Defining the link between indoor environment and workplace productivity in naturally and mechanically ventilated office environments

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Abstract
This paper uses a case study-based approach to empirically explore the relationship between indoor environment and workplace productivity in two naturally and mechanically ventilated office environments. Environmental parameters were continuously monitored over 19 months. Longitudinal surveys (online) recorded occupants' perception of their working environment and self-reported productivity, while performance tasks (numerical tests, proof reading) measured cognitive capability.

Indoor temperature and CO_2 concentrations were found to be higher and more variable in the naturally ventilated (NV) office. Occupant perception of their indoor environment strongly correlated with their perceived productivity in both case studies. Task performance was affected by indoor environmental conditions such as indoor temperature and CO_2 concentration. Interestingly in the NV office the median scores were up to 12% lower for tests conducted at CO_2 levels >1400 ppm compared to those conducted below 1400 ppm, whereas in the MV office this threshold was 1000 ppm.

Keywords: Productivity, office, indoor environment, health, comfort

1. Introduction
Research by Office for National Statistics (ONS) has identified that productivity is an issue for the UK, with output per hour worked 15% below the average for the other G7 nations (1). Absenteeism and presenteeism both negatively affect productivity. With staff costs making up the vast majority of a business's expenses, the incentive to improve productivity is clear. This productivity gap can be attributed to economic factors (e.g. poor investment, inefficient processes), but also human factors such as stress, health and comfort.

CEN standard EN15251 also acknowledges that the indoor environment affects occupant productivity, health and comfort (2) and has recommended limits for optimum performance. Negative factors in relation to productivity are often more obvious than positive factors: an environment that is too hot or too cold can be uncomfortable to work in. However, finding the optimal level of indoor environment parameters where productivity begins to increase is more challenging (3). Recent studies have sought to develop an understanding of the relationship between indoor environment and workplace productivity, although most are conducted in climate chambers that create artificial environments.

The effect of temperature on health and comfort has been widely researched and it is broadly recognised as an important indoor environment factor. In a survey conducted by the British Council for Offices (BCO), one in six respondents perceived that their workplace had a negative impact on their health and wellbeing (4). For a study in naturally ventilated buildings it was found that indoor temperature significantly influenced workers' productivity in the recommended ventilation rate (5). Fang et al. (6) have also identified a link between temperature, RH and performance at different ventilation rates. Lan et al. (7) found that performance in all tasks (with the exception of text typing) decreased in warmer conditions. The results from this study implied that optimum thermal comfort and optimum productivity may not occur at the same temperatures. Seppänen et al.'s (8) meta-analysis suggested the temperature range for optimum performance is close to the optimum range for comfort, particularly for mechanically ventilated buildings in winter. In free-running buildings there was a bigger difference between optimal temperatures for comfort and performance. A 2% decrease in productivity for going 1°C beyond the optimal range will have significant cost implications for the organisation (9).

A peak indoor CO_2 concentration of 1500 ppm is specified for office spaces in order to maintain comfort air quality. In studies by Allen et al. (10), Satish et al. (11) and Kajtar et al. (12), performance was found to decrease as CO_2 concentration was increased. These studies indicate every-day CO_2 levels within the current recommended standards could have significant negative impacts on worker performance (13).

More recently Innovate UK's national research programme on building performance evaluation (BPE) undertook case study investigations of 50 low energy non-domestic buildings located across the UK, measuring the performance of building fabric, energy consumption, environmental conditions and occupant satisfaction. Meta-analysis of the surveys showed that occupant surveys in 12 out of the 21 workspaces reported an increase in perceived productivity due to the environmental conditions perceived by the occupants (14). The meta-study found that when occupants were satisfied with the indoor temperature, noise, lighting and building related features, perceived productivity increased. Conversely when indoor air was perceived as stuffy and smelly, perceived productivity decreased (15).

It is evident that there is growing recognition of a link between indoor environment and perceived productivity in office environments. This study sought to empirically quantify this link between indoor environment, thermal comfort, and perceived and measured productivity. By using two contrasting case-study buildings – an older, mixed-mode office building in central London and a more modern, mechanically-ventilated office building in the south of England – comparisons and contrasts could be identified in how occupants responded to their indoor environment, and any subsequent links to their performance and productivity. The research is part of an EPSRC/Innovate UK funded Whole Life Performance Plus (WLP+) project that seeks to develop a dynamic approach for improving workplace productivity by optimising the indoor environmental conditions.

2. Case study buildings

Two case-study buildings were selected for the study: a naturally-ventilated older building built with aged and inflexible infrastructure and located in central London; and a newer fully mechanically-ventilated office building with infrastructure representative of the bulk of UK workplaces and located in the south of England. The case study buildings were selected in part due to their contrasting characteristics. Case study 'K' was located in central London next to a busy roundabout. It was built in 1938 and fully refurbished in 1995. It was primarily an owner-occupied office building and had heating and cooling provided by fan coil units. The seventh floor of the case study building was selected as the case study working environment for this project with openable windows. It comprised of two open-plan administrative departments (approximately 600m^2 with 120 workstations). Desks, carpets and other furnishing in all areas of this floor were upgraded (replaced) in 2015. Lights were controlled locally.

Case study 'N' was located in a business park in the south of England with woodland to the north and east. It was built in 2004 and the facilities were managed by an on-site external FM company using BMS. Two departments within the building were selected as the case study working environment (approximately 2900m^2 with 260 workstations). Lighting, heating and cooling were controlled centrally.
Operating hours during the working days in both case study buildings were from 08:30 to 17:30.

Case study 'K':

- Central London next to busy road/roundabout
- Built in 1938; refurbished in 1995
- Mixed mode (mostly naturally ventilated)
- Owner occupied
- Open-plan administrative departments
- Average daily occupancy = 88
- Working hours (8:30-17:30. Mon-Fri)

Case study 'N':

- Corporate centre in a business park, surrounded by woodlands in southern England
- Built in 2004
- Mechanically ventilated
- Facilities managed by an on-site external FM company using BMS.
- Open-plan administrative departments
- Average daily occupancy: 155
- Working hours (8:30-17:30. Mon-Fri)

Figure 1 Descriptive characteristics of the two case study buildings

3. Methodology

The methodology adopted had a predominantly three-pronged approach:
(1) Physical monitoring of indoor and outdoor environment using data loggers
(2) Occupant perception of their indoor environment and productivity (through transverse and longitudinal surveys) and
(3) Measured productivity (using performance tasks as a proxy).
Additional business output metrics (calls made/emails sent) and HR data (absenteeism) were also collected. Figure 1 illustrates the methodological approach adopted in the study.

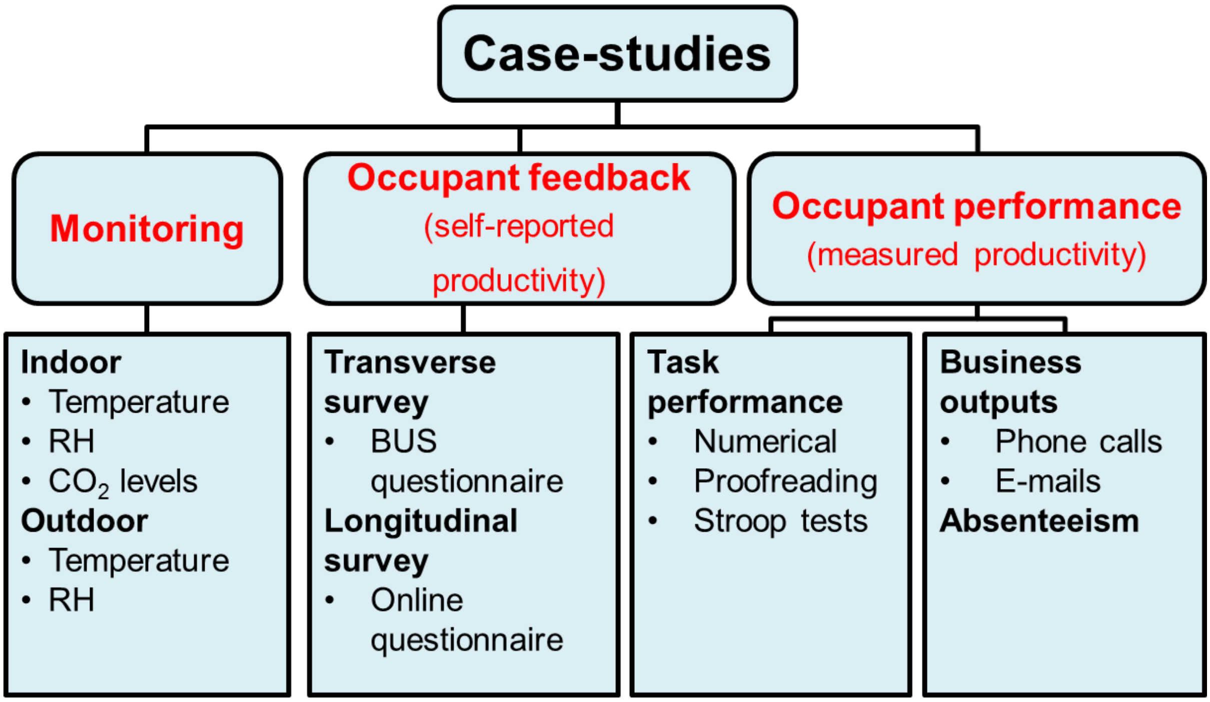


Figure 2 Methodology

Environmental monitoring was implemented over a period of approximately 19 months from March 2017 to September 2018. Indoor environmental parameters (temperature, RH and CO_2 levels) and outdoor environmental parameters (temperature and RH) were recorded at different locations around the case study offices (6 zones in JCMB at 5-minute resolution and 20 zones in NATS at 15-minute resolution), allowing localised conditions to be monitored and cross related to individual occupants.

The *Building Use Studies (BUS) survey* provided an overview of occupant perception of their working environment (16). A total of 99 surveys were received from JCMB (representing a response rate of approximately 80%), and 109 received from NATS (representing a response rate of approximately 40%).

The results of this transverse survey informed the design of an *online survey* which was used to record longitudinal feedback from occupants. Key questions identified from the BUS responses were adapted and incorporated into the online surveys. The surveys were sent via email three times a day (morning, early afternoon and late afternoon) during a baseline period of three weeks in the spring/summer of 2017, and during four-week intervention periods from autumn 2017 to summer 2018 (case-study buildings having two intervention periods each). In total, 3082 surveys (20% response rate) were completed by occupants in JCMB and 2680 surveys (10% response rate) were completed by occupants in NATS.

The surveys consisted of introductory questions to establish the responder's location within the building, followed by seven questions relating to their indoor environment:

- Temperature: How will you describe the thermal conditions in your work area at this moment? *(response options from 1 (Much too cool) to 7 (Much too warm))*
- You would prefer to be: *(5 response options from "Much warmer" to "Much cooler"))*

- Air quality: How will you describe the air quality in your work area at this moment? *(response options from 1 (Fresh) to 7 (Stuffy))*
- Noise: How will you describe the overall noise in your work area at this moment? *(response options from 1 (Unsatisfactory) to 7 (Satisfactory))*
- Light: How will you describe the overall lighting in your work area at this moment? *(response options from 1 (Unsatisfactory) to 7 (Satisfactory))*
- Overall comfort: How will you describe your overall comfort at this moment? *(response options from 1 (Uncomfortable) to 7 (Comfortable))*
- Productivity: At present, please estimate how you think your productivity has decreased or increased by the environmental conditions in the building: *(response options from "-20% or less" to "+20% or more" in 5% increments))*

Simulated performance tasks on cognitive capability provided a proxy for measured productivity. The tasks were designed to represent office tasks typical of the case-study workplaces and consisted of: *Numerical tests* (to mentally solve simple mathematical questions), *Proof reading* (to identify spelling errors in a paragraph of text) and *Stroop test* (an interference test, differentiating between the colour of the text and the word) (Figure 3). Both the test score and time taken to complete the task were recorded. Tasks were sent via email twice-daily (morning and afternoon) during a baseline period of three weeks in the spring/summer of 2017, and during the same four-week intervention periods used for the online surveys. About 1179 tasks (16% response rate) were completed by occupants in JCMB and 1186 tasks (8% response rate) were completed by occupants in NATS.

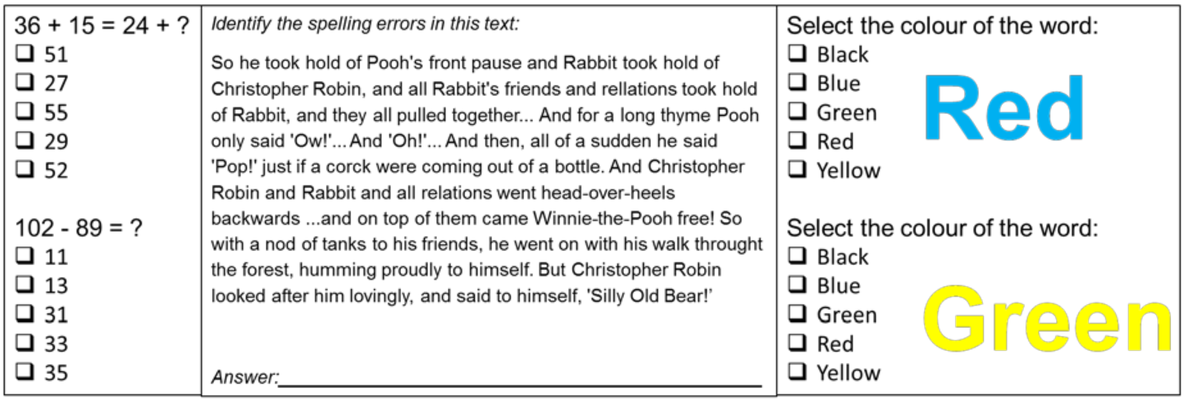


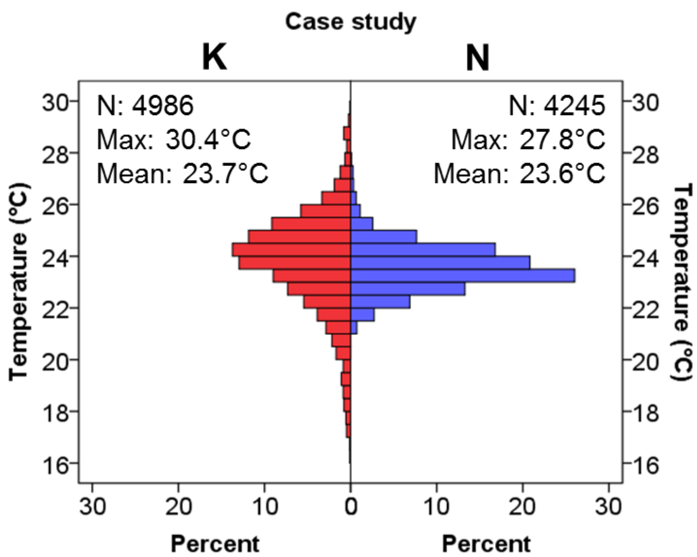
Figure 3 Samples of the performance tasks: Numerical tests (left) consisted of 25 questions; proofreading tasks (centre) consisted of four paragraphs of text each with 5-6 spelling errors to find; Stroop tests (right) consisted of 50 words to match with their colour.

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

Indoor (and outdoor) temperature, relative humidity (RH) and CO_2 concentration were monitored over 19 months in both case study buildings. The range of indoor temperatures (daily, monthly and seasonally) were found to be significantly greater in case study K than in case study N (Figure **4**). During the heating season (October-April) in case study K, the hourly average indoor temperatures were above the recommended 23°C for 58% of working hours, and below the recommended 21°C for

18% of working hours. Hourly average temperatures exceeded 25°C for 11% of working hours, on occasion reaching close to 28°C and falling below 19°C for 8% of working ours, on occasion falling below 15°C. In contrast, during the heating season in case study N, although the hourly average indoor temperatures were above the recommended 23°C for 58% of working hours, the same as in case study K, they only exceeded 25°C for 1% of working hours, reaching a peak of 25.7°C. Interestingly the hourly average indoor temperatures in case study N never fell below the recommended 21°C.

During the non-heating season (May-September) in case study K, the hourly average indoor temperatures were above the recommended 24°C for 61% of working hours, and below the recommended 22°C for 8% of working hours. Hourly average temperatures exceeded 26°C for 15% of working hours, on occasion exceeding 30°C. In contrast, during the non-heating season in case study N, the hourly average indoor temperatures were above the recommended 24°C for 38% of working hours, but only exceeded 26°C for 2% of working hours, reaching a peak of 27.7°C. Hourly average indoor temperatures in case study N fell below the recommended 22°C for only 1% of working hours during the non-heating season.

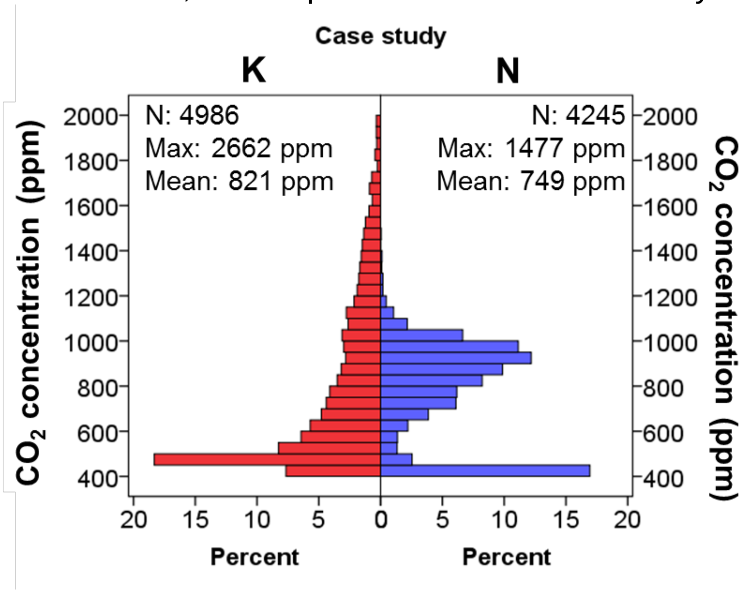


	Case study K		Case study N	
	Heating season	Non-heating season	Heating season	Non-heating season
Mean (°C)	22.8	24.4	23.1	23.8
Median (°C)	23.4	24.4	23.1	23.8
Max (°C)	27.6	30.4	25.7	27.8
Min (°C)	14.8	19.3	21.0	20.5

Figure 4 Hourly average working hours indoor temperatures (Mar 2017 - Sep 2018) (left) and descriptive statistics for the heating and non-heating seasons in both case study buildings (right)

As with indoor temperatures, daily, monthly and seasonal variations in CO_2 concentrations were much greater in the naturally ventilated case study K than in the mechanically ventilated case study N (Figure 5). During the heating season in case study K, the hourly average CO_2 concentrations reached in excess of 2600 ppm. They were above the ASHRAE recommended 1000 ppm for 45% of working hours, and above 1400 ppm for 20% of working hours. Despite some occupants being aware that their working environment felt "stuffy" they were reluctant to open the windows due to the cold outdoor temperatures and pollution from the traffic below. In contrast, during the heating season in the mechanically ventilated case study N, CO_2 concentrations were more tightly controlled. The hourly average CO_2 concentrations only exceeded 1000 ppm for 8% of working hours and never exceeded 1400 ppm.

During the non-heating season, the CO_2 profile in the NV case study K changed significantly as occupants were more likely to open windows in an attempt to lower the temperatures or at least to allow more air flow. Mean CO_2 concentrations fell by 27% and exceeded 1400 ppm for only 2% of working hours – on days when the windows were not opened due to adverse outdoor weather conditions. However, on the rate occasions when CO_2 concentration did exceed 1400 ppm, it spiked at over 2400 ppm. Conversely there was little seasonal variation in CO_2 concentrations in the mechanically ventilated case study N building. Mean concentrations increased by less than 2%, but the peak concentration was only 1240 ppm.



	Case study K		Case study N	
	Heating season	Non-heating season	Heating season	Non-heating season
Mean (ppm)	970	700	744	753
Median (ppm)	902	614	772	832
Max (ppm)	2662	2468	1477	1240

Figure 5 Hourly average working hours indoor CO2 concentration (Mar 2017 - Sep 2018) (left) and descriptive statistics for the heating and non-heating seasons in both case study buildings (right)

The seasonal contrast in CO_2 profiles in the two case study buildings is shown in Figure 6. At the start of the working day, concentrations increase steeply, levelling off in the late morning and remaining relatively stable until the end of the working day when they decrease over the evening hours back to ambient levels. In the sample heating month of February 2018, the closed windows and lack of mechanical ventilation in case study K were evident as the CO_2 concentrations continued to rise until after midday and beyond 1400 ppm. The BMS in the mechanically ventilated case study N was able to keep CO_2 concentrations below 1000 ppm. Whilst the CO_2 profile looks much the same in the sample non-heating month of July 2017 for case study N, it has changed significantly for case study K where concentrations remain below 1000 ppm throughout the day.

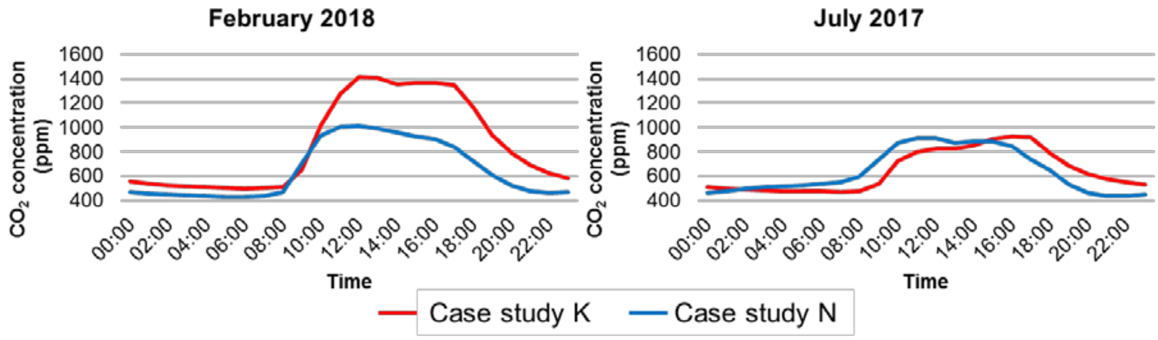


Figure 6 Hourly average CO2 concentration in case studies K and N (indoor and outdoor) during sample months (Feb 2018, left, and Jul 2017, right)

5. Perceived productivity and indoor environment

Transverse survey: BUS survey

The BUS surveys, conducted during the spring of 2017 in both case studies, provided a snapshot of occupant perception of their working environment, and allowed analysis into the relationship between occupants' perception of their productivity and different aspects of their working environment. The survey was paper-based and conducted over a single day in each case study building: surveys were distributed early in the working day and collected later the same day. Despite significant differences in the indoor environments of the two buildings, as shown above, the trends were quite similar.

The two categories that showed the strongest correlations with perceived change in productivity were overall comfort ("All things considered, how do you rate the overall comfort of the building environment?") and perception of health ("Do you feel more or less healthy when you are in the building?") (Figure 7).

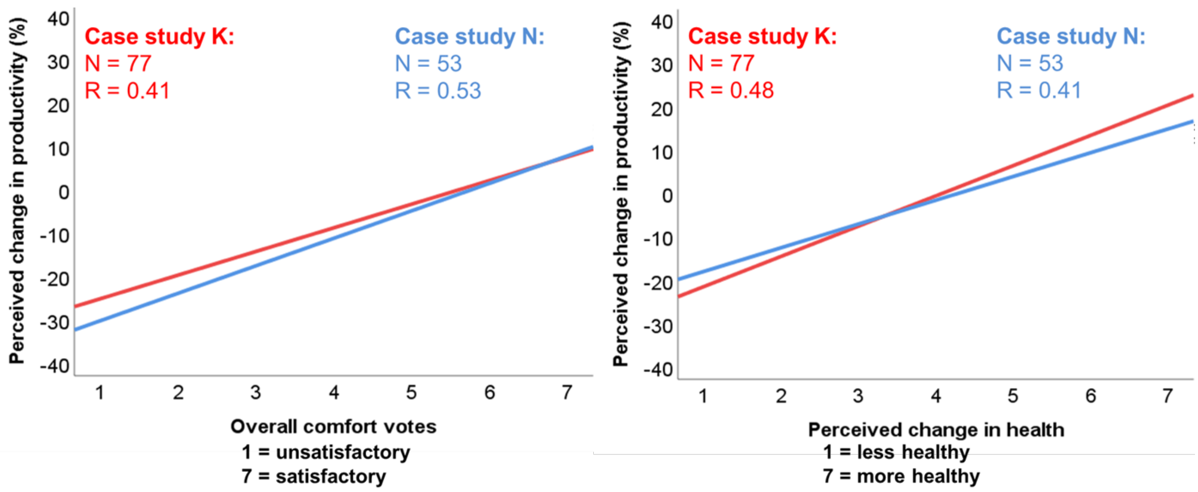


Figure 7 BUS responses to overall comfort (left) and perceived change in health (right) plotted against perceived change in productivity.

Questions in the survey relating to the indoor temperature and air in the winter and summer also showed interesting links to perceived change in productivity. When occupants found the temperature to be uncomfortable or the air to be unsatisfactory, they perceived their productivity to be decreased. The correlations shown in Table 1 indicate the strength of these relationships. It is worth noting that the correlations were much stronger in case study N than in case study K, indicating that N's occupants were significantly more sensitive to their indoor environmental conditions than their counterparts in K.

Table 1 Spearman's correlations between comfort responses and perceived change in productivity

	Case study K (n=77)	Case study N (n=53)
Temperature in winter: overall	R = 0.214	R = 0.325*
Air in winter: overall	R = 0.274*	R = 0.335*
Temperature in summer: overall	R = 0.199	R = 0.338*
Air in summer: overall	R = 0.255	R = 0.522**

*Correlation is significant at the 0.05 level (2-tailed)
**Correlation is significant at the 0.01 level (2 tailed)

Longitudinal survey: Online survey

Where the BUS surveys provided an overview of the occupants' perceptions of their working environments, the online surveys provided longitudinal data where perceptions could be directly compared to the concurrent conditions. . An e-mail was sent to occupants containing a link to the survey three times a day during the baseline period (morning, early afternoon and late afternoon) every day for three weeks. During the intervention periods, surveys were conducted three times a day as per the baseline, but only on Mondays and Tuesdays for the four weeks of each intervention. Again, the trends in both case study buildings were very similar. Figure 8shows the four key survey response questions plotted against perceived change in productivity.

As with the equivalent BUS survey question, occupants' perception of comfort overall showed a strong correlation with their perceived change in productivity (R = 0.54 (case study K) and R = 0.62 (case study N))(top left): when occupants felt uncomfortable overall they perceived their productivity to be negatively affected and vice versa. When occupants perceived the air to be stuffy (bottom left) they also perceived their productivity to be negatively affected (R = -0.33 (case study K) and R = -0.32 (case study N).

The curvilinear relationships between thermal sensation votes and perceived change in productivity (top right) and between thermal preference votes and perceived change in productivity (bottom right) mean correlations (R's) are not appropriate measures. However the R2 values, an indication of what percentage of perceived change in productivity can be explained by thermal sensation and thermal preference votes, show that when occupants were too cool or too warm, or would have preferred to be warmer or cooler, they perceived their productivity to be negatively affected. Interestingly in both case study buildings, occupants felt that feeling too warm (and wanting to be cooler) had a greater negative effect on their productivity than feeling too cool (or wanting to be warmer).

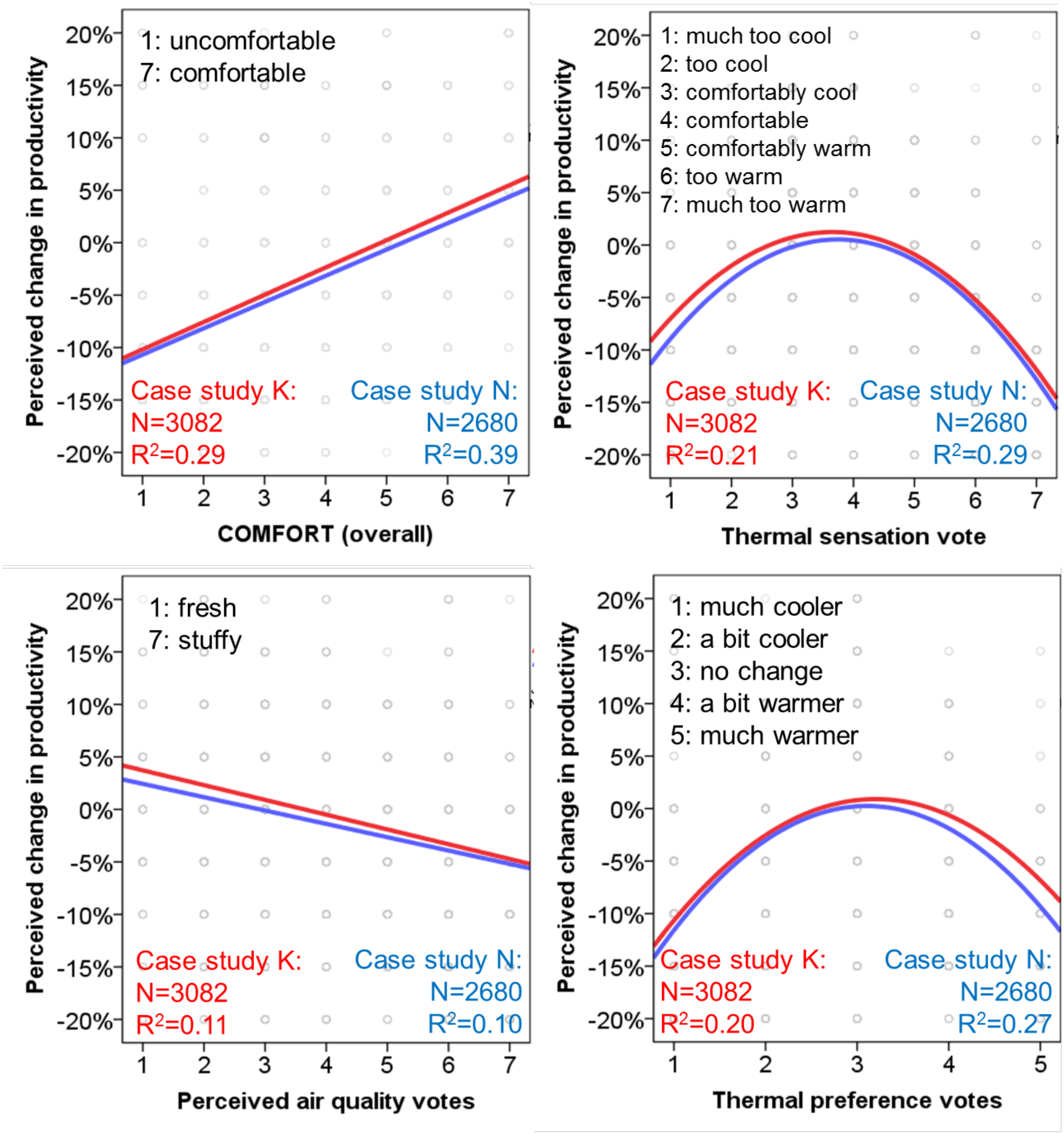


Figure 8 Survey responses plotted against perceived change in productivity for both case study buildings

Despite these significant correlations between occupants' perception of their environment and their perceived change in productivity, there were no statistically significant correlations between their perceived change in productivity and the concurrent indoor environmental conditions. Plotted trendlines indicated that perceived productivity may decrease at higher temperatures, but the correlations were very weak and not statistically significant at the 0.05 level. No correlation was found between perceived change in productivity and either RH or CO_2 concentration. This suggests that how occupants feel about their indoor environment has a more significant impact on how productive they perceive themselves to be than the actual indoor environmental conditions.

6. Measured productivity and indoor environment

Performance tasks

The surveys provided the occupants' perceptions of their working environments. Online tasks were used as a proxy measure of productivity, with both task score and task duration (the time taken to complete the tasks) recorded. As with the online surveys, these results could be directly compared to concurrent conditions. An e-mail was sent to occupants containing a link to the task twice a day during the baseline period (morning and afternoon) every day for three weeks. During the intervention periods, tasks were conducted twice a day as per the baseline, but only on Wednesdays, Thursdays and Fridays for the four weeks of each intervention. Over the course of a baseline, two interventions and a validation period in each case study building, over 2,000 performance tasks were completed. The distributions of test scores were statistically similar in both buildings for each of the three test types. Although the most popular task type, data from the Stroop tests did not provide any meaningful correlations as the scores were consistently very high (most respondents scoring 95-100%) and the durations were consistently very short (most respondents taking only 2-3 minutes to complete the task).

However, when the scores for all of the numerical and proofreading tasks were combined and plotted against the temperatures concurrent to when the tasks were completed, it was evident that for respondents in case study N, higher temperatures had a negative effect on their test scores (Figure 9). The equivalent correlation in case study K was virtually non-existent, which was particularly interesting considering this case study building experienced much greater extremes of temperature, especially at the high end. As with the survey responses, this indicated that Case study N's occupants were more sensitive to their indoor environment being in tightly-controlled conditions whereas occupants in case study K had got used to their more adverse indoor conditions.

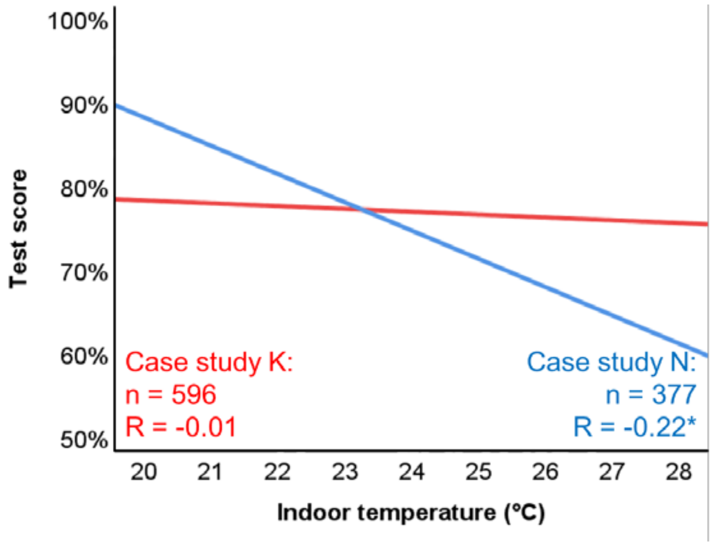


Figure 9 Test scores (for numerical and proofreading) plotted against concurrent indoor temperatures in both case studies. (*This correlation is significant at the 0.01 level).

In case study K, during a 4-week intervention in the early spring of 2018, the tests were conducted over a wide range of concurrent CO_2 concentrations. When these test scores were grouped according to the concurrent CO_2 concentration, it was found that the median score for tests conducted below 1400 ppm was 6% higher than for those conducted above 1400 ppm (Figure 10 (left) and Table 2). Taking the proofreading tests as a subset of this intervention, the median test score was 12% higher for tests conducted below 1400 ppm compared to tests conducted above 1400 ppm (Figure 10 (right) and Table 2).

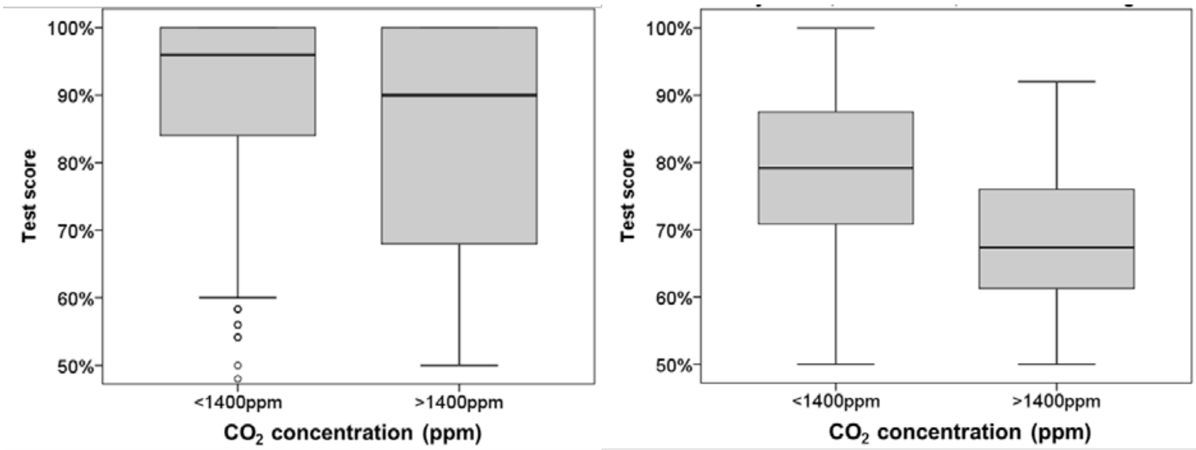


Figure 10 Boxplots showing distribution of test scores during a CO_2 intervention in case study K for all tests (left) and for proofreading tests (right).

Table 2 Descriptive statistics for test scores in case study K during a CO_2 intervention, grouped by CO_2 concentration.

All tests	**CO_2 concentration <1400 ppm**	**CO_2 concentration >1400 ppm**
N	308	34
Mean	89%	84%
Median	96%	90%
S.D.	15%	16%
Proofreading tests	**CO_2 concentration <1400 ppm**	**CO_2 concentration >1400 ppm**
N	77	16
Mean	78%	70%
Median	79%	67%
S.D.	12%	12%

In case study N during a 4-week intervention in the autumn of 2017, the tests were conducted over a narrower range of CO_2 concentrations. Nevertheless, grouping the numerical test scores and test durations according to the concurrent CO_2 concentrations showed that median scores for numerical tests conducted at concentrations below 1000 ppm were 12% higher than for those conducted above 1000 ppm (Figure 11 (left) and Table 3). The mean numerical test durations were 5 minutes longer for those conducted at concentrations above 1000 ppm compared to those conducted below 1000 ppm (Figure 11 (right) and Table 3). (It should be noted that the number of tests conducted above 1000 ppm was small, and less than a third of the number of tests conducted below 1000 ppm).

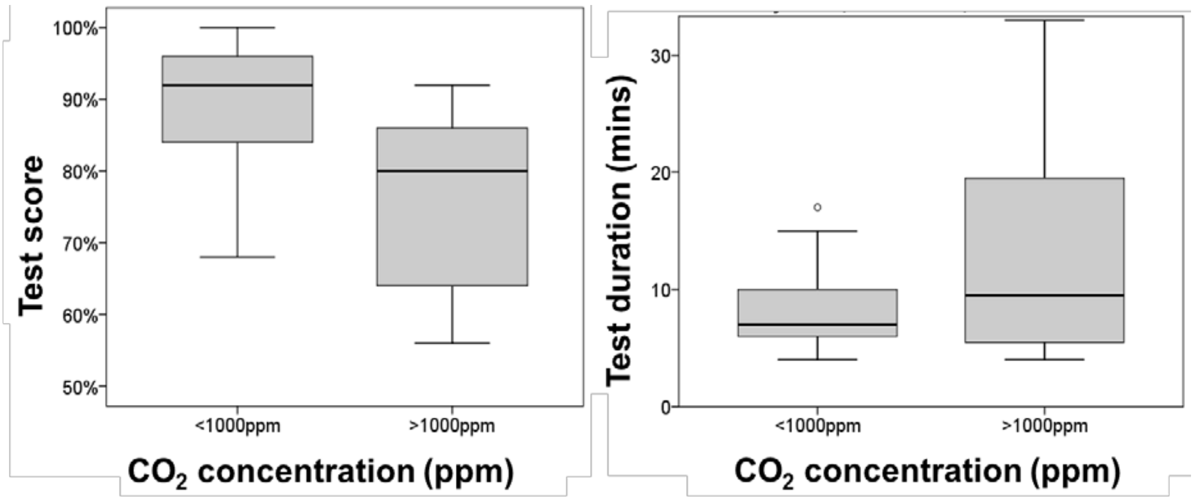


Figure 11 Boxplots showing distribution of test scores (left) and test durations (right) during a CO_2 intervention in case study N for numerical tests.

Table 3 Descriptive statistics for numerical test scores and durations in case study N during a CO_2 intervention, grouped by CO_2 concentration.

Numerical test score	**CO_2 concentration <1000 ppm**	**CO_2 concentration >1000 ppm**
N	25	8
Mean	88%	76%
Median	92%	80%
S.D.	15%	13%
Numerical test duration	**CO_2 concentration <1400 ppm**	**CO_2 concentration >1400 ppm**
N	25	8
Mean	8 mins 14 seconds	13 mins 15 seconds
Median	7 mins 0 seconds	9 mins 30 seconds
S.D.	3 mins 34 seconds	10 mins 49 seconds

Once again, this lower threshold for grouping test scores and durations in case study N compared to case study K is evidence that N's occupants were more sensitive to changes in their environmental conditions: there were no statistically significant differences between test scores or test durations when grouped according to a 1000ppm CO_2 concentration threshold in case study K.

7. Discussion

It is evident from the transverse and longitudinal surveys that occupant perception of their environment mattered for improving productivity. There was a clear link found between occupants' perception of their environment and their perceived productivity in both case studies, regardless of the age of the building or the nature of the ventilation system (natural or mechanical). When occupants felt too warm or too cold, they perceived their productivity to be negatively affected. When they perceived the air to be stuffy, they also perceived their productivity to be negatively affected.

Task performance, which was used as a proxy for measuring productivity, was affected by indoor environmental conditions such as indoor temperature and CO_2 concentration. It was found to be negatively affected by high temperatures (particularly over 26°C during the non-heating season) and high CO_2 concentrations (particularly over 1400 ppm in the naturally ventilated case study K and 1000 ppm in the mechanically ventilated case study N). The most popular task was the Stroop test, perhaps because it took much less time to complete than the others and respondents could also score much higher. However, this meant that there was a very narrow distribution of test durations and test scores, and no meaningful cross-relations were to be found. The numerical and proofreading tasks gave a spread of results closer to a normal distribution but were less popular with respondents, possibly because they were more time consuming and more difficult.

Neither the business output metrics provided by case study K or the absenteeism data provided by case study N proved usable as a measure of productivity which could show any meaningful correlation to the indoor environment. The indoor environment is dynamic, so comparing the number of phone calls made or e-mails sent over a week to the average temperature, RH or CO_2 concentration does not capture the extreme conditions that may have an adverse effect on these figures. For business output metrics to be usable as a measure of productivity, they need to have higher resolution in terms of space and time. Furthermore, these data sets (business output metrics and absenteeism) proved difficult to obtain. Despite the case study organisations being engaged in the project at some level, they were still reluctant to share information that could be considered sensitive for evaluating workplace productivity.

Statistical links between perceived productivity and perceptions of the indoor environment provided by the surveys were stronger than links between measured productivity (using task scores and durations as a proxy) and measured indoor environment. Response rates for the surveys were also greater than for the tasks. However, both data sets were necessary to provide a fuller understanding of the link between indoor environment and workplace productivity.

8. Conclusions

This paper has adopted a case study-based approach to empirically explore the relationship between indoor environment and workplace productivity in a naturally-ventilated and fully mechanically-ventilated office environment. It is evident that occupant perception of their indoor environment matters for improving productivity. Task performance was affected by indoor environmental conditions such as indoor temperature and CO_2 concentration.

Perceived productivity and task performance offered complementary approaches in defining the link between indoor environment and workplace productivity. While measurement of perceived indoor environment and productivity helped to identify if there was a link, task performance helped to define the threshold beyond which worker performance deceased. Although there is potential for business output metrics to provide a usable measure of productivity, the data needs a high resolution to provide meaningful cross-relation to indoor environmental conditions.

The study has also shown that measuring productivity directly can be challenging for many reasons, whereas measuring productivity indirectly through occupant perception surveys can provide meaningful data that is more easily obtainable and arguably at lower cost. Such occupant surveys can also be deployed in building performance evaluation studies, and also investigations into occupant well-being. Despite the challenges faced in conducting this research in a real-world working environment, the results have provided empirical evidence of the links between workplace productivity and indoor environment.

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