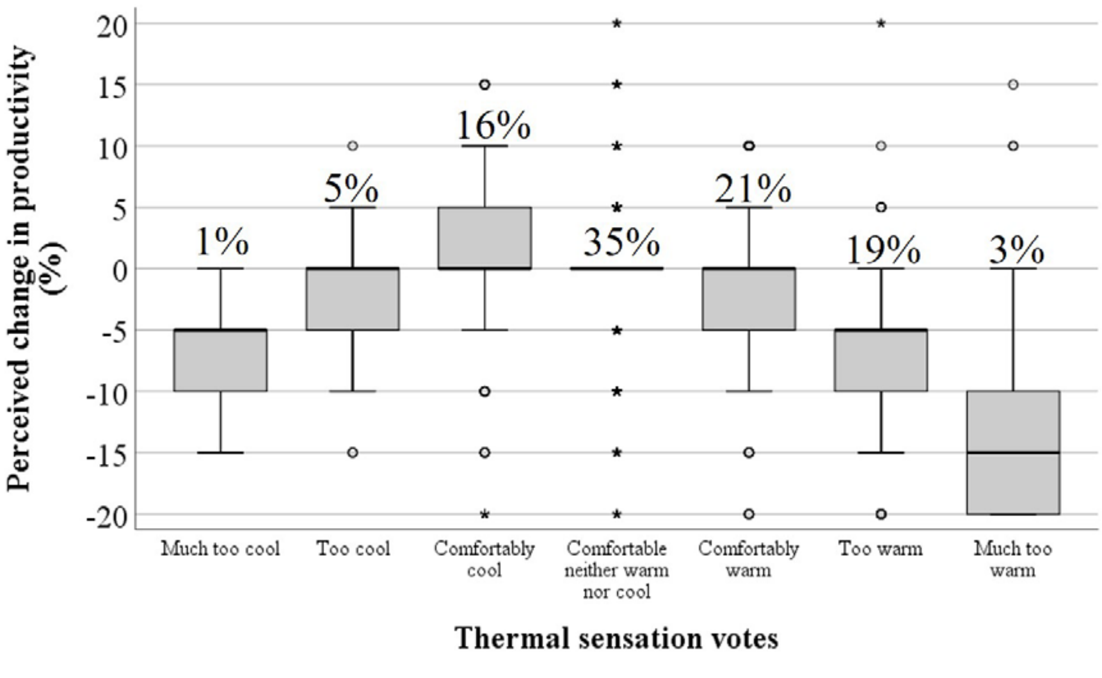


Figure 14 Boxplot of thermal sensation votes vs. perceived change in productivity votes (n=953).

By comparison, plotting thermal sensation votes against concurrent indoor temperatures showed very little variation in the distribution of temperatures except towards the 'warm' end of the scale (Figure 15). Temperatures in the 23.5-24.5°C range were perceived by some to be ‘much too cool’ and others to be ‘much too warm’ (and everything in between), indicating how subjective thermal comfort was, particularly in such a tightly controlled environment.

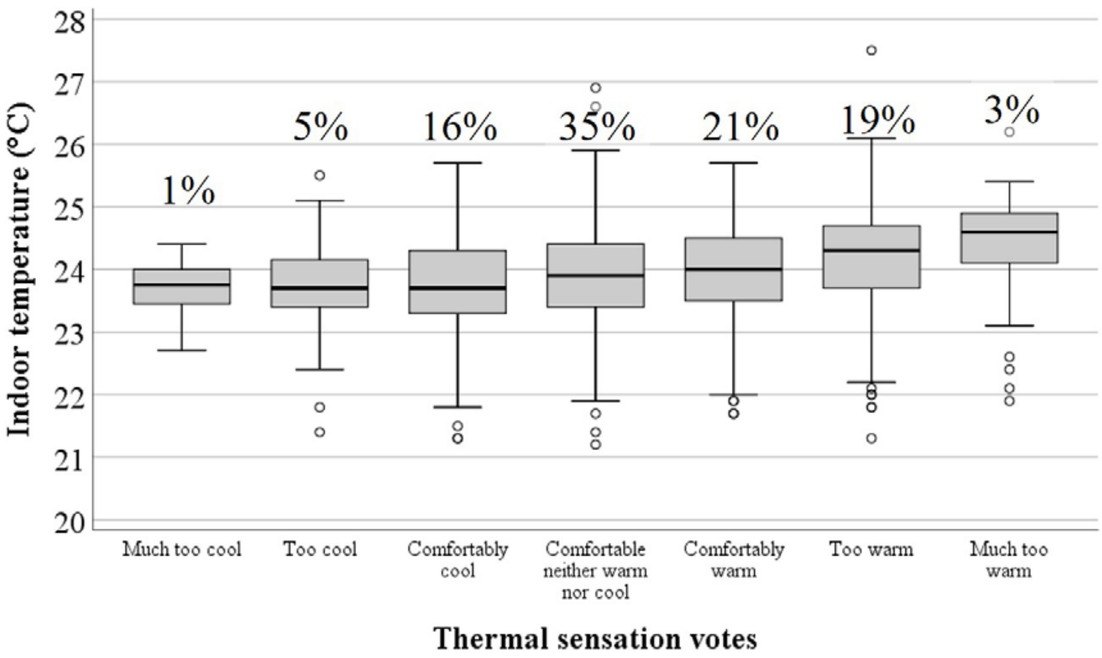


Figure 15 Boxplot of thermal sensation votes vs. concurrent indoor temperatures (n=953).

Thermal preference votes similarly showed that when respondents wanted to be warmer or cooler, they perceived their productivity to be negatively affected (Figure 16). Close to 49% of responses indicated they were content with the thermal conditions (‘no change’), with 41% wanting to be cooler and only 10% wanting to be warmer.

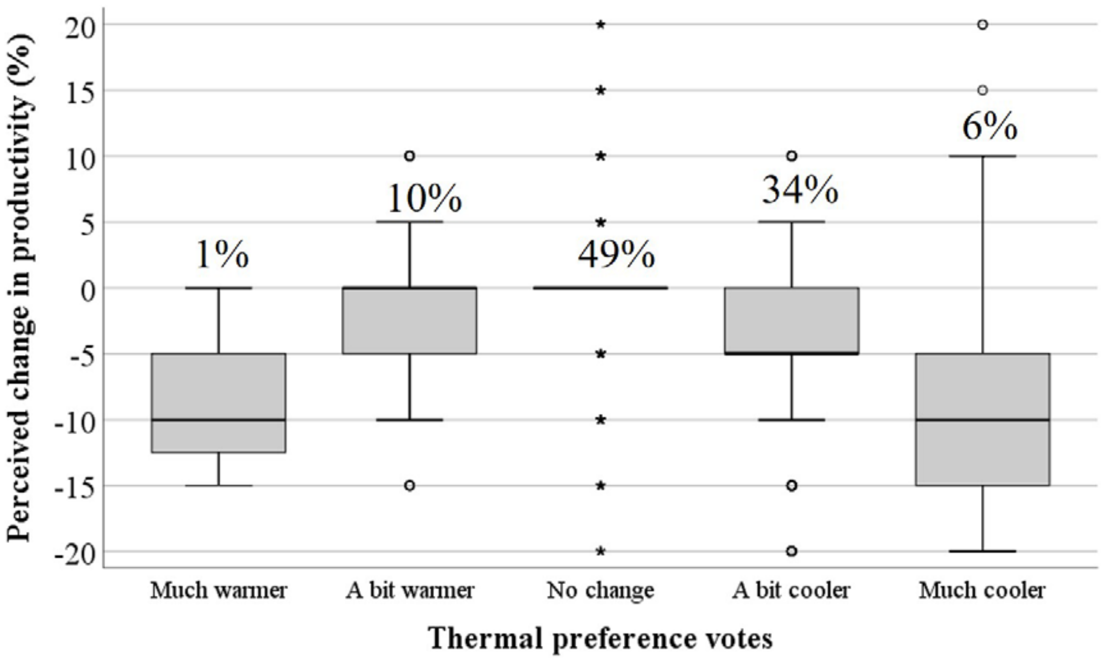


Figure 16 Boxplot of thermal preference votes vs. perceived change in productivity (n=953).

The relationship between perceived air quality and perceived change in productivity was weaker by comparison, but still showed that as occupants perceived their environment becoming more stuffy, they also perceived their productivity deteriorating (Figure 17). Notably, as with thermal sensation and measured temperature, there was no significant correlation found between perceived air quality votes and any measures of the indoor environment (temperature, RH or CO_2 concentration).

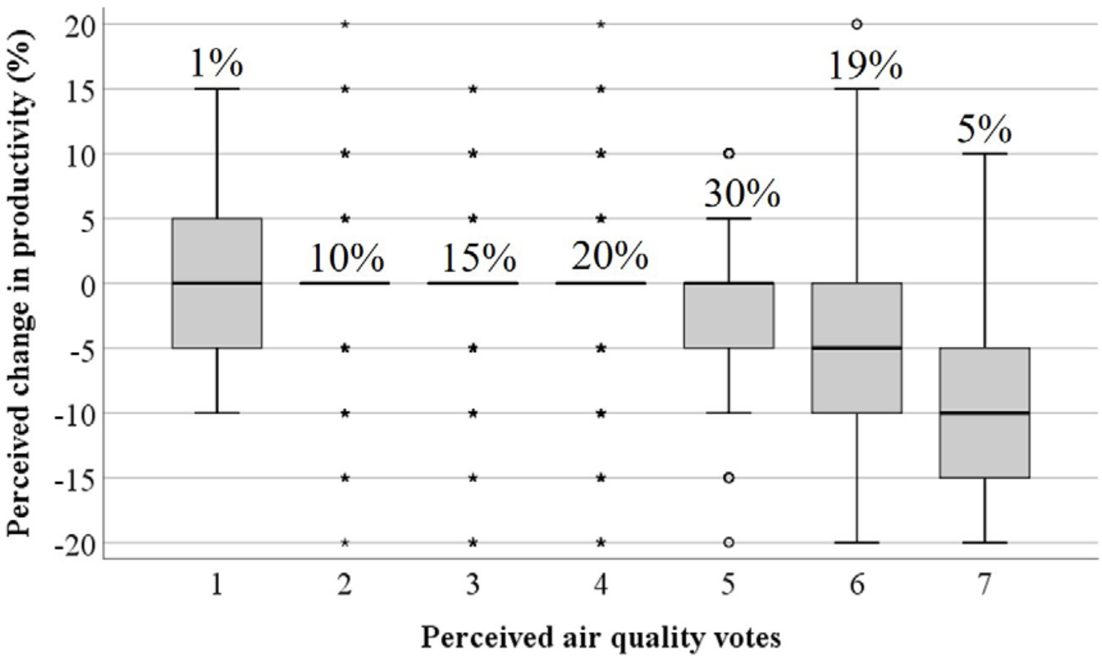


Figure 17 Boxplot of perceived air quality votes vs. perceived change in productivity (n=953): 1 = 'fresh, 7 = 'stuffy'.

Plotting perceived overall comfort votes against perceived change in productivity had similar results: when occupants felt comfortable overall, they perceived their productivity to be neutral or slightly improved, whereas the more uncomfortable they felt overall, the more negatively affected they perceived their productivity to be (Figure 18).

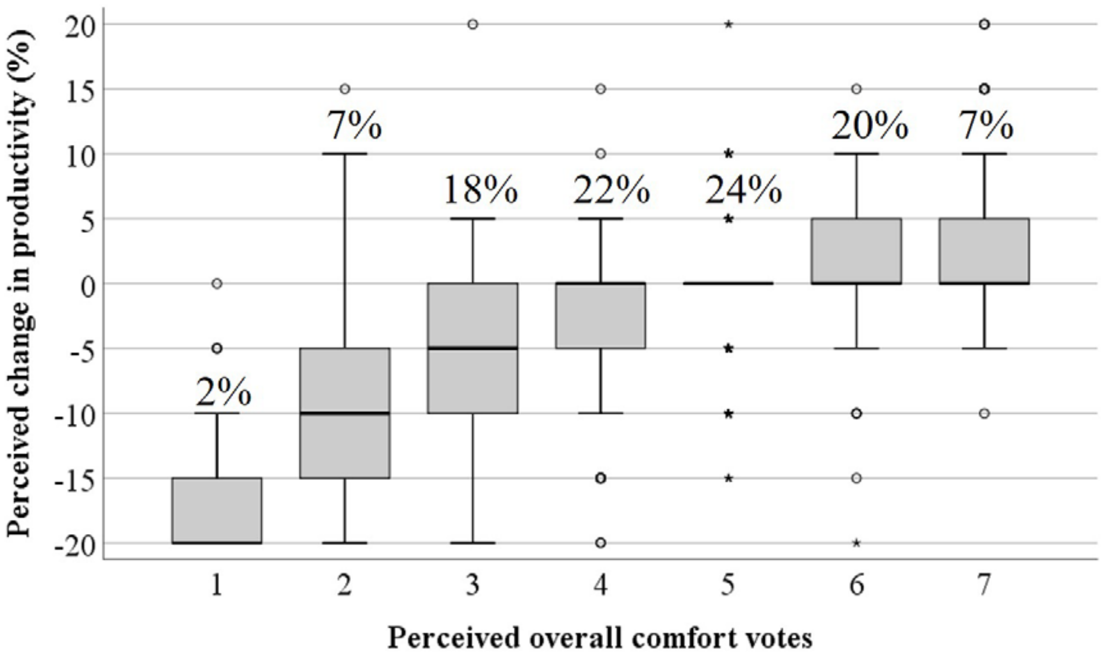


Figure 18 Boxplot of perceived overall comfort vs. perceived change in productivity (n=953): 1 = uncomfortable, 7 = comfortable.

The relationship between how occupants perceived their environmental conditions and how they perceived their productivity to be affected was evident. However, plotting measured indoor environmental conditions against perceived change in productivity produced no statistically significant relationships, indicating the subjective nature of both perceptions of the indoor environment and perceptions of how this environment contributes to changes in productivity.

Measured productivity and indoor environment

Performance tasks were conducted from 5 to 9 June and from 24 to 28 July 2017 (n: 285). As with the surveys, tasks were time stamped so concurrent indoor conditions could be cross-related. Links to the online tasks were sent via e-mail twice a day (mid-morning and mid-afternoon. The Stroop test was the most popular test type, receiving 53% of responses, followed by the proofreading test (27%) and numerical (20%). Performance tasks were given to the same cohort of individuals as was given the BUS and longitudinal surveys, and there was significant overlap in the individuals who chose to respond.

The range of indoor temperatures concurrent with task completion was small (predominantly 22-25°C), therefore making it difficult to identify significant correlations. Although a (weak) negative correlation was found (Pearson correlation $r = -0.07$), indicating that as indoor temperature increased, the proportion of correct answers decreased, this was not statistically significant at the 0.05 level (Figure 19).

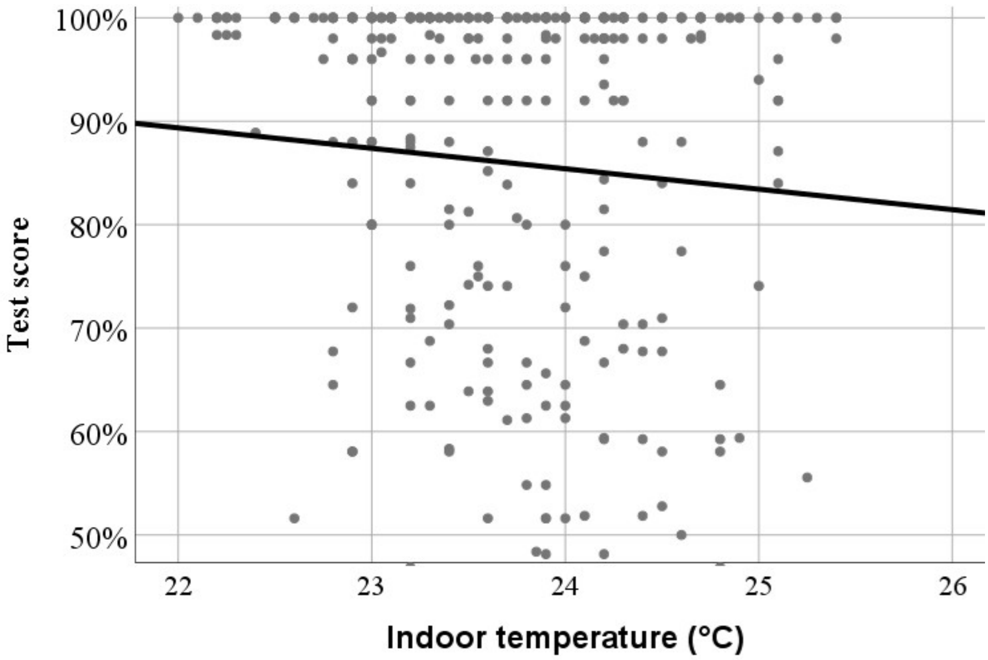


Figure 19 Indoor temperature vs. test score.

To investigate if there were any statistically significant correlations between the measured indoor environment (temperature, RH or CO_2 concentration) and task results (test score or test duration), interventions were conducted.

6. Intervention period

Based on the findings from the baseline period, the BMS was used to control the indoor environment over two four-week periods:

- During the first intervention period (23 October to 17 November 2017), the temperature was more tightly controlled to set-points of 21.5°C, 22.0°C, 22.5°C and 23.0°C (one set-point per week).

- During the second intervention period (15 May to 12 June 2018), CO_2 concentrations were more tightly controlled to set-points of 1000 ppm, 1200 ppm and 1500 ppm (one set-point per week following a week of ambient levels).

Maintaining these set-points proved challenging for the BMS, and as an indication of how intolerant occupants could be to perceived uncomfortable conditions, the temperature set-point of 21.5°C had to be abandoned mid-week due to the facilities management team receiving complaints from occupants that they were too cold. As there was significant overlap in measured temperatures and CO_2 concentrations within the intervention weeks, the results of the surveys and tasks have been considered as a whole rather than by set-point weeks.

During both periods, online surveys and performance tasks were repeated and time stamped, with surveys being conducted three times a day (mid-morning, early afternoon and late afternoon) on Mondays and Tuesdays and tasks twice a day (mid-morning and mid-afternoon) on Wednesdays, Thursdays and Fridays.

Perceived productivity and indoor environment

The distribution of responses to thermal comfort votes was shifted mainly due to the temperature set-points during the first intervention period creating a cooler environment than experienced during the baseline period. Around 70% of responses were in the 'comfortably cool'/ 'comfortable' / 'comfortably warm' range, with 16% at the warm end of the scale and 14% at the cool end. 45% of thermal preference votes were for 'no change', with 30% wanting to be cooler and 25% wanting to be warmer. Plotting these results as boxplots against perceived change in productivity produced very similar outputs to the baseline. The distribution of perceived air quality votes and overall comfort votes were similar during both intervention periods to the baseline period, and again, the boxplots against perceived change in productivity produced very similar outputs to the baseline. These results served to emphasise the strong relationship between occupant perception of their environment and their perception of how this affects their productivity.

Measured productivity and indoor environment

As with the baseline, indoor temperatures concurrent with task completion covered a narrow range (21-25°C), although the temperature intervention provided a more even spread of temperatures within this. The correlations between indoor temperatures and both test scores and test durations were very weak and not significant at the $p = 0.05$ level. Similarly, there were no statistically significant correlations between RH and either test score or test duration, despite RH levels being below the recommended 40% for 39% of tasks completed.

Allowing CO_2 concentrations to rise higher than occupants were used to during the second intervention period provided more test results conduced at the higher end of the CO_2 range than in the baseline. Splitting the test scores and test durations between those conducted below 800 ppm and those conducted above 800 ppm (Figure 20) showed that for the proofreading tests, the median score was 94% for those conducted below 800 ppm, compared to 79% for tests conducted above 800 ppm. For proofreading tests, the median time to complete the test (test duration) was 5 minutes for those conducted below 800 ppm, compared to 6 minutes for those conducted above 800 ppm. It is notable that this 800 ppm is the limit recommended by the WELL Building Standard (Delos Living 2016).

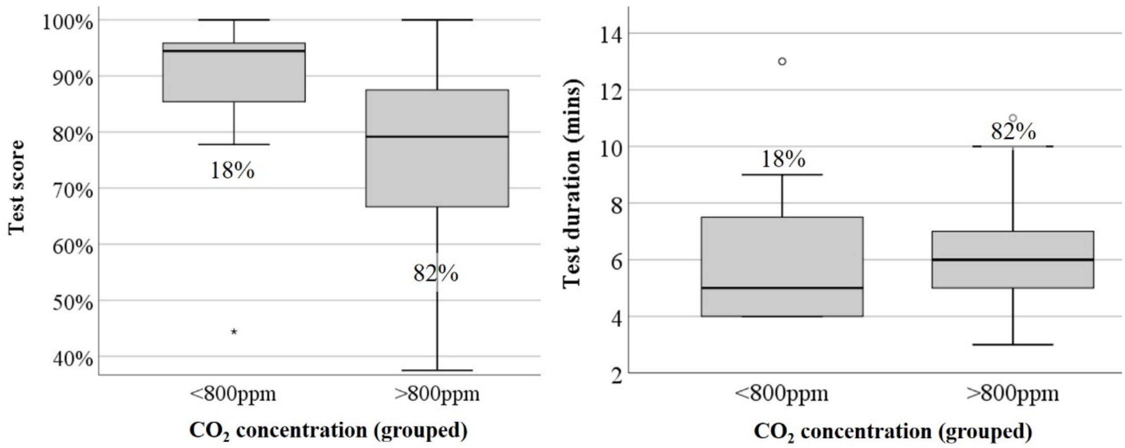


Figure 20 Boxplots of CO_2 concentration against test score (left) and test duration (right) for the proofreading tests during the intervention periods.

It is evident from these results that temperatures and RH levels within the ranges experienced by the occupants were not extreme enough to show any negative impact on the performance tasks used in this study. However, when CO_2 concentrations exceeded 800 ppm there was a significant detrimental effect on both the test scores and durations for the proofreading tests.

Participant response rates

It is worth commenting on the participant engagement in both the surveys and performance tasks. Measuring response rates proved to be challenging on a technical and logistical level: the occupancy of the workspace throughout the day was not monitored by the organisation in any way and the nature of their work meant that occupants would regularly be in and out of the workspace for meetings (both on and off site). For the purpose of this study, a member of the facilities team was tasked with conducting a headcount during each period when a survey or performance task had been e-mailed to the occupants. This gave an indication of occupancy and therefore allowed an approximate response rate to be calculated. These counts were conducted for the first three weeks of the intervention period, the results of which are shown in Figure 21.

It is evident that the surveys consistently received higher response rates than any of the performance tasks, and the Stroop test was consistently the most popular type of performance task. The fact that the surveys and Stroop tests took only a couple of minutes to complete compared to the numerical and proofreading tasks which took between four and ten minutes to complete for the majority of respondents may or may not have been a significant factor influencing the occupant response rates.

It is clear that the response rates dropped over the three weeks for which data were available. Further analysis also indicated that the response rate decreased throughout the week (Monday to Friday) and throughout the day (morning to early afternoon to late afternoon).

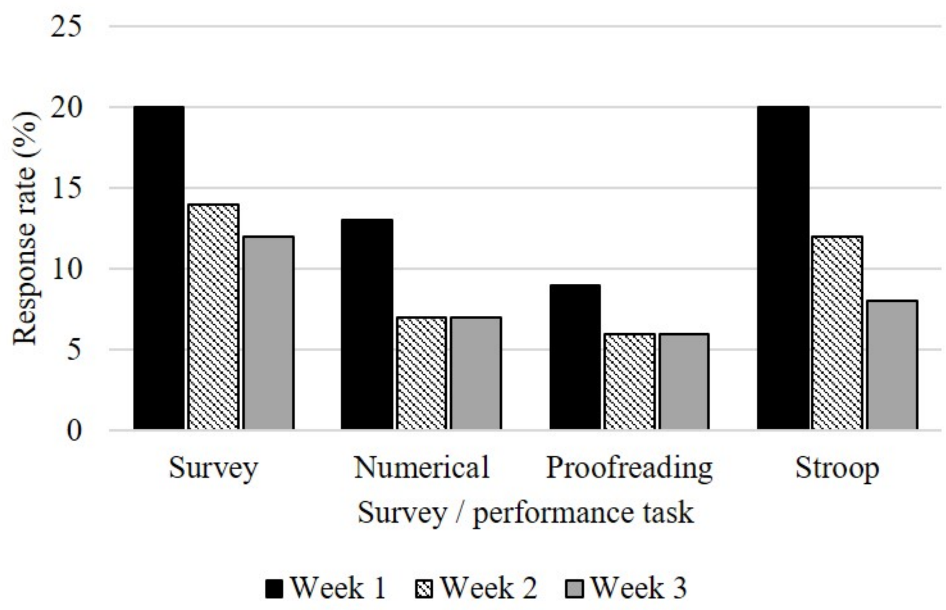


Figure 21 Weekly response rates for the surveys and performance tasks.

As surveys and performance tasks required respondents to indicate their desk number, it was possible to get an indication of how often individuals were responding (Figure 22).

A total of 75 individuals gave responses during the intervention period. However, twenty of these only responded once, and only nine responded more than ten times.

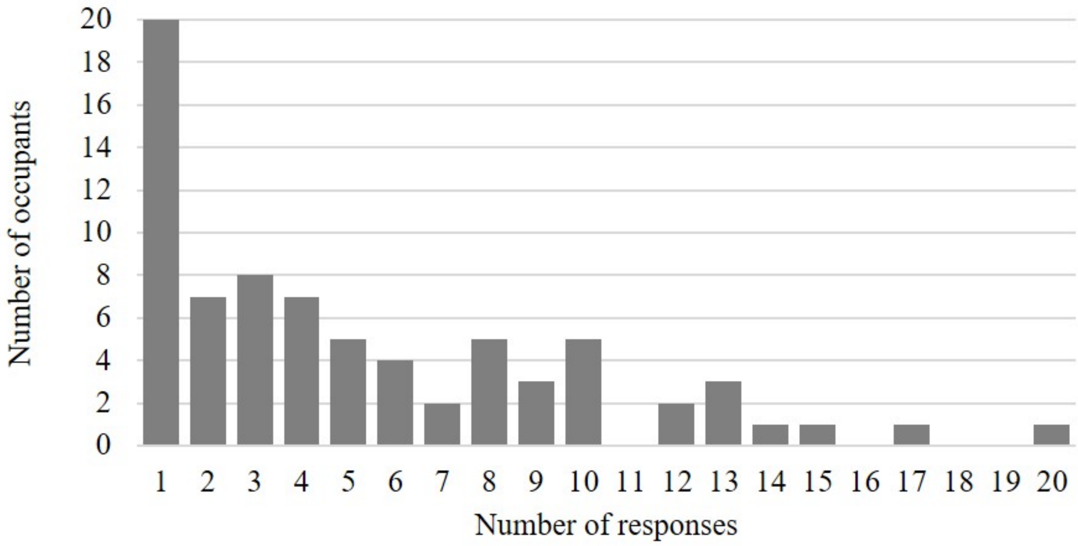


Figure 22 Number of occupants responding to surveys and tasks.

Throughout the baseline and intervention period, occupant engagement proved to be a challenge. The timings of the surveys and performance tasks were chosen so as to reduce the interruption to the occupants' working day: mid-morning when they may have been taking a short break, early afternoon when they may have been returning from a lunch break, later in the afternoon, but not too late that it interrupts work that they want to complete before the end of the day. Thought was given as to possible incentives/rewards to offer occupants for their participation. However, as responses were anonymised this would have proved difficult, and it would have also risked getting responses which were disingenuous ('speeders' who answer quickly but randomly or 'straight-liners' who answer the same for every question). Occupants were instead incentivised by being regularly thanked for their ongoing participation and reminded about the purpose of the research and the potential benefits to them in the longer term in terms of potential improvements to their working environment.

Nevertheless, the response rates were only around 10-15% for the surveys and 5-10% for the tasks, highlighting the challenge of actively engaging participants who had been recruited to the project due to the fact that they were occupants in the case study workspaces, and were expected to participate in the study at the same time as conducting their regular daily workload. However, the essence of this project was to study occupants in their natural working environment, so the challenge of engagement was inherent in the process.

7. Discussion

This study has discovered interesting results through environmental monitoring, occupant surveys and performance tasks in the case study building, during the baseline and intervention periods. The building's BMS ensured that the workplace operated within relatively ranges of temperature (22-25 °C), RH (25-55 %) and CO_2 concentration (below 1000 ppm) for the majority of working hours.

Although indoor temperatures had a moderate correlation with outdoor temperatures, they remained stable throughout the working day: a large change in outdoor temperature would correspond to only a small change in indoor temperature. It was also observed during the CO_2 intervention (May-June 2018) that profiles of CO_2 concentration were not much different whether the set-points were 1200 ppm or 1500 ppm, suggesting that energy could be saved by having more relaxed set points without compromising levels of CO_2 significantly.

Although no strong correlations were observed between measured indoor environment (particularly temperature and RH) and perceived or measured productivity, the proportion of occupants who expressed discomfort due to feeling *too cool* (6% and 14% in the baseline and intervention periods respectively), *too warm* (21% and 16% in the baseline and intervention periods respectively), or *air feeling too stuffy* (55% and 52% in the baseline and intervention periods respectively), also perceived their productivity to decrease. Perceived changes in productivity were found to have much stronger links to *perceived thermal sensation* and *perceived air quality* than to actual *measured* temperature, RH and CO_2 concentration. These results suggest that an occupant's experience of their environment can have a greater impact on their perceived productivity, indicating the need to consider occupants' needs and expectations when optimising indoor environments of workplaces.

Test scores and durations were used as a proxy measure of productivity. While in the baseline period, there was a weak correlation between indoor temperature and test score (though not statistically significant at the 0.05 level) which indicated that higher temperatures were linked to lower test scores, during the intervention periods, proofreading tests scores conducted at CO_2 concentrations below 800 ppm corresponded a median test score of 94% (n = 11) compared to 79% (n = 60) for those conducted above 800 ppm. Neither the numerical nor particularly the Stroop test were able to provide the distribution of test scores and test durations required to be able to make any statistically significant links between these datasets and concurrent indoor environment measurements. Throughout the study, no statistically significant differences were found between genders or for respondents in different age categories.

It is worth noting that, although no direct relationship was found between RH and either perceived or measured productivity, the low levels experienced in the building (below the recommended 40% RH for 66% of working hours during the heating season) were attributed by some occupants as contributing to dry throats, dehydration, dry skin and the spreading of germs. Quotes from the BUS questionnaire included, "Air con drys [sic.] me out. Drink a lot more water. Dry throat. Germs spread so end up getting illness that's going around", "The air quality, being dry, is cause for concern" and "My skin is very dry because of the low humidity. I often suffer irritable skin as a result". Although these detrimental effects on health were not monitored as part of this research project, they may indirectly have a negative impact on productivity.

Conducting this research in a real-world working office environment posed a number of challenges, particularly in terms of occupant engagement and data gathering: response rates for the surveys fell from 17% during the baseline period to 7% during the second intervention period; response rates for the tasks fell from 13% during the baseline period to 4% during the second intervention period. The proofreading tasks proved to be the least popular of the three task types, possibly because they took longer to complete and were more difficult. However, as the results have shown, having easier tasks that take less time to complete may improve the response rates, but it produces datasets which do not have sufficiently well distributed results to allow meaningful relationships with indoor environmental parameters to be found. Operating in a real-world working office environment also allows a great deal of 'noise' in the data, as a myriad of mitigating factors may influence the results.

8. Conclusion

This paper has adopted a case study-based approach to empirically explore the relationship between indoor environment and workplace productivity in a mechanically-ventilated office environment located in the south of England. Through continuous physical monitoring, occupant surveys and performance tasks, the study has revealed a relationship between the indoor environment and both occupant perception of their productivity and their measured productivity (using performance tasks as a proxy measure for cognitive capability, speed and accuracy). While task performance was affected by indoor environmental conditions such as CO_2 concentration, it is clear that occupant perception of their indoor environment matters for improving productivity.

Occupants in the case study were busy with their own work and asking them to complete performance tasks over a few weeks was not easy; deep and ongoing engagement was necessary which can be resource intensive. Since many organisations are not able to define and track metrics for productivity, occupant surveys could provide a 'quick and low cost' way to gather data on perceived change in productivity in relation to the indoor environment. Such occupant surveys can also be deployed in building performance evaluation studies, and also investigations into occupant health and well-being. Performance tasks could be delivered to a subset of occupants (perhaps identified by their enthusiasm) to measure their productivity in terms of cognitive capability, speed and accuracy.

Since the research presented here is based on a single case study, there are limitations in drawing general conclusions on the link between indoor environment and workplace productivity in modern UK office buildings. Nevertheless, the methods and findings presented here can be rolled out more widely to provide a more comprehensive coverage of UK offices. Despite the challenges faced in conducting this research in a real-world working environment, evidence gathered in the study suggests that elements of indoor environment (specifically CO_2 concentration) are associated with workplace productivity. It is therefore possible that effective management of the indoor environment could potentially lead to improvements in workplace productivity.

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Declaration of interest

No conflict of interest.

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