Comparative evaluation of measured and perceived indoor environmental conditions in naturally and mechanically ventilated office environments

Rajat Gupta and Alastair Howard

Low Carbon Building Research Group, Oxford Institute for Sustainable Development, School of Architecture, Oxford Brookes University, Oxford, UK

rgupta@brookes.ac.uk

Abstract

This paper uses a case study-based approach to comparatively evaluate the relationship between measured and perceived indoor environmental conditions in two office buildings, one naturally ventilated and one mechanically ventilated, located in south England. Environmental parameters (indoor and outdoor temperature and relative humidity, and indoor CO_2 concentration) were continuously monitored at 5-minute intervals over a 19-month period (March 2017 to September 2018). During this time, occupant satisfaction surveys (both transverse and longitudinal) recorded occupant perceptions of their working environment, including thermal comfort, resulting in approximately 5700 survey responses from the two case studies combined.

In the NV office, CO_2 levels were high (often >2000ppm) and indoor temperature was both high (>27°C) and variable (up to 8°C change in a working day). In contrast, the MV office environment was found to operate within much narrower temperature, RH and CO_2 bands. This was particularly evident in the little seasonal variation observed in the CO_2 levels in the MV office (rarely above 1200 ppm); whereas in the NV office, CO_2 concentrations exceeded

2000 ppm on 12% of working days during the heating seasons and less than 1% in the non-heating season. Despite these differences in measured indoor environmental conditions, occupants' overall satisfaction with their environment was similar in both buildings. Occupants of the NV building were found to be more tolerant of higher indoor temperatures while neutral thermal sensation corresponded to a higher indoor temperature, indicating the role of adaptation. This has important implications for energy use in managing the indoor environment.

Keywords

Indoor environment, occupant perception, thermal comfort, monitoring, occupant survey

1 Introduction

The UK has a service-based economy, with 71% of GDP coming from the service sector and 18% from industry (Plecher, 2020). A substantial proportion of service and industry based employees are office based, accounting for a significant proportion of the UK workforce. A UK-based survey revealed that office workers spend more time per day at their desk or workstation (6.8 hours) than they do in bed (6.4 hours), relaxing at home (3.5 hours) or outdoors (37 minutes) (Bean, 2018). The workplace environment therefore has an important role to play in the health and wellbeing of its occupants, as well as having an impact, whether positive or negative, on their productivity (Gupta et al., 2020).

A number of studies have investigated occupant perception of their working environment – particularly relating to thermal comfort – and its relationship with measured environmental conditions (Barlow and Fiala, 2007, Luo et al., 2015, Geng et al., 2017). Thermal comfort has been defined as the condition of mind that expresses satisfaction with the thermal environment. The Predicted Mean Vote (PMV) model, developed by Fanger (Fanger and

Toftum, 2002) is amongst the most recognised models and has been the basis for several standards including EN ISO 7730 (AC08024865, 2005) and ASHRAE Standard 55 (Brager et al., 2015). However, this model makes the key assumption that temperatures, relative humidity (RH) and CO_2 concentrations remain stable – steady state conditions. Tightly controlled, mechanically ventilated workspaces may be able to maintain an indoor environment within relatively narrow ranges. But naturally ventilated, free-running workspaces (typical of the UK building stock) experience a much wider range of indoor environmental conditions over the course of the working day. This is why field studies of thermal comfort assess the dynamic state of the indoor environment by cross-relating subjective responses of occupants with concurrent measured indoor environmental conditions, enabling a better understanding of the acceptable ranges of indoor temperatures.

This study conducted a longitudinal comparative evaluation of the measured and perceived indoor environmental conditions in naturally ventilated (NV) and mechanically ventilated (MV) workplaces, to explore any similarities and differences, and to provide insights for managing the indoor environment. To achieve this, two contrasting case study offices (one naturally ventilated in central London, the other mechanically ventilated in semi-rural southern England) were monitored (temperature and relative humidity (RH) – indoors and outdoors – and CO_2 concentration – indoors) over a 19-month period.

2 Evidence to date

Thermal comfort models attempt to understand the relationship between a building's indoor environmental conditions and how the occupants of the building will respond to those conditions. Static models (most notably the PMV model) and adaptive models have been the subject of many field studies to establish how well they fit with real-world working environments. In 1998, de Dear and Brager analysed data from around 21,000 observations in

160 buildings around the world to develop an adaptive model of thermal comfort (De Dear and Brager, 1998). They found that the static PMV model worked well in mechanically ventilated (MV) buildings, but that occupants in naturally ventilated (NV) buildings had a wider range of temperatures which they could tolerate. This difference was attributed to behavioural adjustments and psychological adaptations.

Some studies have taken a climate-chamber approach to investigate the relationship between occupants and their environmental conditions. In 2017, Geng et al. used a survey and productivity test on participants in a climate chamber (Geng et al., 2017), where temperature was varied in 2°C steps from 16 to 28°C and other IEQ parameters kept constant. They found that optimum productivity correlated with thermal sensation votes of "neutral" or "slightly cool". When the thermal environment was unsatisfactory, it weakened the comfort expectation of other IEQ factors (i.e. there was less dissatisfaction with other IEQ factors), and conversely when satisfied with the thermal environment, comfort expectations were raised. Although interesting findings in themselves, the controlled conditions of a climate chamber do not reflect the dynamic, multifaceted environments of real-world office environments.

Some researchers have used field study evidence to develop models (Ncube and Riffat, 2012), or have developed models which they have then tested in the field (Andargie and Azar, 2019). But the majority of studies have considered the established models and further investigated the relationships between the indoor environment and thermal comfort, extending the analysis to include broader occupant satisfaction and perceptions of health and productivity. An overview of relevant studies is provided in Table 1.

A study of 12 MV buildings in Canada found positive relationships between job satisfaction and satisfaction with air quality, ventilation, temperature (Haghighat and Donnini, 1999).

More health symptoms were reported by those who perceived IAQ to be poor, but job dissatisfaction did not correlate with self-reported health symptoms. Other studies have also found a relationship between perceptions of the indoor environment and sick building syndrome (SBS) symptoms (Wong et al., 2009). Studies which have compared the fit of comfort models on occupants of NV and MV buildings have found that the PMV model fits best with occupants of MV offices, whereas ASHRAE's Standard 55 fits best with occupants of NV offices (Hellwig et al., 2006, Wagner et al., 2007). Hellwig et al.'s finding that NV occupants were more satisfied with their thermal environment than MV occupants has also been found in other studies (Hummelgaard et al., 2007).

Other studies have compared occupant perceptions of their environments in different building types: Green-Mark-Platimum certified and non-Green-Mark-Certified in Singapore (Tham et al., 2015) and BREEAM (Building Research Establishment Environmental Assessment Method) and non-BREEAM certified offices in UK (Altomonte et al., 2017). In both cases, the differences between the certified and non-certified buildings was marginal at best. Although the Green-Mark-Platinum certified office was perceived to have cooler, fresher and cleaner air than the non-certified office, there was no statistically significant difference in reported SBS or recorded sick leave between the two buildings. Occupants of BREEAM offices tended to be less satisfied with air quality than occupants of non-BREEAM offices.

The subjective nature of occupant's perception of their environment has also appeared in several studies, along with behavioural and control factors. A trans-European study of 167 'modern' office buildings used statistical analysis to examine the relationships between overall comfort and a range of IEQ-related factors (Sakellaris et al., 2016). It found overall comfort to be most highly associated with "noise", followed by perceived air quality and satisfaction with light. Thermal satisfaction came fourth in strength. Unusually, this study did not include measurements of the indoor environment, but perhaps by doing so, it allowed for a much greater sample size for the surveys. A field study in a Swedish hospital found subjective sensory ratings to be significantly better predictors of overall comfort than objective indoor environmental measurements (Fransson et al., 2007). A study of 59 office buildings across Europe found a variety of influencing factors on perceived comfort beyond the conventional thermal, air quality, noise and light factors commonly investigated (Bluyssen et al., 2011). These included office layout, satisfaction with the view and personal control. The degree of personal control was also found to be a factor in several other studies (Wagner et al., 2007, Liu et al., 2012), where occupants' level of control of their local environment, and also the perceived effectiveness of this control, strongly influenced occupant satisfaction with their thermal conditions. Occupants were also found to use behavioural changes to adapt to their environment (Liu et al., 2012, Yao et al., 2010).

Table 1 Overview of field studies investigating indoor environment and occupant perception.

Study	**Study type and location**	**Procedure**	**Results**
Impact of psycho-social factors on perception of the indoor air environment studies in 12 office buildings (Haghighat and Donnini, 1999)	Field study in 12 MV buildings (varied use), Canada	IAQ and energy consumption monitored alongside occupant surveys.	56% of occupants were dissatisfied with the IAQ. Only 63% (summer) and 27% (winter) of responses were within ASHRAE Standard 55-92 summer comfort zone. 69% of those surveyed agreed with the comfort zones.
Thermal comfort in offices – natural ventilation vs. air conditioning (Hellwig et al., 2006)	Field study in 14 offices (6 NV and 8 MV), Germany	IEQ measured and cross-related with occupant interviews	Thermal comfort in MV offices best predicted by PMV model, and in NV offices best predicted by ASHRAE. NV occupants significantly more satisfied with their thermal environment than MV occupants. Several perceived parameters influence thermal comfort: lighting, draughts, temperature variations, acoustics, olfactory quality, glare and perceived control.
Thermal comfort and workplace	Field study in one NV	Thermal comfort	Thermal sensation votes had good agreement with adaptive comfort models,

occupant satisfaction—Results of field studies in German low energy office buildings (Wagner et al., 2007)	office followed by 16 further offices, Germany	surveys with 50 occupants.	but not with PMV. Occupants' control of (and perceived effect on) the indoor climate strongly influence their satisfaction with thermal indoor conditions.
Indoor air quality and occupant satisfaction in five mechanically and four naturally ventilated open-plan office buildings (Hummelgaard et al., 2007)	Field study in 5 MV and 4 NV open-plan office buildings, Denmark.	Temperature and CO_2 concentration monitored for a week; occupants surveyed.	Temperature and CO_2 concentration varied more and were often higher in the NV buildings, but occupant feedback differed only modestly between the two building types. Although rarely supported by statistical significance, results indicated more satisfaction with the indoor environment and a lower prevalence/intensity of SBS among the occupants of the NV buildings
In search of the comfortable indoor environment: A comparison of the utility of objective and subjective indicators of indoor comfort (Fransson et al., 2007)	Field study in a hospital, Sweden.	Environmental monitoring and occupant surveys.	Subjective sensory ratings were significantly better than objective indicators at predicting overall rated indoor comfort.
Occupants' adaptive responses and perception of thermal environment in naturally conditioned university classrooms (Yao et al., 2010)	Field study in NV university classrooms, Chongqing, China	Indoor environment and survey conducted monthly over a year.	Adaptive comfort range broader than ASHRAE Standard 55-2004 in general, but narrower in the extreme cold and hot months. Severe summer and winter thermal conditions in classrooms. Behavioural adaptation (changing clothing, adjusting indoor air velocity, taking hot/cold drinks, etc.) and psychological adaptation helped occupants adapt to the thermal environment.
Comfort of workers in office buildings: The European HOPE project (Bluyssen et al., 2011)	Field study of 59 office buildings across Europe.	Occupant surveys cross-related with building-specific data from European Health Optimisation	Perceived comfort strongly influenced by personal, social and building factors in a complex relationship – more than just the average of perceived indoor air quality, noise, lighting and thermal comfort.

		Protocol for Energy-efficient Buildings (HOPE) study.	
Occupants' behavioural adaptation in workplaces with non-central heating and cooling systems (Liu et al., 2012)	Field study in one office building, Chongqing, China.	Occupant survey alongside onsite monitoring of the physical environment.	Occupants actively able to control environmental. Adaptive responses were strongly driven by ambient thermal stimuli – varied seasonally, daily and within the same day.
Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK – A preliminary study (Ncube and Riffat, 2012)	Model developed based on questionnaire data from 2 case study buildings, UK.	IEQ measured alongside occupant questionnaires. Results used to develop a model for rapid assessment of IEQ.	Multiple regression analysis used to develop a model – Indoor Environment Quality Assessment Tool (IEQAT), which agreed well with AHP tool developed by Chiang et al. (Chiang et al., 2001). Model's strongest weightings for IAQ and thermal comfort.
Indoor environmental quality, occupant perception, prevalence of sick building syndrome symptoms, and sick leave in a Green Mark Platinum-rated versus a non-Green Mark-rated building: A case study (Tham et al., 2015)	Field study of two office buildings: one Green-Mark-Platinum-certified (GMP), the other non-Green-Mark certified (NGM), Singapore.	Surveyed 65 employees on perceptions of IEQ and prevalence of SBS.	Significant differences in occupant perception: GMP cooler, fresher, cleaner air and better ergonomics. Common SBS symptoms in NGM: dry/irritated throat, lethargy. Common SBS symptoms in GMP: stuffy nose, dry/irritated throat, dry skin, lethargy. No statistically significant association between SBS and the offices. Analysis of sick leave records showed no evidence that GMP occupants had fewer sick days than NGM occupants.
Perceived Indoor Environment and Occupants' Comfort in European "Modern" Office	Field study in 167 'modern' office buildings in 8 European	Survey of occupant perception of IEQ.	The highest association with occupants' overall comfort was found for "noise", followed by "air quality", "light" and "thermal" satisfaction. Recommended that workplace design should consider both occupant and building characteristics to

Buildings: The OFFICAIR Study (Sakellaris et al., 2016)	countries.		provide healthier and more comfortable conditions.
Satisfaction with indoor environmental quality in BREEAM and non-BREEAM certified office buildings (Altomonte et al., 2017)	Field study of occupants in two BREEAM and two non-BREEAM certified offices, UK.	Cross-sectional occupant satisfaction surveys.	BREEAM certification did not substantively influence building/workspace satisfaction. Conversely, occupants of BREEAM offices tended to be less satisfied with air quality and visual privacy than users of non-BREEAM buildings. Lower satisfaction also in BREEAM offices for occupants having spent over 24 months in their building.
An applied framework to evaluate the impact of indoor office environmental factors on occupants' comfort and working conditions (Andargie and Azar, 2019)	Model developed then tested in a case study building in Abu Dhabi, UAE.	Framework developed. Temperature, lighting and noise monitored, occupants surveyed.	Both environmental conditions and occupants demographics had significant impacts on perception of the indoor environment, affecting overall satisfaction, reported happiness, reported productivity levels, and basic cognitive abilities.

These studies have found evidence of complex interactions between different environmental parameters that can affect occupant perception of their environment. In several field studies, the evidence suggested that occupants of NV buildings were more tolerant of (and able to adapt to) a wider range of environmental conditions, particularly thermal conditions, compared to their counterparts in MV buildings.

This paper builds on this existing body of research, using a combination of continuous environmental monitoring and transverse and longitudinal occupant surveys in two contrasting office buildings (NV and MV). The results of these data streams provide insight into how occupants perceive their indoor environment in a more stable MV office space than the free-running NV office space.

3 Methodology

In order to understand the relationship between the measured indoor environment and occupant perception of their environment, the methodology adopted in the study had a two-pronged approach: (1) Physical monitoring of indoor and outdoor environment using data loggers and (2) Occupant surveys (transverse and longitudinal) (Table 2). Two case study buildings (naturally ventilated ‘K’ and mechanically ventilated ‘N’) were studied in parallel using this methodology.

Table 2 Methodological approach adopted for the study.

	Monitoring		**Occupant feedback**	
What	Indoor conditions: Temperature Relative humidity CO_2 concentration	Outdoor conditions: Temperature Relative humidity	Transverse survey: BUS questionnaire	Longitudinal surveys
Where	‘K’: 6 zones ‘N’: 20 zones	1 location at each case study site	At each case study site	
When	5-minute readings from March 2017-September 2018		‘K’: Mar 2017 ‘N’: Apr 2017	3x a day: ‘K’ – 40 days: Apr-Jul 2017; Feb-Apr 2018; Jul 2018; Sep 2018. ‘N’ – 31 days: May-Jul 2017; Oct-Nov 2017; May-Jun 2018.
No. of data points	10 million +	400 thousand +	‘K’: 78 ‘N’: 52	‘K’: 3082 ‘N’: 2680

In both of the case study buildings, case study work areas were divided into zones. For the physical monitoring, Hobo data loggers in each zone recorded indoor temperature and relative humidity (RH), and TinyTag data loggers in each zone recorded CO_2 concentration. In addition, an outdoor Hobo data logger at each site recorded outdoor temperature and RH.

Specifications for the loggers used are given in Table 3. The loggers recorded at five-minute resolution from spring 2017 through to autumn 2018 – approximately 19 months in total.

Table 3 Specifications for the installed data loggers.

Data logger	**Measure**	**Specifications**
Hobo UX100-003	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	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	CO_2 concentration	Range: 0 – 5000ppm Accuracy: < ±(50ppm or 3% of measured value) Resolution: 0.1ppm
HOBO MX2301	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%

Occupant feedback was collected in two forms – a transverse (one-time) Building Use Studies survey and a longitudinal online survey, repeated many times during different periods of the study. Ethics approval for these studies was granted by the university's ethics committee (approval number 161047). The Building Use Studies (BUS) survey was conducted in both case study buildings in the early spring of 2017. This transverse survey asks respondents questions about their experience of their workplace. The survey consists of over seventy questions, with a range of nominal, ordinal and scale responses along with several opportunities to provide short comments. The questions covered aspects such as thermal comfort, ventilation, lighting, noise, personal control and perception of changes to health and productivity due to the building environment (BUS). The surveys were distributed to staff members at the start of the working day and collected later on the same day. Case study 'K' provided 78 survey responses (representing a response rate of approximately 80%), and case study 'N' provided 52 survey responses (representing a response rate of approximately 40%). The age distribution of respondents in case study 'K' was younger than those in case study 'N' (54.5% aged under 30 in 'K' compared to 15.4% in 'N'), but the gender balance of respondents was about the same (58% female in 'K'; 57% in 'N').

The results of the transverse survey were used to inform the design of the longitudinal survey. The longitudinal surveys were conducted over several different periods during the 19 months when physical monitoring was underway. Surveys were conducted three times a day (morning, noon, afternoon) on selected days (often Mondays and Tuesdays) during the periods shown in Table 2. As the surveys were conducted during different seasons, it was also possible to analyse the responses seasonally, taking May to September as the non-heating season and October to April as the heating season. To conduct the surveys, an e-mail link was sent to each member of staff in the case study working areas. Their responses were time-stamped, and respondents indicated their desk number, which could then be cross-related with the concurrent measured indoor environmental parameters in the nearest monitored zone. A total of 3082 surveys were received from case study 'K' (representing a response rate of approximately 20% overall), and 2680 from case study 'N' (representing a response rate of approximately 10% overall).

This approach for conducting the surveys did mean that respondents were a self-selecting group, with opportunities for individuals to respond multiple times over the course of the study (though only once for each timeslot). With a degree of 'hot-desking' in both case study buildings, it was impossible to know for sure how many times each individual responded over the course of the study. However, based on the desk identification numbers submitted by respondents, it was estimated that, over the course of the study, there were approximately 129 different respondents from case study ‘K’ (representing approximately 77% of the workforce) and approximately 196 different respondents from case study ‘N’ (representing approximately 76% of the workforce). Although a similar proportion of occupants contributed at some stage to the surveys, the average number of responses was much greater in case study ‘K’ than in case study ‘N’ (18 compared to 10 respectively). The age group of respondents was not asked for the online surveys, but based on the BUS survey and overall demographics of the workforce, it was assumed that the respondents in ‘K’ were much more likely to be in the “under 30” age range than those in ‘N’. In an interesting contrast to the BUS survey responses, 70% of responses in ‘K’ came from females (and 30% from males) compared to 47% of responses in ‘N’ from females (and 53% from males) in the online surveys. One individual responded to 66 of the 78 surveys sent out. This invariably introduced respondent-bias into the survey results. However, by repeating the surveys over three different time slots throughout the day, over several weeks and over different periods during the year, any potential bias based on when the surveys were issued has been minimised.

4 Case study buildings

Descriptive characteristics of the two case study buildings are provided in Table 4. The naturally ventilated case study building, ‘K’, was located in central London next to a busy roundabout which experiences heavy traffic throughout the day and night including a number of bus routes serving the city. The brick building was constructed in 1938 and fully refurbished in 1995. It was owner-occupied and managed, and primarily used for offices. Heating and cooling was provided by fan coil units (FCUs), with occupants able to open windows for ventilation, use venetian blinds for shading, and control their own lighting. The case study offices were on the seventh floor, one below the top floor, and consisted of two open-plan areas approximately 400 m^2 and 200 m^2 with 120 workstations. Desks were primarily allocated, but with some hot-desking.

The mechanically ventilated case study building, ‘N’, was a modern office building in southern England, located on the edge of a business park with woodlands to the north and east. The steel-framed brick building was constructed in 2006. Its facilities were managed by an on-site external facilities management company, with mechanical ventilation, non-openable windows and centrally controlled lighting. The case study offices were on the second (top) floor of one block and the first floor of an adjacent block, with connecting corridors on each floor. They consisted of open plan areas approximately 1500 m^2 and 1400 m^2 with 260 workstations. Desks were a mix of allocated and hot-desks.

Table 4 Case study characteristics for naturally ventilated 'K' and mechanically ventilated 'N'.

Descriptor	**NV case study ‘K’** 	**MV case study ‘N’** 
Location	Central London	Southern England business park.
Year built	1938 (refurbished in 1995)	2004-2006
Facility management	Owner managed	Subcontractor
Energy systems	Mains gas and electricity	Mains gas and electricity
Heating/cooling systems	Fan coil units located under windows throughout case study area	Mechanically ventilated (and heated) throughout. No openable windows
Ventilation systems	Openable windows (user operated)	
Energy rating	DECC-69	EPC rating: C and D
Building operating hours	Weekdays: 7am-10pm Weekends: 9am-5pm	Weekdays: 7am-6pm

Normal working hours	Weekdays: 8:30am-5:30pm	Weekdays: 7am-6pm
Case-study work area type	Open plan, administrative	Open plan administrative
Case-study floor area	600 m^2 approx.	2,900 m^2 approx.
Number of workstations	123	262
Working arrangement	Allocated desks	Allocated desks and some hot-desking
ICT equipment	Desktop computers on all workstations	Desktops and/or laptops on all workstations
Typical occupancy	65	156

In summary, the two case study buildings shared a number of features – both home to open-plan administrative offices, with occupants working on desktop computers – but were distinct from one another in their location (‘K’ urban, ‘N’ semirural), age, and most notably in how the indoor environment was managed: locally by ‘K’s occupants; centrally by ‘N’s occupants.

5 Results

5.1 Measured indoor environmental conditions

5.1.1 Indoor temperature

Measured indoor environmental parameters (air temperature, RH and CO_2 concentration) alongside outdoor air temperature and RH provided valuable insight into the similarities and differences between the two case study working environments. The results presented predominantly focus on conditions during working hours (as specified above).

The boxplot of monthly average temperatures during working hours (Figure 1) shows that temperatures in the naturally ventilated case study ‘K’ had a significantly wider range than those in the mechanically ventilated case study ‘N’, and also a significantly larger seasonal variation. Monthly mean temperatures in ‘K’ ranged from 23.2°C (September 2017) to 26.3°C (July 2018) – 3.1°C range. In contrast, monthly mean temperatures in ‘N’ ranged from 23.0°C (March 2018) to 24.3°C (September 2018) – 1.3°C range.

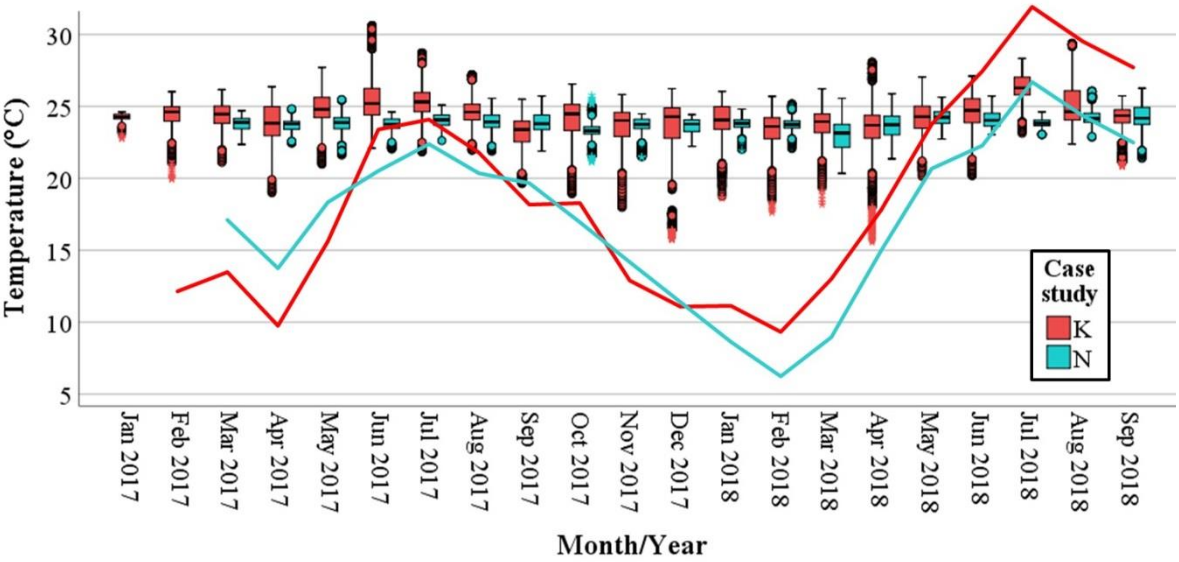
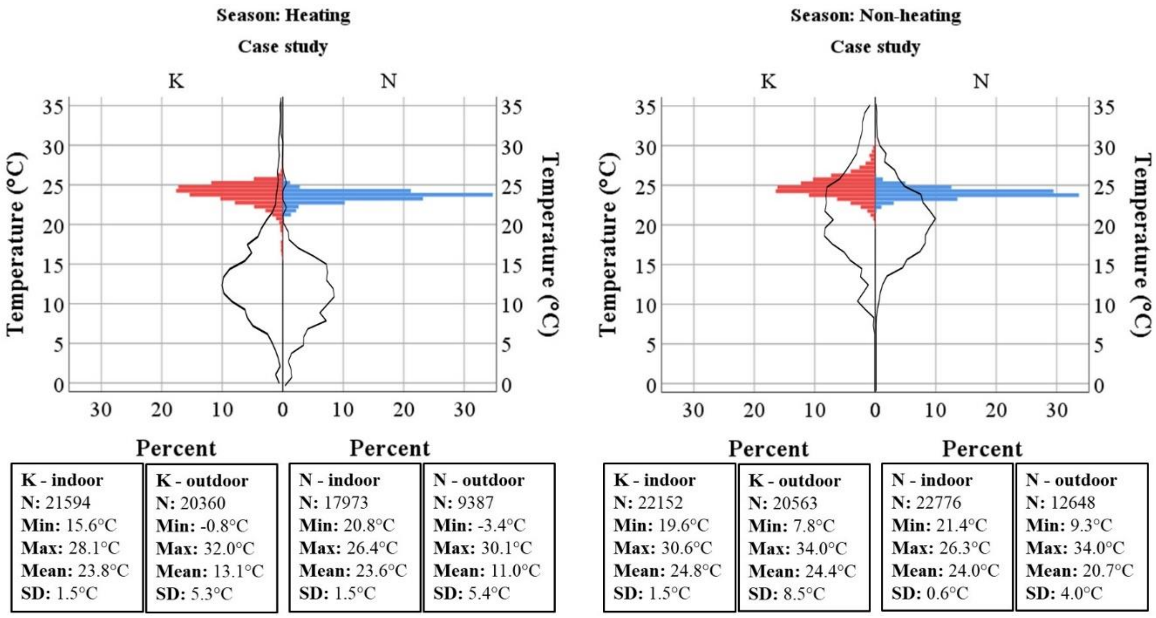


Figure 1 Boxplot showing distribution of monthly indoor temperatures during working hours in case studies 'K' and 'N', with monthly average outdoor temperatures during working hours also shown.

In the UK-based context of the case study buildings, the heating and non-heating seasons are taken as October-April and May-September respectively. The violin graphs (Figure 2) show the distribution of recorded temperatures during working hours in both case study working areas during the heating and non-heating seasons. Two things are immediately evident from these violin plots: (1) temperatures in ‘K’ covered a wider range than in ‘N’ during both heating and non-heating seasons; (2) seasonal variation in temperature distributions was significantly greater in ‘K’ than in ‘N’. In ‘K’, members of staff experienced temperatures as low as 15.6°C at the start of their working day during the heating season. Interestingly, in ‘N’, there was very little difference between the maximum recorded temperatures during the heating and non-heating seasons.



K - indoor
N: 21594
Min: 15.6°C
Max: 28.1°C
Mean: 23.8°C
SD: 1.5°C

K - outdoor
N: 20360
Min: -0.8°C
Max: 32.0°C
Mean: 13.1°C
SD: 5.3°C

N - indoor
N: 17973
Min: 20.8°C
Max: 26.4°C
Mean: 23.6°C
SD: 1.5°C

N - outdoor
N: 9387
Min: -3.4°C
Max: 30.1°C
Mean: 11.0°C
SD: 5.4°C

K - indoor
N: 22152
Min: 19.6°C
Max: 30.6°C
Mean: 24.8°C
SD: 1.5°C

K - outdoor
N: 20563
Min: 7.8°C
Max: 34.0°C
Mean: 24.4°C
SD: 8.5°C

N - indoor
N: 22776
Min: 21.4°C
Max: 26.3°C
Mean: 24.0°C
SD: 0.6°C

N - outdoor
N: 12648
Min: 9.3°C
Max: 34.0°C
Mean: 20.7°C
SD: 4.0°C

Figure 2 Violin graphs showing distribution of indoor temperatures during working hours in case studies 'K' and 'N' during the heating season (left) and non-heating season (right), with distribution of outdoor temperatures (black lines) and descriptive statistics also shown.

Averaged diurnal temperatures (at 5-minute resolution) during the heating and non-heating seasons are shown in Figure 3. Diurnal outdoor temperatures indicated that ‘K’s outdoor temperatures were around 1°C warmer than ‘N’s, likely due to London’s urban heat island. Again, this figure illustrates the much smaller seasonal difference in ‘N’ than in ‘K’. It also shows the much greater range of temperatures experienced by ‘K’s occupants over the course of a typical working day. During the heating season, ‘K’s temperatures increased by an average of 2.9°C over the course of the working day, but with some days increasing by up to 7.4°C. By contrast, temperatures in ‘N’ increased by an average of only 1.3°C over the course of the working day, with the greatest increases experienced being only 4.1°C. During the non-heating season, K’s average working day temperature increases were 2.4°C (up to a maximum of 5.0°C) compared to N’s average of 1.3°C (up to a maximum of 4.6°C).

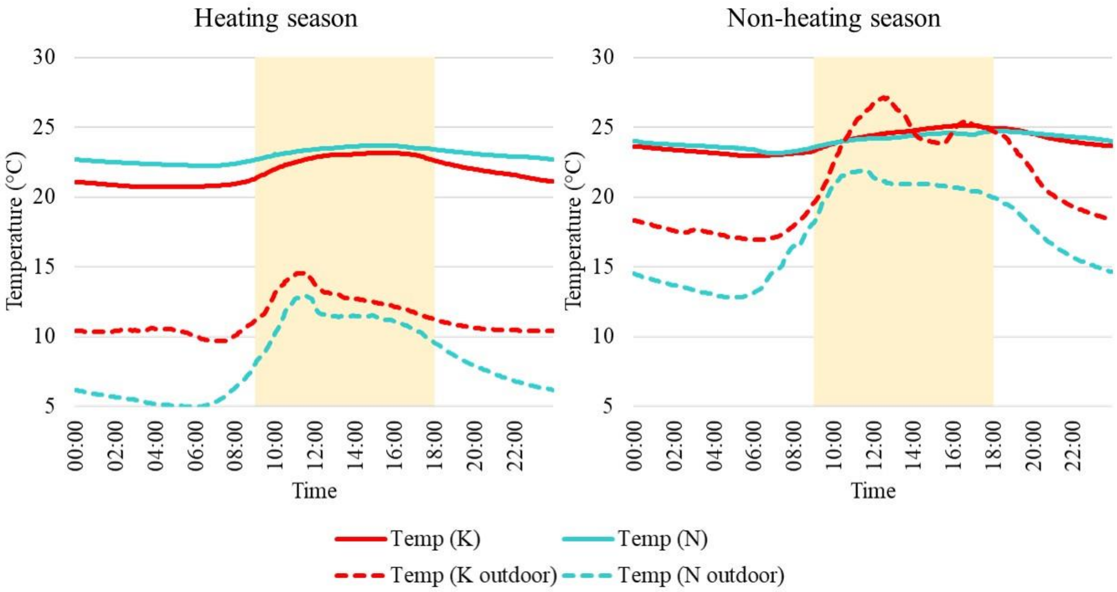


Figure 3 Indoor diurnal temperature variations in case studies 'K' and 'N' averaged over the heating season (left) and non-heating season (right) (shaded area shows working hours), with outdoor diurnal temperatures also shown.

Analysis was conducted into the correlation between outdoor temperature and concurrent average indoor temperature for both case study buildings (Table 5). In ‘K’, there was a much stronger correlation during the non-heating season than during the heating season. A key factor influencing this relationship was the pattern of window opening in the case study offices: during the heating season windows were kept closed for the vast majority of the time; during the non-heating season, windows were much more likely to be open. The correlations were also stronger when factoring in non-working hours, when occupants were not controlling their environment to mitigate against the outdoor conditions. In ‘N’ there was less difference in the strength of correlation between seasons and between working and non-working hours. During the heating season, the correlations were stronger in ‘N’ than in ‘K’ for both working hours and all hours. This is likely due to ‘N’ experiencing more stable indoor temperatures with increases and decreases within a smaller range during the day, as well as a lower difference between indoor and outdoor temperatures. Case study ‘K’, by contrast, experienced more rapid temperature changes, particularly during the heating season when the FCUs heated the working areas more rapidly at the start of the working day compared to more gradual temperature increases in ‘N’. During the non-heating season, ‘N’s correlation during working hours was stronger than during non-working hours.

Table 5 Pearson R correlations between indoor and outdoor temperatures during the heating and non-heating seasons in case studies ‘K’ and ‘N’, with 99% confidence intervals also shown.

			Case study ‘K’		**Case study ‘N’**	
			Heating season	**Non-heating season**	**Heating season**	**Non-heating season**
Working hours	N		20360	19181	9382	12648
	R		0.289	0.515	0.438	0.480
	Confidence interval (99%)	Lower	0.272	0.501	0.416	0.462
		Upper	0.305	0.529	0.459	0.497
All hours	N		82440	78985	36858	48779
	R		0.443	0.638	0.535	0.439
	Confidence interval (99%)	Lower	0.436	0.633	0.525	0.430
		Upper	0.450	0.6434	0.545	0.448

The recommended temperature range for Category II mechanically ventilated office buildings is 22-24°C in summer and 21-23°C in winter (CIBSE, 2015), the implication being that within these ranges there is no negative impact on occupant health and comfort. For naturally ventilated buildings, indoor temperature is more strongly dependent on the outdoor temperature. During the heating season, temperatures exceeded the recommended 23°C for 58% of working hours in both buildings. However, temperatures exceeded 25°C for only 1% of working hours in ‘N’ compared to 11% of working hours in ‘K’. During the non-heating season, temperatures exceeded the recommended 24°C for 41% of working hours in ‘N’ and 60% of working hours in ‘K’. However, temperatures exceeded 26°C for only 1% of working hours in ‘N’ compared to 15% of working hours in ‘K’.

Analysis was conducted to calculate the adaptive thermal comfort temperature during working hours based on the measured outdoor temperature ($T_{comfort} = 0.31*T_{outdoor} + 17.8$). This thermal comfort temperature then informed the range of temperatures within with thermal acceptability was expected to be 80% or higher (i.e. 80% of occupants would be thermally satisfied within this temperature range). Although this adaptive thermal comfort model is usually only applied to naturally-ventilated buildings, it has been applied to both case study buildings here so that the two can be compared directly. This predicted thermally comfortable temperature range was then compared to the measured indoor temperature during working hours in both case study buildings. The proportions of working hours when measured temperatures were within this comfort range are shown in Table 6.

Table 6 Proportion of working hours within adaptive thermal comfort model's 80% acceptability range in both case studies 'K' and 'N'.

		All working hours	**Heating season**	**Non-heating season**
Case study ‘K’	Cold	5.5%	1.1%	9.8%
	Comfortable	83.8%	79.5%	88.0%
	Hot	10.7%	19.4%	2.2%
Case study ‘N’	Cold	0.2%	0.0%	0.3%
	Comfortable	90.7%	78.5%	99.7%
	Hot	9.1%	21.5%	0.0%

Although temperatures during working hours in both buildings were below 27 °C for the majority of the time, this analysis showed that the 80% thermal acceptability range (“Comfortable” in the table) was exceeded in ‘K’ for almost 11% of working hours and in ‘N’ for over 9% of working hours. This “overheating” was much more prevalent during the heating season in both buildings (19.4% in ‘K’ and 21.5% in ‘N’). In the non-heating season, ‘N’ was within the 80% thermal acceptability range almost all of the time, whereas in ‘K’ the workspace was too cold for almost 10% of working hours, and too hot for 2% of working hours. As Figure 3 (above) showed, outdoor temperatures were higher on average in case study ‘K’ than ‘N’, thus bringing more of the higher indoor temperatures in ‘K’ to within the acceptable comfort range than the equivalent temperatures in ‘N’.

In addition, the more varied temperatures experienced over the course of the working day in ‘K’, as mentioned above, added to the less acceptable thermal conditions relative to those experienced in ‘N’. One of the strengths of this research study was that it was conducted in a ‘real world’ context – two workplaces where occupants were experiencing a myriad of conditions and mitigating factors – rather than in an artificially controlled climate chamber where variables would have been, as far as possible, kept constant and varied only in discrete steps. This however, brought with it limitations: It was not possible – or indeed ethical – to artificially force the indoor environmental conditions to be artificially high or low in order to gather occupant feedback at extremes beyond the normally acceptable ranges. The research was therefore limited to the conditions experienced ‘naturally’ within the two case study workspaces. The upper limits thus became less important than the variability experienced by the occupants.

5.1.2 Indoor RH

In both case study buildings, RH followed a similar pattern over the monitored period, being higher during the non-heating season (generally in the 40-60% range) and lower during the heating season (generally in the 30-50% range) when the heating in the offices served to dry the air. In contrast, outdoor RH tended to be higher during the heating season than the non-heating season. The boxplot of monthly RH distributions during working hours in the two case study buildings shows these trends (Figure 4). Interestingly, during the non-heating season, monthly medians tended to be higher in ‘N’ than in ‘K’, whereas during the heating season, monthly medians tended to be higher in 'K' than in 'N'. The violin graphs show similar distributions of RH in 'K' and 'N', with the descriptive statistics showing the subtle differences between the two buildings (Figure 5).

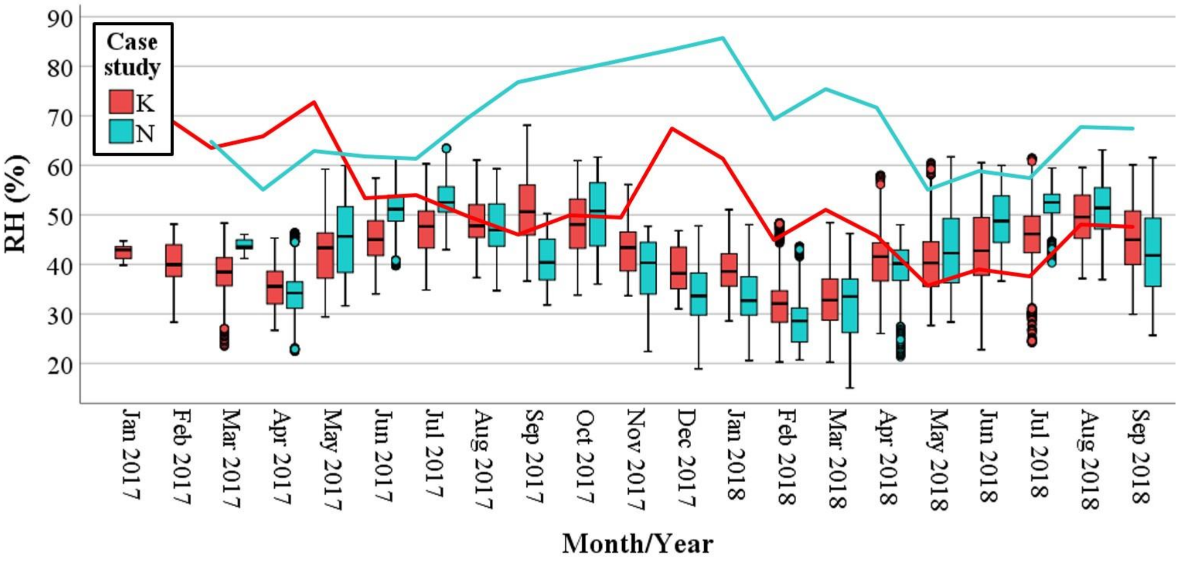


Figure 4 Boxplots showing distribution of monthly indoor RH during working hours in case studies 'K' and 'N', with monthly average outdoor RH during working hours also shown.

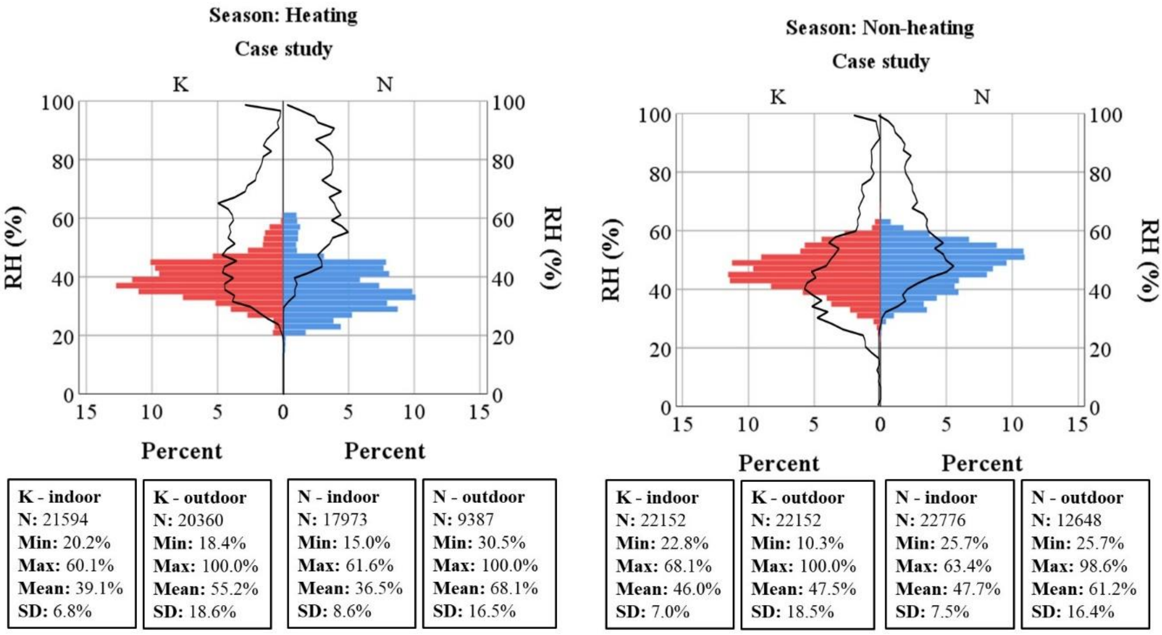


Figure 5 Violin graphs showing distribution of indoor RH during working hours in case studies 'K' and 'N' during the heating season (left) and non-heating season (right), with distribution of outdoor RH (black lines) and descriptive statistics also shown.

Averaged diurnal RH (at 5-minute resolution) during the heating and non-heating seasons are shown in Figure 6. In both seasons, during working hours, RH rose slightly at the start of the working day, then dropped gradually throughout the working day. After occupants had left the offices, RH began to rise back to ambient levels overnight. During the heating season, 'N' had lower RH than 'K' as the heated ventilation system replaced humid air with drier air. During the non-heating season, RH was higher in both buildings and more closely aligned, particularly during non-working hours. There was a much greater change in RH over the working day in 'K' during the non-heating season. Being located in central London, outdoor RH is consistently lower around case study 'K' than the more rurally located 'N'. During the non-heating season, when 'K's windows were more likely to be opened during the working day, the drier outdoor air was able to mix with the indoor air and lower the indoor RH levels.

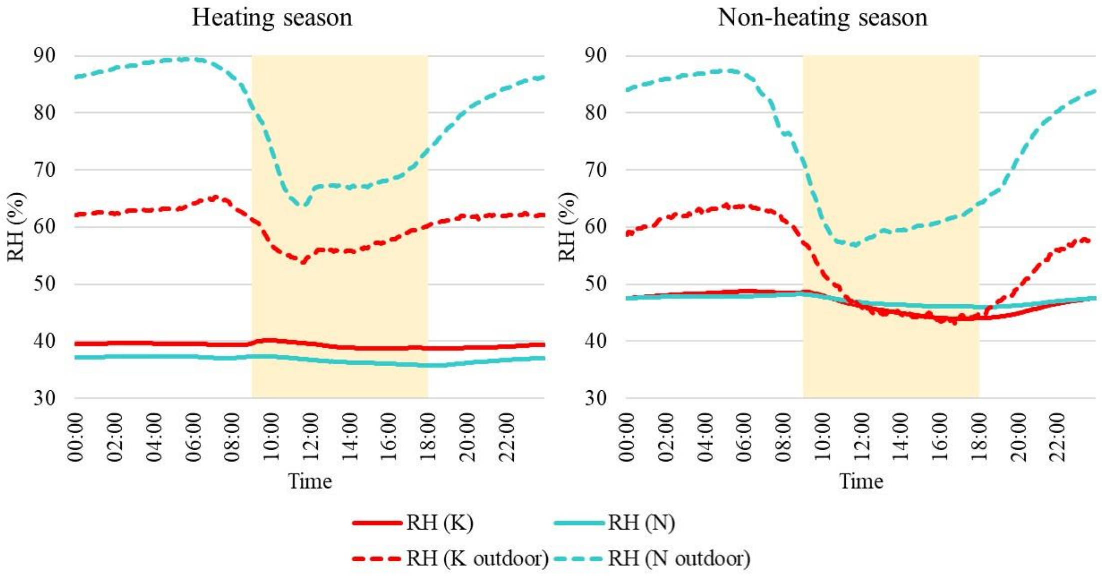


Figure 6 Indoor diurnal RH variations in case studies 'K' and 'N' averaged over the heating season (left) and non-heating season (right) (shaded area shows working hours), with outdoor diurnal RH also shown.

Analysis was conducted into the correlation between outdoor RH and concurrent average indoor RH for both case study buildings (Table 7). As with temperature, in 'K', there was a much stronger correlation during the non-heating season than during the heating season. The correlations were weaker when factoring in non-working hours as with windows were routinely closed overnight. In 'N' there was less difference in the strength of correlation between seasons but a significant difference between working and non-working hours.

Table 7 Pearson R correlations between indoor and outdoor RH during the heating and non-heating seasons in case studies 'K' and 'N'.

		Case study 'K'		**Case study 'N'**	
		Heating season	**Non-heating season**	**Heating season**	**Non-heating season**
Working hours	N	20360	22152	9382	12648
	R	0.28	0.42	0.41	0.56
All hours	N	82440	87579	36858	48779
	R	0.22	0.45	0.29	0.32

5.1.3 CO_2 concentration

Measured CO_2 concentration provided the most significant contrast between the two buildings, particularly during the heating season. The boxplot of monthly CO_2 concentrations during working hours shows that ‘K’ consistently had a much greater interquartile range than ‘N’, and much greater seasonal variations (Figure 7). In case study ‘N’, peak concentrations were kept below 1200 ppm for the vast majority of working hours throughout both seasons. Monthly median concentrations were consistently between 700 and 900 ppm. In ‘K’ during the non-heating season, CO_2 concentrations were similar to those in the MV building, with median levels in the 600-900 ppm range. However, during the heating season, with windows closed for the majority of the time, CO_2 levels increased dramatically, with median levels exceeding 1200 ppm and peaks in excess of 2500 ppm.

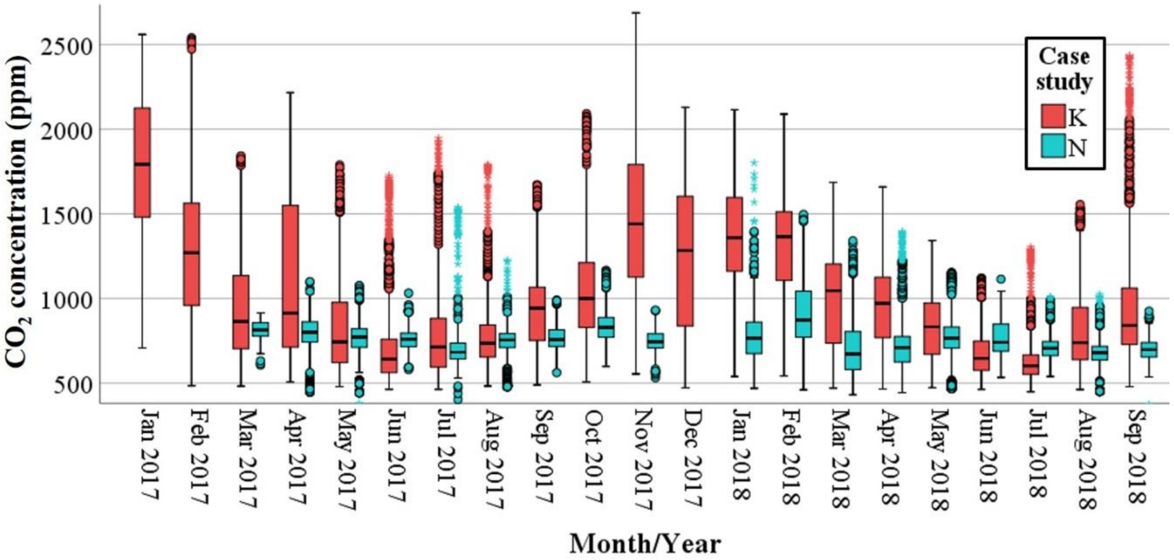


Figure 7 Boxplots showing distribution of monthly indoor CO_2 concentration during working hours in case studies 'K' and 'N'.

The violin graphs further illustrate the great difference between ‘K’s CO2 concentrations in the heating and non-heating seasons (Figure 8). During the heating season, CO_2 concentrations in ‘K’ exceeded 2000 ppm on 12% of monitored days. Although peak concentrations during the non-heating season could still reach in excess of 2400 ppm, these were rare occasions, with peak concentrations exceeding 2000 ppm on less than 1% of monitored days. In contrast, CO_2 concentrations in ‘N’ exceeded 1500 ppm on one heating-season day and one non-heating-season day.

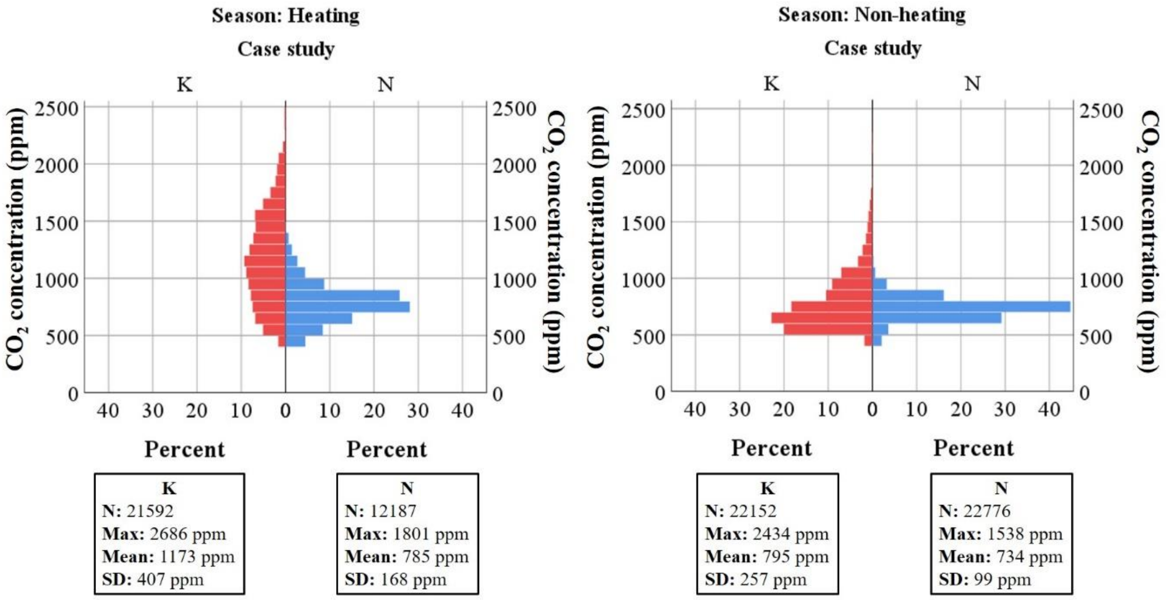


Figure 8 Violin graphs showing distribution of indoor CO_2 concentration during working hours in case studies 'K' and 'N' during the heating season (left) and non-heating season (right), with descriptive statistics also shown.

Averaged diurnal CO_2 concentrations (at 5-minute resolution) during the heating and non-heating seasons are shown in (Figure 9). The trend in both buildings and both seasons was the same: at the start of the working day, concentrations rose sharply, peaking between 11am-12pm. There was often a slight dip in the early afternoon (due to occupancy decreasing as people took their lunchbreaks out of the office), but concentrations remained high until the end of the working day. In the evenings, concentrations fell back to ambient levels. ‘N’s profile did not change much between the heating and non-heating seasons, whereas ‘K’s heating season profile was significantly different. It is notable that it took much longer for concentrations to drop back to ambient levels overnight during the heating season compared to the non-heating season, particularly in ‘K’ where concentrations were still declining by the start of the following working day.

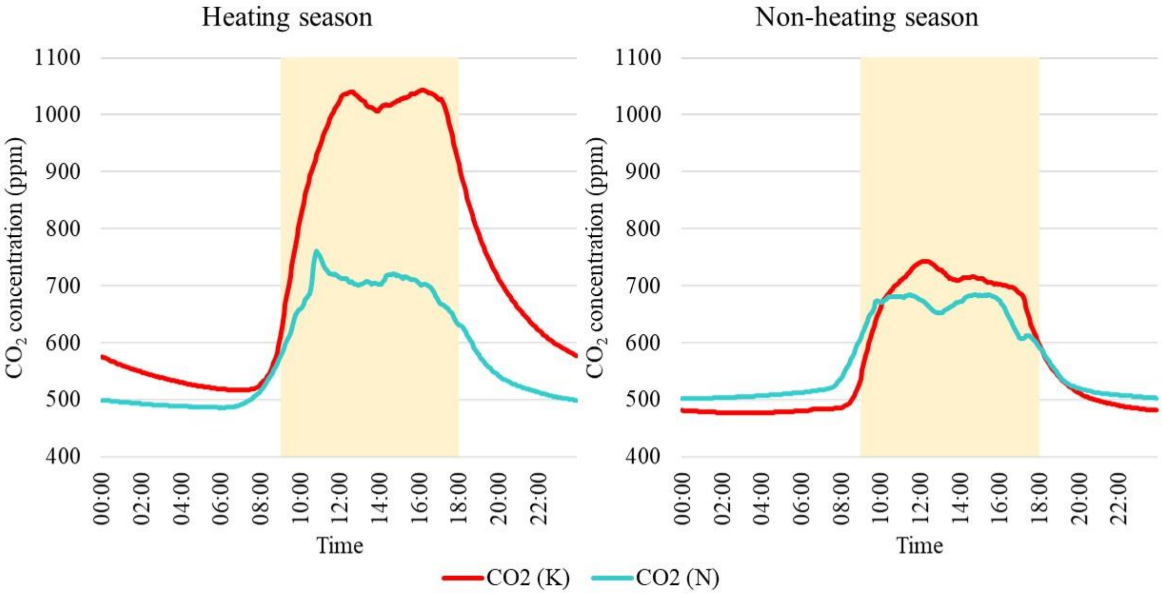


Figure 9 Indoor diurnal CO_2 concentration variations in case studies 'K' and 'N' averaged over the heating season (left) and non-heating season (right) (shaded area shows working hours).

5.2 Transverse survey responses: BUS survey

An overview of occupant perception of their working environment was provided by the BUS survey. Key questions relating to the indoor environment asked respondents to describe typical working conditions in their normal working area in winter and in summer in terms of temperature (unsatisfactory/satisfactory overall; hot/cold; stable/varies), air (still/draughty; dry/humid; fresh/stuffy; odourless/smelly) and overall conditions (unsatisfactory/satisfactory).

For the sake of analysis, the discrete responses to the temperature and air questions were treated as continuous. A one-way between groups analysis of variance was conducted to explore the impact of season (winter/summer) on each of the temperature and air parameters measured (Table 8). In ‘K’, several of the parameters had a statistically significant difference at the p<.05 level in responses for winter and summer. In ‘N’, only one parameter had a statistically significant difference at the p<.05 level between mean responses for winter and summer. This indicated that ‘N’s occupants did not perceive significant differences in the indoor environment between winter and summer other than in finding it colder in the winter and warmer in the summer. In contrast, ‘K’s occupants found temperatures significantly more uncomfortable in the winter than in the summer, temperatures significantly too hot in the winter and too cold in the summer, the air to be drier in the winter than in the summer, and the air to be more stuffy in the summer than in the winter (interesting considering the CO_2 concentration results discussed above and the increased window opening that ‘K’s occupants had in the summer).

Table 8 Analysis of variance results for temperature and air' parameters, showing mean responses for winter and summer, and whether the difference in mean scores was statistically significant (ANOVA). (Note: a score of 4 on the 1-7 scale represented a neutral response).

	Case study ‘K’			**Case study ‘N’**		
	Winter	**Summer**	**Sig?**	**Winter**	**Summer**	**Sig?**
Temperature: 1 – uncomfortable 7 – comfortable	Mean: 4.60 SD: 1.44	Mean: 3.11 SD: 1.52	✓	Mean: 4.66 SD: 1.52	Mean: 4.28 SD: 1.81	✗
Temperature: 1 – hot 7 – cold	Mean: 4.43 SD: 1.19	Mean: 2.48 SD:1.09	✓	Mean: 4.51 SD: 1.06	Mean: 3.50 SD: 1.25	✓
Temperature: 1 – stable 7 – varies	Mean: 4.68 SD: 1.75	Mean: 4.73 SD: 1.61	✗	Mean: 4.91 SD: 1.71	Mean: 4.87 SD: 1.70	✗
Air: 1 – still 7 – draughty	Mean: 3.19 SD: 1.19	Mean: 2.85 SD: 1.33	✗	Mean: 3.91 SD: 1.62	Mean: 3.45 SD: 1.90	✗
Air: 1 – dry 7 – humid	Mean: 3.26 SD: 1.24	Mean: 4.44 SD: 1.70	✓	Mean: 3.13 SD: 1.07	Mean: 3.16 SD: 1.30	✗
Air: 1 – fresh 7 – stuffy	Mean: 4.78 SD: 1.31	Mean: 5.32 SD: 1.44	✓	Mean: 4.59 SD: 1.47	Mean: 4.92 SD: 1.46	✗
Air:	Mean: 3.82	Mean: 4.05	✗	Mean: 2.93	Mean: 3.15	✗

1 – odourless 7 – smelly	SD: 1.45	SD: 1.50		SD: 1.48	SD: 1.57	
Overall conditions 1 – unsatisfactory 7 - satisfactory	Mean: 4.55 SD: 1.30	Mean: 3.42 SD: 1.49	✓	Mean: 4.70 SD: 1.59	Mean: 4.31 SD: 1.64	✗

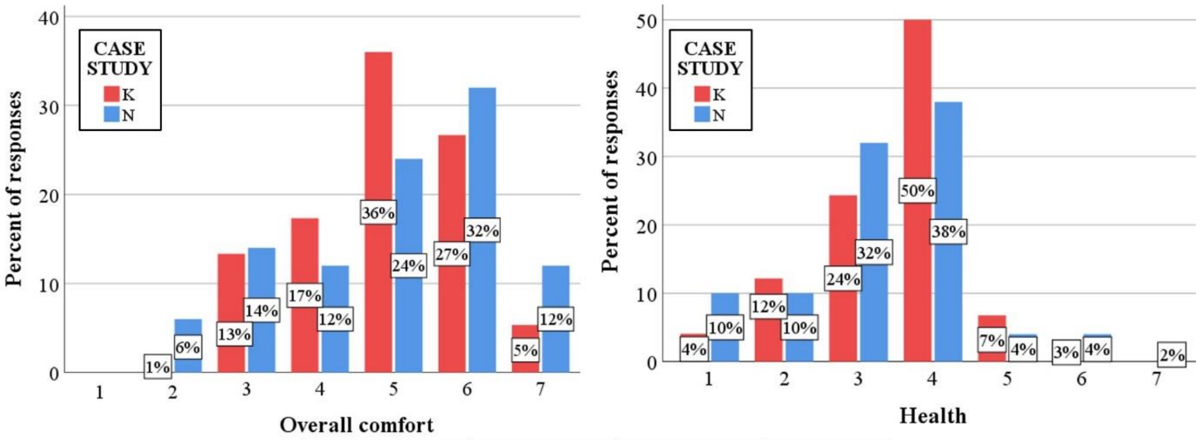
Comparing these BUS results between case study buildings, the distribution of winter responses was only significantly different at the p<.05 level for ‘Air in winter (still/draughty)’ – where ‘K’s occupants found the air significantly more still than ‘N’s occupants – and ‘Air in winter (odourless/smelly)’ – where ‘N’s occupants found the air more odourless than ‘K’s occupants. Comparing responses for summer conditions, all but one of the parameters – ‘Temperature in summer (stable/varies)’ – had statistically significant differences between case studies. Occupants in ‘K’ rated their workspaces hotter and stuffier than those in ‘N’. Occupants in ‘N’ rated the air to be less still, drier and less smelly than their counterparts in ‘K’. Interestingly, ‘K’s occupants rated temperatures to be more comfortable than their counterparts in ‘N’ in winter, despite the significantly wider range of working hours temperatures found in their respective workspaces.

Occupants were asked to rate the overall conditions in winter and summer in relation to temperature and air (on a scale from 1 (unsatisfactory) to 7 (satisfactory). One-way between groups analysis of variance found a statistically significant difference between winter and summer responses in ‘K’, with occupants feeling significantly more satisfied with winter conditions than summer conditions (means of 4.55 (winter) and 3.42 (summer)). In ‘N’, the difference between winter and summer satisfaction was not statistically significantly different (means of 4.70 (winter) and 4.31 (summer)). Comparing the two case studies, the difference in responses for winter conditions was not significantly different. However, summer conditions were rated significantly more satisfactory by ‘N’s occupants than by ‘K’s.

The BUS questionnaire also asked occupants about the level of control they felt they had over their working environment in terms of heating, cooling, ventilation, noise and lighting. Control has been linked to perceptions of thermal comfort in several studies (Barlow and Fiala, 2007, Hellwig et al., 2006, O'Brien and Gunay, 2014, Wagner et al., 2007). In all of the control categories, the most popular response by far was ‘1’ (no control). For each of the five categories, between 75 and 86% of ‘N’s respondents rated their control as ‘1’. ‘K’s respondents felt they had slightly more control, but still between 24 and 59% of respondents rated their control as ‘1’. No respondent in either building for any of the control categories rated their control as ‘7’ (full control).

For each of the control categories, a one-way between groups analysis of variance was conducted to explore the difference in distribution of results between the two case study buildings. ‘N’s occupants felt that they had much less control than ‘K’s occupants, with the greatest differences in means being for control of ventilation and lighting. All of the categories had statistically significant differences between buildings except for control of noise. As both case study buildings have a similar open-plan structure, this is understandable.

The final relevant BUS survey questions for this study asked occupants to rate the overall comfort of the building environment and whether they felt less or more healthy when they are in their respective buildings. The distribution of responses for each of the case studies were similar (Figure 10), despite the significant differences in indoor environment analysed above. One-way between groups analysis of variance conducted on both overall comfort votes and health votes found no statistically significant differences at the $p<.05$ level between the two case studies, ‘K’ and ‘N’.



	Case study 'K'	Case study 'N'	Significant?
Overall comfort: 1 – unsatisfactory 7 – satisfactory	Mean: 4.98 SD: 1.15	Mean: 4.98 SD: 1.44	✗
Health: 1 – less healthy 7 – more healthy	Mean: 3.51 SD: 1.02	Mean: 3.36 SD: 1.27	✗

Figure 10 Distribution of responses relating to overall comfort of the building environment (left) and whether respondents felt less or more healthy when in the building (right), with key statistics.

Treating all of the response votes on the 1-7 scales as continuous, non-parametric Spearman's rho correlations were found between perceptions of the indoor environment (temperature and air parameters discussed above) and overall comfort votes. The statistically significant ($p<.05$) correlations are shown in Table 9. Although more of the temperature and air parameters had significant correlations with overall comfort in 'K' than in 'N', when both buildings showed a significant correlation, it was stronger in 'N' than in 'K'. In both buildings, the strongest correlations were with 'conditions in summer (overall)', 'temperature in winter (overall)' and 'temperature in summer (overall)'.

Table 9 Statistically significant Spearman's correlations with 'Comfort' votes.

Comfort parameter	Case study 'K'		Case study 'N'	
	N	Spearman's rho	N	Spearman's rho
Temperature in winter (overall)	74	0.45**	47	0.60**
Temperature in winter (stable/varies)	74	-0.29*		
Air in winter (fresh/stuffy)	73	-0.23*		
Conditions in winter (overall)	74	0.38**	46	0.62**

Temperature in summer (overall)	61	0.26*	39	0.45**
Air in summer (dry/humid)			37	0.41*
Air in summer (odourless/smelly)	61	-0.33**		
Conditions in summer (overall)	60	0.46**	39	0.65**

***Correlation is significant at the 0.05 level**

****Correlation is significant at the 0.01 level**

In contrast to the 'comfort' correlations, only two of the temperature and air parameters had any significant correlations with occupants' perception of how their health was affected when they were in the building: overall conditions in winter and summer (Table 10). These correlations were both in 'K' – none of the temperature and air parameters had significant correlations with 'health' in 'N'. Analysis of the five 'personal control' parameters found no statistically significant correlations between these and either 'overall comfort' or 'health'.

Table 10 Statistically significant Spearman's correlations with 'Health' votes.

Comfort parameter	Case study 'K'		Case study 'N'	
	N	Spearman's rho	N	Spearman's rho
Conditions in winter (overall)	73	0.24*		
Conditions in summer (overall)	60	0.33*		

***Correlation is significant at the 0.05 level**

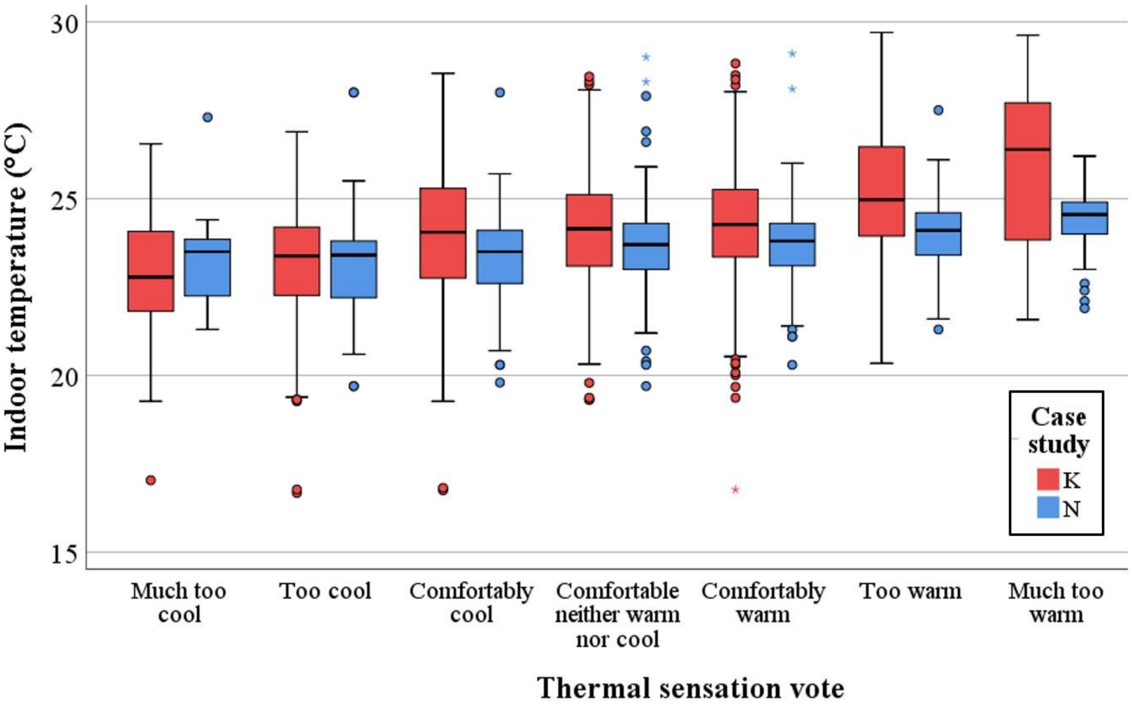
5.3 Longitudinal survey responses: Online survey

5.3.1 Thermal sensation and thermal preference

The data considered up to this point has considered the overall indoor environmental conditions in the workspaces over approximately 19 months, and occupant feedback reflecting on the general overall conditions in their workspaces. The longitudinal surveys provided more long-term data, where occupants could reflect on their localised environment at that moment and their responses could be cross-related to the concurrent environmental conditions (air temperature, RH and CO_2 concentration). A total of 5762 responses were received during the 5 waves of data collection, 53% from ‘K’ and 47% from ‘N’. The majority of the surveys were conducted during non-heating months (May to September), with a minority conducted during the shoulder months when heating was not necessarily required. Therefore the indoor temperatures during these periods were affected to a greater extent by the opening of windows in the naturally ventilated case study ‘K’ and cool air provided by mechanical ventilation in case study ‘N’, rather than the operation of the heating and air conditioning systems respectively.

A one-way analysis of variance was conducted to explore the impact of gender or the period when the surveys were conducted on the occupants’ responses to the survey questions, but there were no statistically significant differences at the p<.01 level. Therefore the following analysis considers all of the survey responses gathered at different periods over the 19 months of monitoring.

Cross-relating the thermal sensation votes with the concurrent indoor temperatures showed a significant distinction between the two case-study buildings (Figure 11). The range of indoor temperatures experienced by the occupants was much greater in ‘K’, and yet they were much more tolerant, particularly at higher temperatures. The median temperature when ‘K’s occupants voted for ‘Comfortably cool’/’Comfortable neither warm nor cool’/’Comfortably warm’ was 24.1-24.3°C, compared to 23.5-23.8°C for ‘N’s occupants. Indeed, 24.1°C in ‘N’ was the median temperature for thermal comfort votes of ‘too warm’. As the whiskers on the boxplots show, respondents in ‘N’ were not experiencing as wide a range of temperatures as their counterparts in ‘K’. Nevertheless, other than at the ‘Cool’ and ‘Much too cool’ end of the scale, median temperatures were higher from ‘K’s occupants than from ‘N’s occupants for each thermal comfort vote.

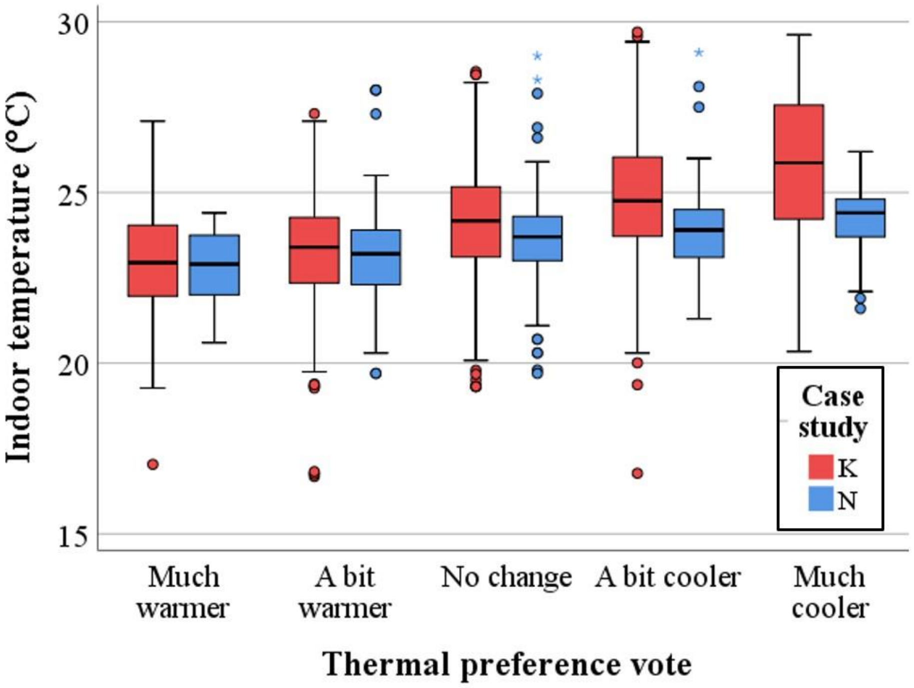


	Much too cool	Too cool	Comfortably cool	Comfortable neither warm nor cool	Comfortably warm	Too warm	Much too warm
K	22.8	23.4	24.1	24.1	24.3	25.0	26.4
N	23.5	23.4	23.5	23.7	23.8	24.1	24.6

Figure 11 Boxplot showing distribution of concurrent indoor temperatures for each thermal sensation vote category in case studies ‘K’ and ‘N’, with table showing median temperatures (°C) experienced for each thermal sensation vote.

A similar pattern was found for the thermal preference votes. The distribution of votes was similar in both buildings and a higher proportion of ‘N’s occupants than ‘K’s occupants expressed a preference to be cooler. Again, the five response categories were converted into numerical values from 1 (‘much warmer’) to 5 (‘much cooler’), allowing a one-way between groups analysis of variance to be conducted. This found a statistically significant difference at the $p<.05$ level between ‘K’s and ‘N’s responses, with F=138, p=0.00. However, the actual difference in group mean scores was small (smaller than for thermal sensation votes). Post hoc comparisons using Tukey HSD test showed the mean score for ‘K’ (m=3.02, SD=0.84) was significantly different from ‘N’ (m=3.28, SD=0.82), where a mean score of 3 would represent ‘no change’.

Plotting thermal preference votes against concurrent indoor temperatures showed a similar pattern to thermal sensation vs. indoor temperatures (Figure 12): the range of concurrent temperatures experienced by ‘K’s occupants was much greater than that experienced by ‘N’s occupants (longer whiskers on the boxplots) and the median temperatures corresponding to each thermal preference vote were higher for ‘K’s occupants than for ‘N’s. The median temperature corresponding to a vote of ‘no change’ was 0.5°C higher for ‘K’s occupants than for ‘N’s. The median temperature for the extreme ‘much cooler’ vote was 1.5°C higher for ‘K’s occupants than for ‘N’s.



	Much warmer	**A bit warmer**	**No change**	**A bit cooler**	**Much cooler**
K	22.9	23.4	24.2	24.8	25.9
N	22.9	23.2	23.7	23.9	24.4

Figure 12 Boxplot showing distribution of concurrent indoor temperatures for each thermal sensation vote category in case studies 'K' and 'N', with table showing median temperatures (°C) experienced for each thermal sensation vote.

Using outdoor temperatures concurrent with completion of the surveys, it was possible to calculate the predicted comfort temperature ($T_{comfort} = 0.31*T_{outdoor} + 17.8$) and therefore the range of temperatures for which there would be 80% acceptability ($T_{comfort} \pm 3.5$ °C) – i.e. that at least 80% of occupants would be satisfied with the thermal condition. As mentioned above, this adaptive thermal comfort model is normally only applicable to naturally ventilated buildings. However, in order to compare the results from the two case study buildings, this temperature range for 80% acceptability has been applied to both case study buildings. For each survey response, the predicted comfort level was calculated based on whether the measured indoor temperature was within the 80% acceptability range ("Comfortable"), above it ("Hot") or below it ("Cold"). This was then cross-related with occupants' thermal sensation votes (Table 11 and Table 12).

Table 11 Cross-relating predicted thermal comfort using adaptive model and measured thermal sensation votes in case study 'K'.

		Predicted thermal comfort			**TOTAL**	**%**
		Cold	**Comfortable (80% acceptability)**	**Hot**		
Thermal sensation vote	**Much too warm**	2	42	5	49	**1.7%**
	Too warm	15	253	95	363	**12.8%**
	Comfortably warm	15	295	138	448	**15.8%**
	Comfortable	19	683	274	976	**34.5%**
	Comfortably cool	16	473	95	584	**20.6%**
	Too cool	7	236	92	335	**11.8%**
	Much too cool	1	56	17	74	**2.6%**
TOTAL		75	2038	716		
%		**2.7%**	**72.0%**	**25.3%**		

Table 12 Cross-relating predicted thermal comfort using adaptive model and measured thermal sensation votes in case study 'N'.

		Predicted thermal comfort			**TOTAL**	**%**
		Cold	**Comfortable (80% acceptability)**	**Hot**		
Thermal sensation	**Much too warm**	2	61	1	64	**3.2%**
	Too warm	15	308	3	326	**16.5%**
	Comfortably warm	25	370	0	395	**20.0%**
	Comfortable	38	641	2	681	**34.5%**

	Comfortably cool	16	331	0	347	**17.6%**
	Too cool	4	128	1	133	**6.7%**
	Much too cool	0	31	0	31	**1.6%**
TOTAL		100	1870	7		
%		**5.1%**	**94.6%**	**0.4%**		

From these thermal sensation votes, thermal satisfaction/acceptability was defined as votes of "Comfortably warm", "Comfortable neither warm nor cool" and "Comfortably cool", and the cross-relation tables simplified (Table 13 and Table 14).

Table 13 Cross-relation of predicted and measured thermal satisfaction thermal satisfaction in case study 'K'. Italicised percentages show proportion of measured thermal satisfaction votes within the predicted comfortable range.

		Predicted thermal comfort			**TOTAL**	**%**
		Cold	**Comfortable (80% acceptability)**	**Hot**		
Measured thermal satisfaction	**Hot**	17	295 *(14.5%)*	100	412	**14.6%**
	Comfortable	50	1451 *(71.2%)*	507	2008	**71.0%**
	Cold	8	292 *(14.3%)*	109	409	**14.5%**
TOTAL		75	2038 *(100.0%)*	716		
%		**2.7%**	**72.0%**	**25.3%**		

Table 14 Cross-relation of predicted and measured thermal satisfaction thermal satisfaction in case study 'N'. Italicised percentages show proportion of measured thermal satisfaction votes within the predicted comfortable range.

		Predicted thermal comfort			**TOTAL**	**%**
		Cold	**Comfortable (80% acceptability)**	**Hot**		
Measured thermal satisfaction	**Hot**	17	369 *(19.7%)*	4	390	**19.7%**
	Comfortable	79	1342 *(71.8%)*	2	1423	**72.0%**
	Cold	4	159 *(8.5%)*	1	164	**8.3%**
TOTAL		100	1870 *(100.0%)*	7		
%		**5.1%**	**94.6%**	**0.4%**		

From these tables, only 72% of surveys in 'K' were conducted within the 80% thermal acceptability limits, compared to 95% of 'N's survey responses. Over a quarter of 'K's surveys were conducted in conditions which the adaptive thermal comfort model would consider too hot, compared to less than half a percent of 'N's surveys. If 72% of 'K's surveys were conducted within the 80% acceptability range, it would be expected that approximately

57.6% (0.720*0.80) of measured survey responses would be within the “Comfortable” range, much less than the measured 71.0% of responses. By comparison, if 94.6% of ‘N’s surveys were conducted within the 80% acceptability range, it would be expected that approximately 75.7% (0.946*0.80) of measured survey responses would be within the “Comfortable” range, slightly more than the measured 72.0% of responses.

Furthermore, only 15% of ‘K’s survey responses had thermal sensation votes on the hot end of the scale compared to the predicted 25%, whereas 20% of ‘N’s survey responses had thermal sensation votes on the hot end of the scale compared to the predicted 0.4%. Considering just the surveys conducted within the 80% acceptability temperature range, both case study buildings had a similar proportion of survey responses in the “Comfortable” range (71.2% in case study ‘K’ and 71.8% in case study ‘N’, the highlighted cells in Table 13 and Table 14), both significantly less than the predicted 80%. Interestingly, in case study ‘K’, a similar proportion of survey responses in this predicted “Comfortable” range gave measured responses on the hot and cold end of the thermal sensation scale (14.5% and 14.3% respectively). In contrast, in case study ‘N’, many more survey responses rated their thermal sensation on the hot end of the scale than on the cold end of the scale (19.7% compared to 8.5% respectively).

5.3.2 Perceived air quality

Perceived air quality votes were on a scale from 1 (fresh) to 7 (stuffy). The perceptions in both buildings were skewed towards the ‘stuffy’ end of the scale (Figure 13). During the heating season both buildings had windows closed and yet despite the mechanical ventilation in operation, a similar proportion of responses in both buildings expressed feeling stuffy. The distribution of votes in ‘K’ was very similar in both seasons, whereas ‘N’s occupants’ votes were more skewed towards the ‘stuffy’ end of the scale in the non-heating season than in the heating season, perhaps due to their perceived lack of control of their environment. The seven response categories were converted into numerical values from 1 (‘fresh’) to 7 (‘stuffy’), allowing a one-way between groups analysis of variance to be conducted. This found a statistically significant difference at the p<.05 level between ‘K’s and ‘N’s responses, with F=19, p=0.00. The actual difference in group mean scores was smaller than for thermal sensation or thermal preference votes. Post hoc comparisons using Tukey HSD test showed the mean score for ‘K’ (m=4.29, SD=1.38) was significantly different from ‘N’ (m=4.45, SD=1.44).

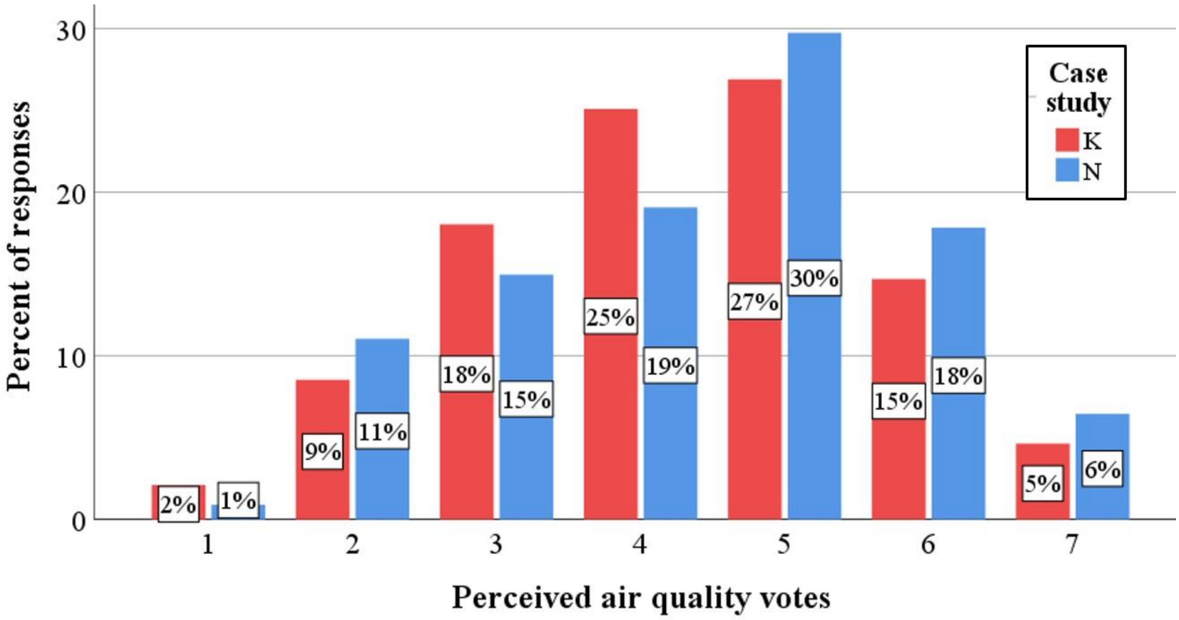


Figure 13 Distribution of perceived air quality votes in case studies 'K' and 'N' (1 = ‘fresh’, 7 = ‘stuffy’).

Treating air quality votes as continuous data allowed Spearman’s rho correlations with concurrent IEQ parameters to be found. In ‘K’, perceived air quality was found to correlate with temperature (n=2892, rho=0.16) and CO_2 concentration (n=2586, rho=0.08). In ‘N’, perceived air quality was found to correlate with temperature (n=1977, rho=0.12). All correlations were significant at the 0.01 level. Perceived air quality had no statistically significant correlation with RH in either building. These low correlations indicated that the perception of air quality is a more subjective sensation.

5.3.3 Overall comfort and measured IEQ

Finally, respondents were asked to rate their overall comfort on a scale from 1 (unsatisfactory) to 7 (satisfactory). Again, the distribution of results was similar in ‘K’ and ‘N’, with slightly over 50% of responses being on the more satisfactory end of the scale (5, 6 or 7) in the two buildings (Figure 14). One-way between groups analysis of variance found a statistically significant difference at the $p<.05$ level between ‘K’s and ‘N’s responses, with $F=5$, $p=0.02$. The difference in mean scores was the smallest of any of the survey response means. Post hoc comparisons using Tukey HSD test showed the mean score for ‘K’ ($m=4.56$, $SD=1.23$) was significantly different from ‘N’ ($m=4.48$, $SD=1.45$). This result is surprising in that it shows a statistically significant higher level of overall comfort satisfaction in the naturally ventilated case study ‘K’ – with the variable temperatures, higher highs and lower lows of temperature, and regularly high CO_2 concentrations – than in the mechanically ventilated case study ‘N’ – with the more stable, less extreme temperatures and consistently lower CO_2 concentrations.

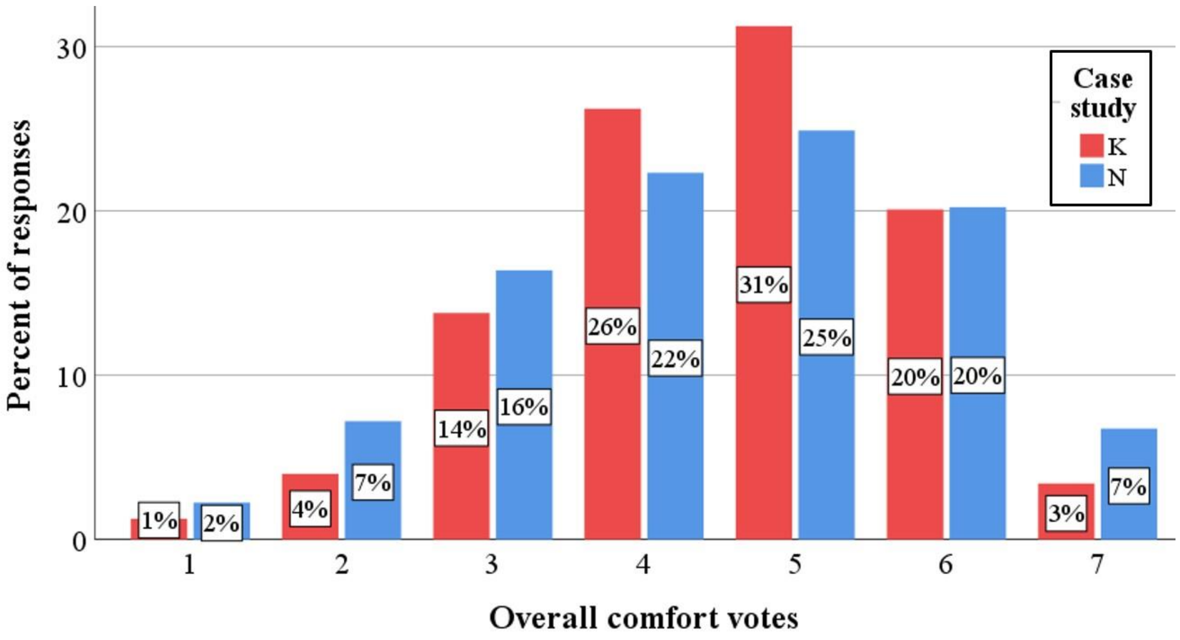


Figure 14 Distribution of perceived overall comfort votes in case studies 'K' and 'N'. (1 = 'unsatisfactory', 7 = 'satisfactory').

Treating overall comfort votes as continuous data allowed Spearman's rho correlations with concurrent IEQ parameters to be found. In 'K', overall comfort was found to correlate with temperature (n=2892, rho=-0.06) (the negative correlation indicating that as temperature increased, overall comfort votes decreased) and in 'N', overall comfort was found to correlate with RH (n=1977, rho=-0.06) (the negative correlation indicating that as RH increased, overall comfort votes decreased). Overall comfort votes had no statistically significant correlation with CO2 concentration. Although both of these correlations were significant at the 0.01 level, they were very small, indicating that the actual indoor environmental conditions were a poor indicator of how an individual would rate their personal overall comfort and that other factors were involved.

Standard multiple regression was used to assess the ability of three independent variables (thermal comfort votes, thermal preference votes and perceived air quality votes) to predict overall comfort votes. In 'K', initial analysis showed no violation of the assumptions of normality, linearity, multicollinearity and homoscedasticity. The total variance explained by the model as a whole was $R^2 = 11.8\%$, F = 137, p<.001. The perceived air quality votes recorded a higher beta value (beta = -0.39, p<.001) than either thermal comfort votes (beta = 0.08, p<0.05) and thermal preference votes (beta = -0.01, not significant at the p=0.05 level). In 'N', initial analysis showed no violation of the assumptions of normality, linearity, multicollinearity and homoscedasticity. The total variance explained by the model as a whole was $R^2 = 14.7\%$, F = 153, p<.001. The perceived air quality votes recorded a higher beta value (beta = -0.35, p<.001) than either thermal comfort votes (beta = 0.04, not significant at the p=0.05 level) and thermal preference votes (beta = 0.10, p<.005). So in both 'K' and 'N', the strongest indicator of overall comfort vote was perception of air quality.

In summary, although the survey responses showed statistically significant differences in the distributions of votes for the perception of the environment (thermal sensation, thermal preference, air quality and overall comfort), these differences were much smaller than might have been expected from the measured indoor environmental conditions that the occupants were experiencing. Indeed, overall comfort was rated more satisfactory in the naturally ventilated 'K' than in the mechanically ventilated 'N'.

6 Discussion

Analysis of the indoor environment showed that the two case study buildings performed differently in heating and non-heating seasons. Mean indoor temperatures during working hours were warmer in the naturally ventilated building 'K' in both the heating and non-heating seasons. As compared to building 'N', building 'K' experienced more extreme and wider range of temperatures over the course of the working day. RH was similar in both buildings during the summer, but in winter was lower in 'N' than in 'K', with some of 'N' occupants commenting on the air feeling dry and causing headaches. Summertime CO_2

concentrations were similar in both buildings, but during the winter, levels were much higher in ‘K’. Due to ‘K’s location in central London, there was sometimes a reluctance to open windows, even in the height of summer – occupants having to balance a desire for ‘fresh air’ with a desire to keep out the noise and pollution from the streets below. High CO_2 concentrations have been linked to occupant dissatisfaction and decreases in worker performance (Allen et al., 2015, Satish et al., 2012, Kajtar et al., 2003). In short, the overall indoor environmental conditions appeared much less satisfactory in the naturally ventilated building, ‘K’, than in the mechanically ventilated building, ‘N’.

Responses to the BUS survey from ‘K’s occupants reflected the significant differences in the indoor environmental conditions between winter (heating season) and summer (non-heating season). ‘N’s occupants by comparison had little difference in the distribution of results for summer and winter. Overall conditions were not rated significantly differently for winter, but in summer, ‘N’s occupants were more satisfied with conditions than ‘K’s. In both buildings, the majority of occupants felt that they had little or no control over heating, cooling, ventilation, noise or lighting, but ‘N’s occupants felt that they had significantly less control than ‘K’s – an accurate reflection of the buildings: ‘K’s occupants were able to open and close windows, turn their FCUs up or down, vary natural lighting with blinds – albeit with the consensus of neighbouring colleagues – whereas ‘N’s occupants worked in an environment that was centrally monitored and controlled, with little opportunity to change things if they were not happy. It is noteworthy that lack of control has been linked to perceptions of decreased comfort, health and productiveness in several studies (Feige et al., 2013, Mulville et al., 2016, Lipczynska et al., 2018, Wagner et al., 2007). Despite all of the differences in the measured indoor environment, and the different attitudes highlighted in the BUS responses above, *there was no statistically significant difference between the two case study buildings in the responses to occupants’ overall comfort and how they perceived their health to be* *affected by the building*. This was an important find, and indicated that despite the specific issues occupants had with temperature extremes and the like, those in the naturally ventilated building were just as satisfied (or dissatisfied) with their conditions as those in the mechanically ventilated building.

The occupant surveys also revealed interesting trends, providing a series of snapshot perceptions of the environment over a more representative range of indoor environmental conditions throughout the seasons and across different times during the working day. Although there were statistically significant differences between the two buildings in the distributions of thermal sensation votes and thermal preference votes, these differences were very small – much less than might have been expected based on the concurrent temperatures. Indeed, the naturally ventilated occupants who rated their thermal sensation as ‘comfortable neither warm nor cool’ did so at a higher temperature than their mechanically ventilated counterparts. Similarly, those naturally ventilated occupants whose thermal preference was for ‘no change’ did so at a higher temperature than their mechanically ventilated counterparts. This suggests the role of *adaptation*, whereby the occupants of the naturally ventilated building had adapted to their environment, becoming more accepting of a wider range of temperatures and other environmental conditions. Similarly, these results suggest that the occupants of the mechanically ventilated building had adapted to their tightly controlled environment by becoming less tolerant of small changes in temperature and other environmental conditions. This was further evidenced by the survey responses which showed the naturally ventilated respondents perceiving the air to be fresher than those in the mechanically ventilated building, and most significantly of all, the *naturally ventilated respondents rating their overall comfort as more satisfactory than their mechanically ventilated counterparts*.

The implications of these findings are important. Levels of energy use in the two case study buildings were not measured, so it was not possible to speculate on the comparative amounts of energy used in each building for heating, cooling and ventilation. Nevertheless, it is evident that the mechanically ventilated building inherently expended a significant amount of energy to control its indoor environment. Although it was successful in doing so, the levels of satisfaction expressed by its occupants were no better than those expressed by the occupants of the naturally ventilated building. This raises the question whether it is worth delivering a more tightly controlled indoor environment if occupants become less tolerant of changes to their environment and therefore no more satisfied with their overall conditions. than if they had been working in a cheaper to run naturally ventilated environment.

7 Conclusions

The research presented has empirically and systematically assessed the indoor environment and occupants' experience of that environment in two contrasting case study offices - one naturally-ventilated and the other mechanically-ventilated, using continuous monitoring of indoor temperature, RH and CO_2 concentration in heating and non-heating seasons, cross-related with transverse and longitudinal surveys of occupant perception. The study found that despite conditions in the MV building being more stable and operating over a much narrower band of temperatures and CO_2 concentrations, occupant satisfaction with the working environment was no better than in the NV building.

The wider range of temperatures, both seasonally and over the course of a working day, alongside the much higher CO_2 concentrations during the heating season, would suggest a much less favourable working environment in the NV building compared to the MV building. Indeed, in some aspects of the occupants' feedback from transverse and longitudinal surveys, this was evident. Although the occupants of the NV building were aware of when their localised conditions were more adverse, they were more accepting of them. With no evidence of any difference in the demographic makeup of the two groups of occupants, it is evident that those in the NV building had adapted to their variable environment, having a wider tolerance band for temperatures and CO_2 concentrations. Furthermore, the evidence suggests that those in the MV building had also adapted to their much more stable environment, having a much narrower tolerance band for temperatures and CO_2 concentrations.

The role of control should not be overlooked. Occupants in the MV building felt that they had little to no control over their environment, much less than their NV counterparts. This lack of choice, whether perceived or real, is recognised as having a negative effect on people's outlook to the extent that even if the conditions that are forced upon them are those which they would have freely chosen, they can resent them and feel discontent. Although some of the more extreme conditions in the NV building were sub-optimal and need to be addressed through better management of the indoor environment, this should be balanced with the need to keep some level of control with the occupants and allow a wider range of conditions than a fully MV building may provide. This has important implications for energy use in managing the indoor environment.

Acknowledgements

This paper presented data gathered as part of the *Whole Life Performance Plus* (WLP+) research project. The authors would like to thank EPSRC (Grant ref: EP/N509000/1) and Innovate UK (Application number: 54815-413475) for funding the project under the *Building Whole-Life Performance* competition.

8 References

AC08024865, A. 2005. *Ergonomics of the thermal environment-Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*, ISO.

ALLEN, J. G., MACNAUGHTON, P., SATISH, U., SANTANAM, S., VALLARINO, J. & SPENGLER, J. D. 2015. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. *Environmental health perspectives,* 124**,** 805-812.

ALTOMONTE, S., SAADOUNI, S., KENT, M. G. & SCHIAVON, S. 2017. Satisfaction with indoor environmental quality in BREEAM and non-BREEAM certified office buildings. *Architectural Science Review,* 60**,** 343-355.

ANDARGIE, M. S. & AZAR, E. 2019. An applied framework to evaluate the impact of indoor office environmental factors on occupants' comfort and working conditions. *Sustainable Cities and Society,* 46**,** 101447.

BARLOW, S. & FIALA, D. 2007. Occupant comfort in UK offices—How adaptive comfort theories might influence future low energy office refurbishment strategies. *Energy and Buildings,* 39**,** 837-846.

BEAN, S. 2018. *UK office workers spend limited time outside and over half complain of lack of fresh air* [Online]. Online: Workplace Insight. Available: https://workplaceinsight.net/uk-office-workers-spend-limited-time-outside-and-over-half-complain-of-lack-of-fresh-air/ [Accessed 31st January 2020].

BLUYSSEN, P. M., ARIES, M. & VAN DOMMELEN, P. 2011. Comfort of workers in office buildings: The European HOPE project. *Building and Environment,* 46**,** 280-288.

BRAGER, G., ZHANG, H. & ARENS, E. 2015. Evolving opportunities for providing thermal comfort. *Building Research & Information,* 43**,** 274-287.

BUS. *BUS methodology* [Online]. Available: http://www.busmethodology.org.uk [Accessed].

CHIANG, C.-M., CHOU, P.-C., LAI, C.-M. & LI, Y.-Y. 2001. A methodology to assess the indoor environment in care centers for senior citizens. *Building and Environment,* 36**,** 561-568.

CIBSE 2015. Guide A: Environmental design. CIBSE London.

DE DEAR, R. & BRAGER, G. S. 1998. Developing an adaptive model of thermal comfort and preference.

FANGER, P. O. & TOFTUM, J. 2002. Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy and buildings,* 34**,** 533-536.

FEIGE, A., WALLBAUM, H., JANSER, M. & WINDLINGER, L. 2013. Impact of sustainable office buildings on occupant's comfort and productivity. *Journal of Corporate Real Estate,* 15**,** 7-34.

FRANSSON, N., VÄSTFJÄLL, D. & SKOOG, J. 2007. In search of the comfortable indoor environment: A comparison of the utility of objective and subjective indicators of indoor comfort. *Building and Environment,* 42**,** 1886-1890.

GENG, Y., JI, W., LIN, B. & ZHU, Y. 2017. The impact of thermal environment on occupant IEQ perception and productivity. *Building and Environment,* 121**,** 158-167.

GUPTA, R., HOWARD, A. & ZAHIRI, S. 2020. Defining the link between indoor environment and workplace productivity in a modern UK office building. *Architectural Science Review***,** 1-14.

HAGHIGHAT, F. & DONNINI, G. 1999. Impact of psycho-social factors on perception of the indoor air environment studies in 12 office buildings. *Building and Environment,* 34**,** 479-503.

HELLWIG, R., BRASCHE, S. & BISCHOF, W. Thermal Comfort in Offices–Natural Ventilation vs. Air Conditioning. Proceedings of congress Comfort and Energy Use in Buildings–Getting it Right, Winsor, 2006.

HUMMELGAARD, J., JUHL, P., SÆBJÖRNSSON, K., CLAUSEN, G., TOFTUM, J. & LANGKILDE, G. 2007. Indoor air quality and occupant satisfaction in five mechanically and four naturally ventilated open-plan office buildings. *Building and Environment,* 42**,** 4051-4058.

KAJTAR, L., HERCZEG, L. & LANG, E. Examination of influence of CO2 concentration by scientific methods in the laboratory. Proceedings of healthy buildings, 2003. 176-181.

LIPCZYNSKA, A., SCHIAVON, S. & GRAHAM, L. T. 2018. Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics. *Building and Environment,* 135**,** 202-212.

LIU, J., YAO, R., WANG, J. & LI, B. 2012. Occupants' behavioural adaptation in workplaces with non-central heating and cooling systems. *Applied Thermal Engineering,* 35**,** 40-54.

LUO, M., CAO, B., DAMIENS, J., LIN, B. & ZHU, Y. 2015. Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate. *Building and environment,* 88**,** 46-54.

MULVILLE, M., CALLAGHAN, N. & ISAAC, D. 2016. The impact of the ambient environment and building configuration on occupant productivity in open-plan commercial offices. *Journal of Corporate Real Estate,* 18**,** 180-193.

NCUBE, M. & RIFFAT, S. 2012. Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK–A preliminary study. *Building and Environment,* 53**,** 26-33.

O'BRIEN, W. & GUNAY, H. B. 2014. The contextual factors contributing to occupants' adaptive comfort behaviors in offices–A review and proposed modeling framework. *Building and Environment,* 77**,** 77-87.

PLECHER, H. 2020. *Distribution of GDP across economic sectors in the United Kingdom 2018* [Online]. Online: Statistica. Available: https://www.statista.com/statistics/270372/distribution-of-gdp-across-economic-sectors-in-the-united-kingdom/ [Accessed 31st January 2020].

SAKELLARIS, I., SARAGA, D., MANDIN, C., RODA, C., FOSSATI, S., DE KLUIZENAAR, Y., CARRER, P., DIMITROULOPOULOU, S., MIHUCZ, V. & SZIGETI, T. 2016. Perceived indoor environment and occupants' comfort in European "modern" office buildings: The OFFICAIR study. *International journal of environmental research and public health,* 13**,** 444.

SATISH, U., MENDELL, M. J., SHEKHAR, K., HOTCHI, T., SULLIVAN, D., STREUFERT, S. & FISK, W. J. 2012. Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance. *Environmental health perspectives,* 120**,** 1671-1677.

THAM, K. W., WARGOCKI, P. & TAN, Y. F. 2015. Indoor environmental quality, occupant perception, prevalence of sick building syndrome symptoms, and sick leave in a Green Mark Platinum-rated versus a non-Green Mark-rated building: A case study. *Science and Technology for the Built Environment,* 21**,** 35-44.

WAGNER, A., GOSSAUER, E., MOOSMANN, C., GROPP, T. & LEONHART, R. 2007. Thermal comfort and workplace occupant satisfaction—Results of field studies in German low energy office buildings. *Energy and Buildings,* 39**,** 758-769.

WONG, S.-K., LAI, L. W.-C., HO, D. C.-W., CHAU, K.-W., LAM, C. L.-K. & NG, C. H.-F. 2009. Sick building syndrome and perceived indoor environmental quality: A survey of apartment buildings in Hong Kong. *Habitat International,* 33**,** 463-471.

YAO, R., LIU, J. & LI, B. 2010. Occupants' adaptive responses and perception of thermal environment in naturally conditioned university classrooms. *Applied Energy,* 87**,** 1015-1022.