Investigating the link between indoor environment and workplace productivity in an office environment

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SUMMARY
Most studies on indoor environment and productivity have been conducted in controlled, static conditions. This paper uses a real world case study to empirically explore the relationship between indoor environment and workplace productivity in a naturally-ventilated office environment. Environmental parameters (relative humidity (RH), CO_2 concentration and air temperature) are continuously monitored during February 2017.Occupant perceptions of their working environment in winter (and summer) are recorded using the Building Use Studies (BUS) questionnaire.

Analysis of the monitoring data shows that indoor RH is very low (< 30 %), while CO_2 concentrations are high (>2500 ppm). Air temperature is both high (>27 °C) and variable (up to 8 K change) indicating lack of window opening. Occupant feedback aligns with the measurements indicating low satisfaction with the indoor environment. Perceived productivity is found to strongly correlate with the perceived health and overall comfort. Insights from the study can be used to optimize indoor office environments to improve workplace productivity.

KEYWORDS
Productivity, office, indoor environment, health, comfort.

1 INTRODUCTION

A growing body of research suggests that workplace productivity – a measure of efficient output to produce effective results (British Council for Offices, 2017) – could be improved by 2-3 % by improving the working environment (ibid., Kang et al., 2017). The financial benefits of such improvements far outweigh the potential savings to be made by reducing energy demand. Increased absenteeism and presenteeism, and links to cardiovascular disease (Smith et al., 2016) and sick building syndrome (Shahzad et al., 2017) among the many health issues associated with poor working environments.

Previous intervention and office-based studies have found increased productivity from improvements to indoor environment, but have focussed on individual elements such as air temperature or ventilation rates (Niemelä et al. 2002; Seppänen et al. 2006; Park & Yoon 2011). In reality, office environments are dynamic, experiencing varying air temperatures, RH and CO_2 concentrations over the course of a day.

This paper empirically investigates the relationship between indoor environment and productivity in a naturally ventilated office building in central London (UK). Indoor environmental parameters (RH, CO_2 concentration and air temperature) and outdoor parameters (RH and air temperature) are monitored continuously using data loggers. Occupant surveys are used to provide evidence of occupant perception of their working environment during the winter period, including self-reported changes in productivity.

This study is part of research project, *Whole Life Performance Plus* (WLP+), which seeks to develop a dynamic approach for improving workplace productivity by optimizing the indoor environmental conditions. The project is funded by Engineering and Physical Sciences and Research Council (EPSRC).

2 METHODS AND CASE STUDY

The methodology adopted in this study has two main elements: (1) Continuous monitoring of indoor and outdoor environment using data loggers and (2) Survey of occupant perception of their working environment.

Indoor environmental parameters (RH, CO_2 concentration and air temperature) and outdoor environmental parameters (RH and air temperature) were recorded at five-minute intervals using devices described in Table 1. Internal devices were located at desk level, away from potential sources of interference such as radiators and computer cooling vents. External devices were located on window ledges outside the trial spaces. The devices were chosen due to their appropriate range, level of accuracy and resolution.

Table 1. Specification, resolution and accuracy of data loggers.

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

The Building User Survey (BUS) was used to provide a record of occupant perception of their working environment. In the UK, BUS survey is an established way of benchmarking occupant satisfaction against a large database of results from similar buildings (BUS methodology, 2018). The survey's 45 questions record feedback on aspects including thermal comfort, ventilation, personal control over the environment and change in perceived productivity. The survey was conducted as a paper-based questionnaire on 28th March 2018, with copies handed out in the morning and collected towards the end of the working day.

The survey received 62 responses, representing approximately 75 % of the occupants of the case study working environment. 55 % of respondents are under 30 years old and 58 % are female. 30 % of respondents have worked in the building for less than a year. Analysis of the BUS results focuses on the questions relating to the indoor environment during winter. This is then cross-related with the measured indoor environmental conditions (RH, CO_2 concentration and air temperature) for the month of February 2017 (representing winter season).

The case study building is a brick and block construction with insulated cavity, located in central London next to a busy roundabout. It was built in 1938, fully refurbished in 1995 and, in the case study working environment, desks, carpets and other furnishings were replaced in 2015. It is primarily an owner occupied building (an advantage when conducting studies that involve monitoring and interventions), with heating and cooling provided by fan coil units. The case study working environment is located on the seventh floor of the building and is home to an open-plan administrative department, approximately 400 m². There are 78 workstations, with an average daily occupancy of 48 (62 % occupancy rate). Lights are locally controlled and official operating hours (for heating and cooling) are weekdays, 08:30 to 17:30.

3 RESULTS

Measured Indoor Environment

The recommended RH for offices in the UK is between 40-70 %. Monitoring of the case study working environment for February 2017, showed a mean RH of 40.5 %, with RH below 40 % for 47 % of the working hours, getting as low as 24.8 % in the afternoons and rarely exceeding 50 % (Figure 1). Low RH can cause occupants to experience sore eyes and dry throats, itchy skin and a stuffy nose. BUS response comments included occupants complaining that the dry air triggers their allergies.

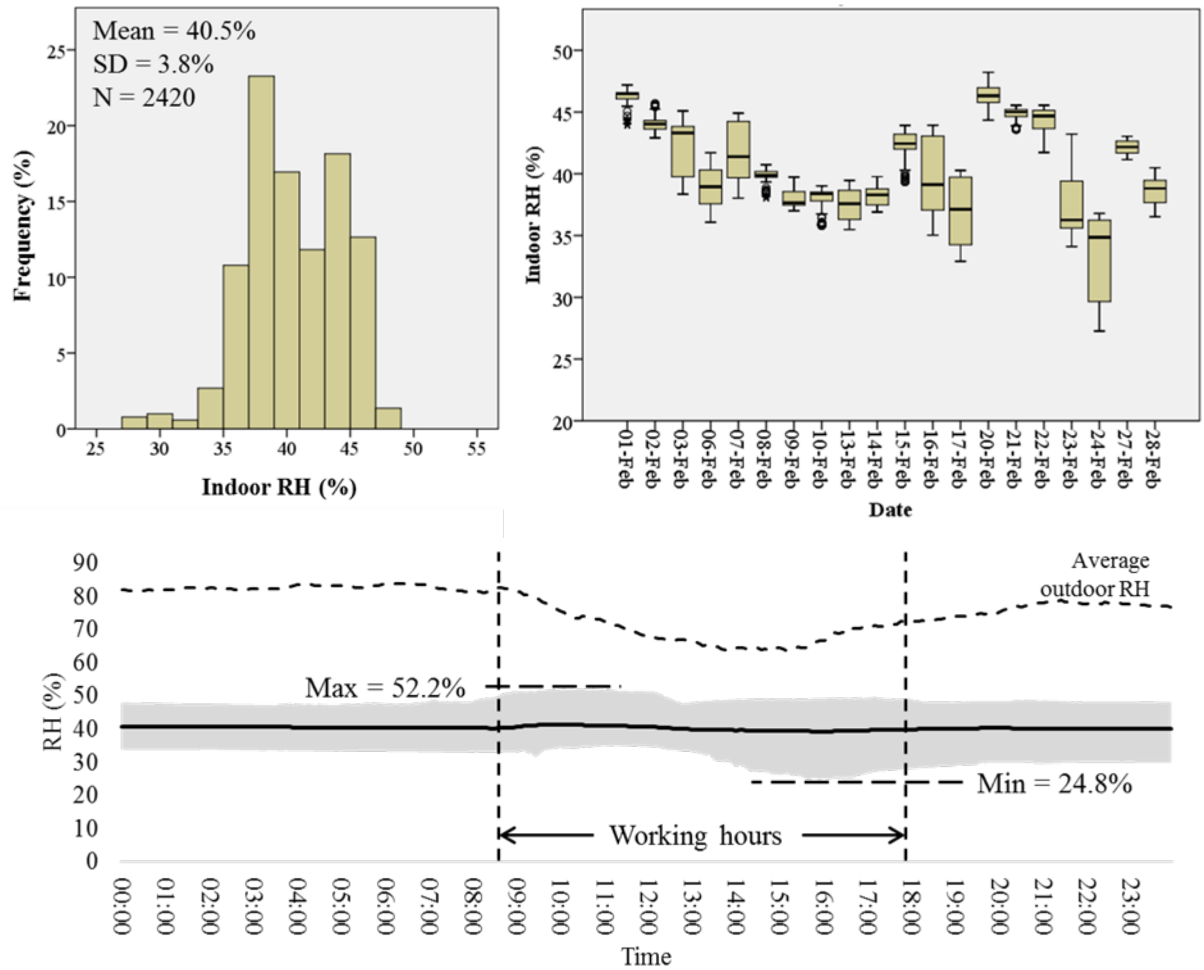

Figure 1 Relative humidity during working hours (Feb 2017): Distribution histogram (top left), RH boxplots for working days (top right) and daily profile showing average indoor RH (solid line), with maximums and minimums (shaded area) and outdoor RH (bottom).

In the naturally ventilated case study working environment, windows often remain closed during the winter period. Survey response comments indicated that this was due not only to low outdoor air temperatures, but also noise and air pollution. Consequently the CO_2 concentrations in the case study working environment reached as high as 2660 ppm during February working hours. Levels exceeded 1500 ppm for 30 % of working hours, and exceeded 2000 ppm for 11 % of working hours. The daily profile (Figure 2, bottom) shows how levels increase steeply during the morning to an average of around 1500 ppm by midday. Concentrations remain high until the end of the working day, when they gradually decrease towards ambient levels.

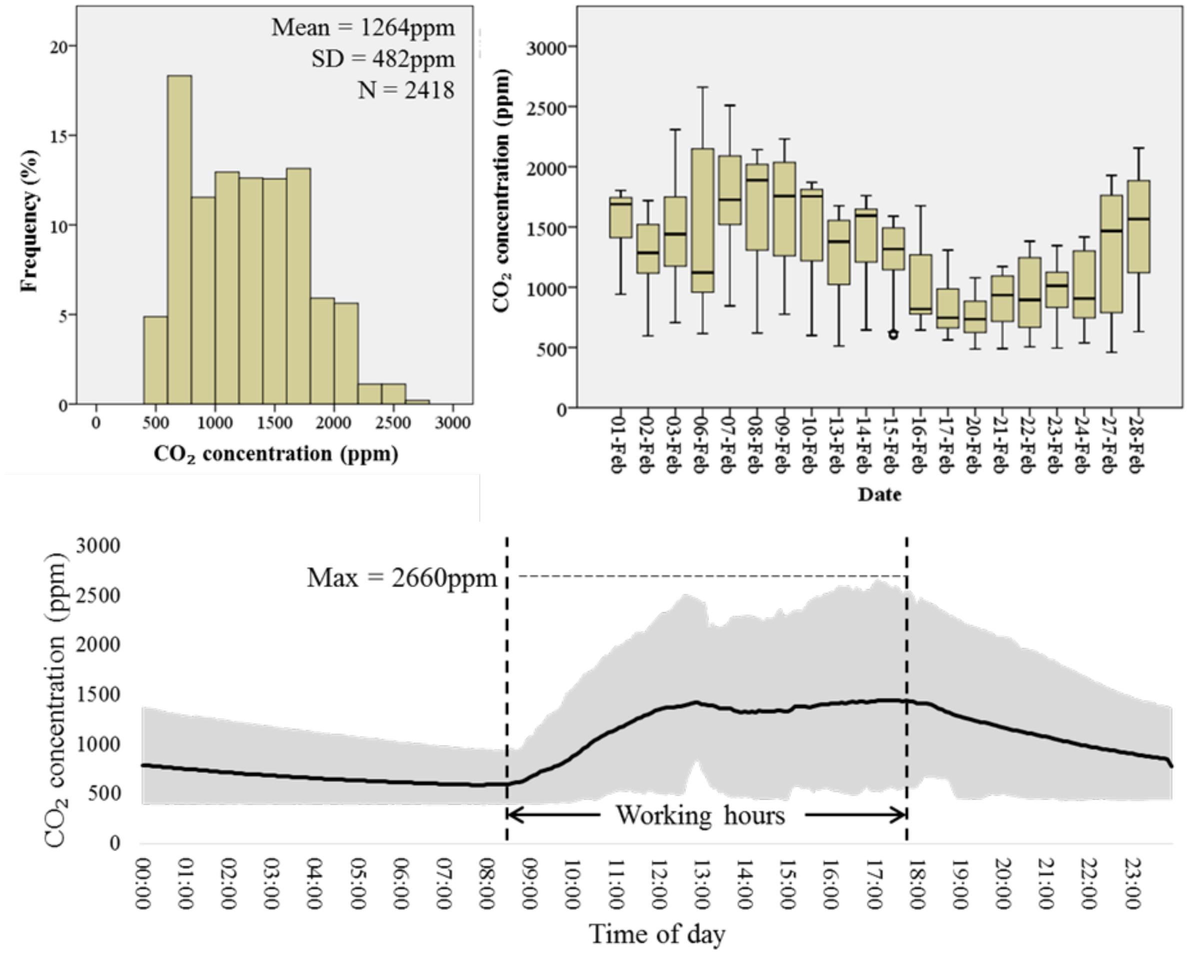

Figure 2 CO_2 concentrations during working hours (Feb 2017): Distribution histogram (top left), CO_2 concentration boxplots for working days (top right) and daily profile showing average CO_2 concentration(solid line), with maximums and minimums (shaded area) (bottom).

Comments throughout the BUS questionnaires indicated that the case study working environment had a tendency to be too hot, particularly in the summer, but also in the winter. This was evident from the monitoring. The average indoor air temperature at the start of the working day was around 22 °C, rising to over 24 °C by midday and not falling back into the 21-23 °C range recommended for offices in winter (CIBSE, 2015) until after 22:00. During working hours, air temperatures were within this 21-23°C range for only 14 % of the time. 83 % of the time air temperatures were above 23 °C, and 34 % of the time air temperatures were above 25 °C (Figure 3).

Occupants also complained about the variation in air temperature throughout the day, and this was again evident from the monitoring: Air temperatures below 18 °C could be found at the start of the working day, and above 27 °C by the early afternoon, with an average range of 5 K over the course of a working day (and a maximum range of 8 K).

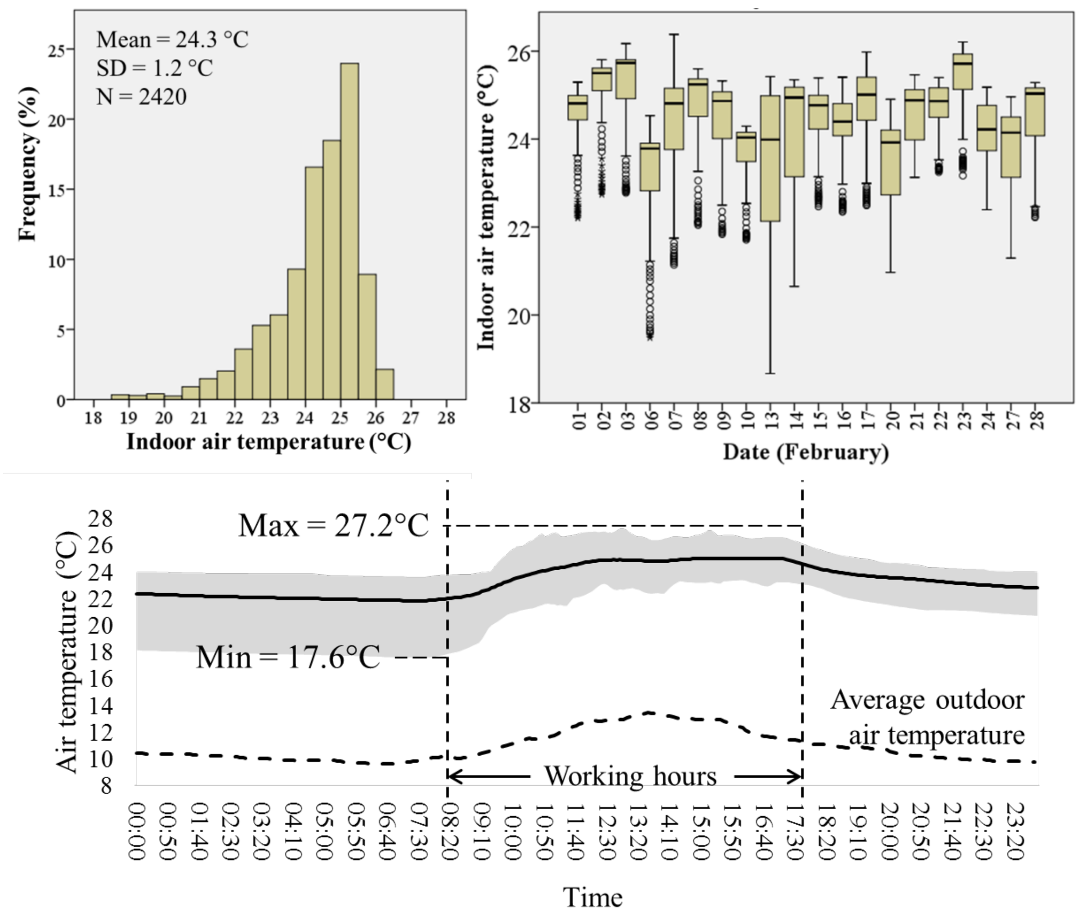

Figure 3 Indoor air temperatures during working hours (Feb 2017): Distribution histogram (top left), air temperature boxplots for working days (top right) and daily profile showing average air temperature (solid line), with max/min (shaded area) and outdoor air temperature (bottom).

Research has shown that an individual's ability to control their local environmental conditions can affect their tolerance of those conditions (Shahzad, S. et al., 2016). An individual who feels more in control of their environment (air temperature, ventilation, etc.) is likely to have a wider tolerance range for their comfort. The BUS questionnaire asks how much control respondents feel they have over their environment, with responses on an integer scale of 1 (no control) to 7 (full control). Significantly, therefore, 58 % of respondents said they had no control (1) over heating (mean response = 2.1, SD = 1.5) and 45 % of respondents said they had no control (1) over cooling (mean response = 2.4, SD = 1.6). There was a wider spread of responses concerning control over ventilation (mean response = 3.0, SD = 1.5), as occupants are able to open windows (although this will have to be with the consensus of colleagues who will also be affected). However, even with ventilation, over 60 % of responses were on the negative half of the scale (1-3). These results are of value when considering responses to the following questions.

Perceived indoor environment and productivity

The BUS questionnaire gave occupants the opportunity to describe perceptions of their working environment and its impact on their comfort, health and productivity. Occupants were asked to describe their typical working conditions in their normal working environment in winter. Notable trends apparent from these responses included the perception that air temperatures varied during the day and that the air was dry (Figure 4). Occupants also perceived the air to be still in winter, the mean score of 3.2 putting the case study working environment on the 27th percentile when compared with the benchmark of other similar buildings. The air was perceived to be stuffy during the winter period, placing it on the 87th percentile when compared against similar buildings.

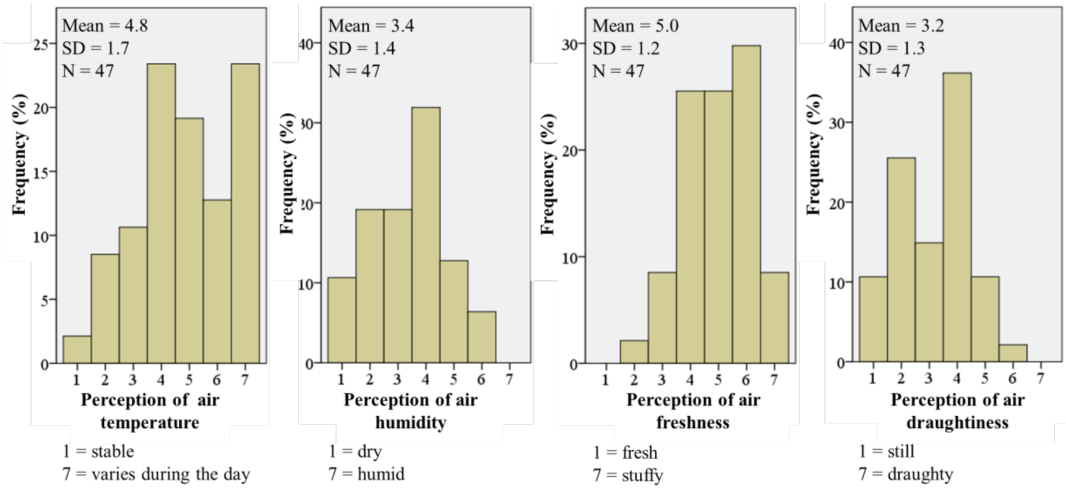

Figure 4 Occupant perception of (left to right): the variability of air temperatures during the day; the humidity of the air; the freshness of the air; the stillness of the air.

When asked to rate their overall comfort, occupants offered a wide range of opinions (Figure 5, left). Over 60 % of responses were positive (5-7); only 20 % negative (1-3). Negatively respondents cited issues with high air temperatures and stuffiness, particularly in winter, as being the main concern, with a perception that illness spreads more easily in these conditions.

Despite these results, many occupants perceived their health to be negatively affected by the building's environment (Figure 5, centre). 46 % of responses were negative (1-3 on the scale), with respondents citing the lack of ventilation, the dry and stuffy air and the rapid spread of airborne diseases, particularly in the winter, all contributing to their feeling less healthy.

Occupants were asked to estimate their change in productivity due to the environmental conditions in the building. Fewer than 14 % of respondents said that the environment helped to increase their productivity (Figure 5, right). 62 % of respondents perceived the building's environment to have a negative impact on their productivity, placing it on the lowest 23rd percentile when compared with the benchmark buildings. As with comfort and health, comments focussed on high air temperatures and stuffy air, which make it harder to concentrate and harder to focus, thereby affecting their productivity.

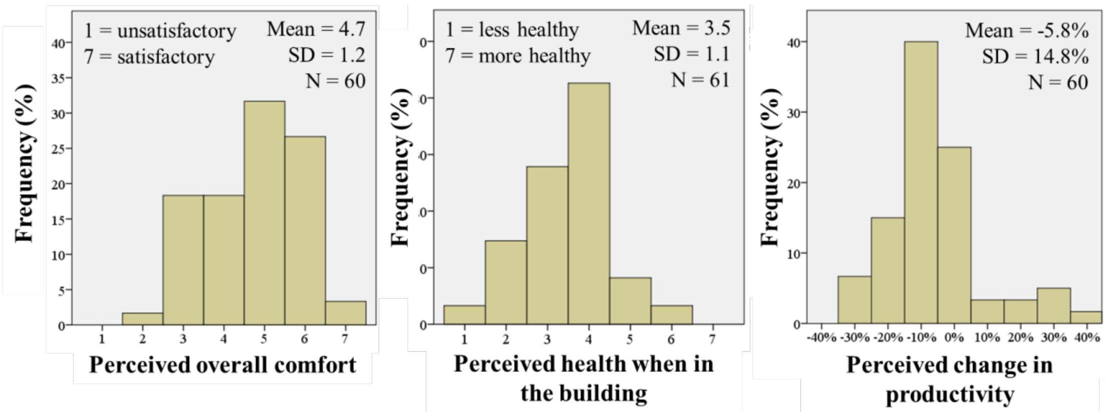

Figure 5 Distribution of responses to overall comfort in the building environment (left), perceived change to health when in the building (centre) and perceived change in productivity (right).

Correlations become apparent when comparing the responses to perceived comfort, health and productivity. Although the questions produce discrete data responses, the large number of responses (62) make it is possible to plot fit lines to show the general trend of the relationships. This is not a statistically rigorous analysis, and serves only to show these trends. It is evident from the graphs that as perceived comfort and perceived health deteriorate, perceived change in productivity is also negatively affected (Figure 6). Respondents' comments served to reinforce this correlation.

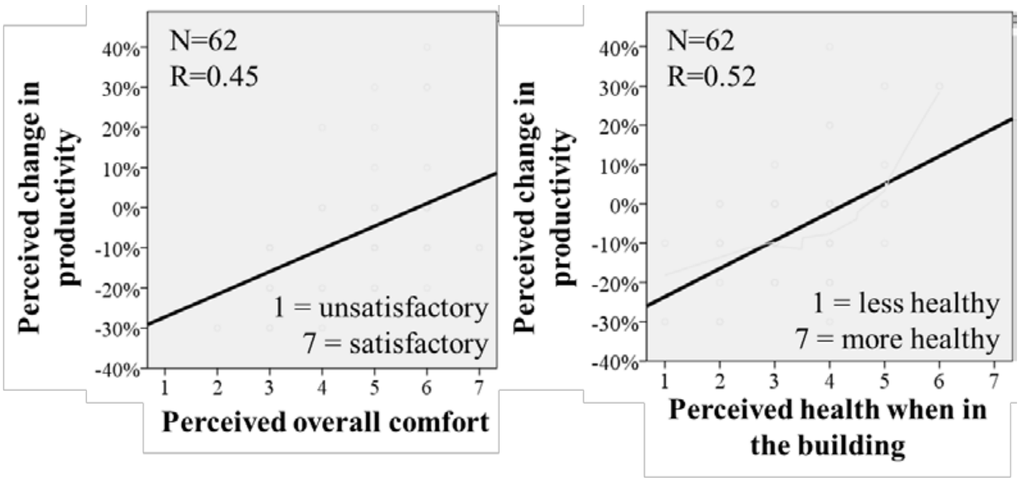

Figure 6 Relationship between perceived change in productivity and perceived comfort (left) and perceived health (right).

4 DISCUSSION

The results of the indoor environmental monitoring and the BUS questionnaire show some interesting cross-relations. The case study working environment was found to have dry air, below the recommended range of 40-70 % relative humidity for almost half of the working hours in February. Occupants described the air as feeling dry during the winter period, commenting that the dryness caused headaches and contributed to a feeling of unhealthiness. CO_2 concentration exceeded 1000 ppm (CIBSE standard for good levels of ventilation (CIBSE, 2015)) for 60 % of February's working hours. Occupants described the air in winter as stuffy leading to complaints about an increase in the spread of airborne diseases. Indoor air temperatures varied by up to 8 K over the course of a day. Again, the survey results reflected this, with occupants describing, indoor air temperature as highly variable throughout the day. Over 50 % of occupants described having to change their behaviour due to conditions in their workplace, saying that they layer their clothes to address the fact that it can be too cold in the mornings and too hot in the afternoons.

Occupants described their comfort, health and productivity as being negatively affected by the environmental conditions of their building. Relatively strong correlations were found between perceptions of both comfort / change in productivity, and health / change in productivity. Negative characteristics of the measured winter indoor environment (low RH, high CO_2 concentrations, high and variable air temperatures) all contribute to the negative change in productivity that the occupants perceive.

5 CONCLUSIONS

This paper sought to identify empirically links between the indoor environment of a central London office and the perceived change in productivity. It considered both the measured and perceived environmental conditions from both technical and occupants' perspectives.

Many of the responses in the BUS questionnaire reflected the measured environmental conditions: low measured RH was reflected in the perceived dry air; high measured CO_2 concentrations were reflected in the perceived stuffy air; measured variations in air temperature were reflected in the perceived variable air temperatures. Each of these contributed to the perceived decrease in comfort, health and productivity.

It was evident from the survey results that occupants' experience of their environment can be varied: the same conditions may be described by one occupant as too hot or stuffy, and by another as too cold or fresh. Whilst there may be some variation in conditions depending on desk location, measurements taken in various locations within the workspace suggest that these differences are small and generally cancel each other out over time. It is therefore important that significant proportions of occupants contribute to the surveys so that results are a fair representation of the whole population and general trends can become apparent.

Further study looking at summer environmental conditions and comparing these to the BUS questionnaire responses will be part of the larger WLP+ project. In addition, using performance tasks as a proxy for productivity will provide an opportunity to directly compare current environmental conditions to speed and accuracy of performance.

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