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An Empirical Investigation of the Link between Indoor Environment and Workplace Productivity in a UK Office Building

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ABSTRACT: Most studies on indoor environments and productivity have been conducted in controlled, static conditions often not representative of the real world. This paper uses a case study-based, real-world approach to empirically investigate the relationship between the indoor environment and workplace productivity in a mechanically-ventilated office environment in southern England. Evidence gathered during a baseline period is used to implement an intervention (limiting peak temperature) with the aim of improving productivity. Environmental parameters (temperature, relative humidity and CO_2) were monitored continuously. Transverse and longitudinal surveys recorded occupant perceptions of their working environments, thermal comfort and self-reported productivity, while performance tasks objectively measured productivity. Although the building was operating within narrow temperature, RH and CO_2 bands, workplace productivity was perceived to decrease when occupants were thermally uncomfortable and when they perceived the air as stuffy. Correlations with perceived changes in productivity were stronger for the perceived environment than for the measured environmental conditions. In addition, median scores were 16% lower for tests conducted when CO_2 levels were in the 1000-1200ppm range compared to those conducted below 800ppm. Insights from the study can be used to optimise indoor office environments to improve staff productivity.
KEYWORDS: Productivity, office, survey, indoor environment, comfort

1. INTRODUCTION

Productivity in the workplace has become a major concern, particularly in the UK where research suggests UK productivity is around 16% lower than the G7 average [1]. Improvements in the working environment could reduce this deficit by around 3% [2] - hugely significant in financial terms.

This paper uses a case study-based real-world approach to empirically investigate the link between indoor environment and workplace productivity in a mechanically-ventilated office environment in southern England. It uses a *baseline (observation)* and *intervention* approach, where a range of environmental parameters (indoor air temperature, relative humidity (RH) and CO_2 levels) are monitored continuously, alongside outdoor temperature and RH for six months (March-August 2017) in the *baseline* period and for one month (October-November 2017) in the *intervention* period. During these two periods, longitudinal online surveys record occupant perceptions of their working environment, thermal comfort and self-reported productivity, while performance tasks are designed to objectively measure productivity. In addition, a transverse Building Use Studies (BUS) survey [3] was conducted in April 2017 to gather occupants' perception of their working environment.

2. EVIDENCE TO DATE

CEN standard EN15251 acknowledges that the indoor environment affects occupant productivity, health and comfort [4] and limits were therefore set to optimise performance. Negative factors related to productivity (e.g. temperatures or CO_2 concentrations being too high) were often more obvious than positive factors (i.e. finding the optimal environment to increase productivity). Studies have therefore sought to understand these relationships more fully, although many of these have been conducted in controlled, static conditions which minimise or eliminate the myriad of potential influencing factors present in dynamic real world offices.

The effect of temperature on health and comfort has been widely researched and it is broadly recognised as an important indoor environment factor. The recommended limits for Category II mechanically ventilated office buildings are 20-26 °C, implying that within this range there is no direct risk to occupants' health and comfort. Tham [5] found that indoor temperature significantly influences workers' productivity, and Fang et al. [6] identified a link between temperature, RH and performance at different ventilation rates. Lan et al. [7] found that performance decreased in warmer conditions, but the results from the study imply that optimum thermal comfort and optimum productivity may not occur at the same temperatures – a finding supported by others [8]. Seppänen et al's meta-analysis [9] suggests the temperature range for optimum performance is close to the optimum range for comfort, particularly for mechanically ventilated buildings in winter.

An indoor CO_2 concentration upper limit 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 can have significant negative impacts on worker performance.

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. Meta-analysis of the occupant surveys showed 12 out of 21 workspaces reporting an increase in perceived productivity due to the environmental conditions perceived by the occupants [13]. When occupants were satisfied with the indoor temperature, noise and lighting, perceived productivity increased; conversely, when indoor air was perceived as stuffy and smelly, perceived productivity decreased.

It is evident that research suggests a growing recognition of a link between indoor environment and perceived productivity in workplaces. This paper uses a case study office building in the south of England to investigate this link empirically.

3. CASE STUDY AND METHODS

The case study building selected is a modern office building in Southern England. It is a typical representation of a modern office building in the UK [14]. Construction of the building was completed in 2006. The facilities are managed by an on-site external facilities management company using a BMS system, with mechanical ventilation and non-openable windows. The second-floor work space in block B was selected as the case study office environment. The gender mix of occupants in this workspace (approximately 57% male, 43% female), and the distribution of age groupings (approximately 10% under 30 years, 90% 30 years and over) was representative of a typical working office.

The methodology adopted in the study has a three-pronged approach: (1) *Physical monitoring of indoor and outdoor environment* using data loggers; (2) *Occupant survey* (transverse and longitudinal) and (3) *Performance tasks* (productivity tests) which act as a proxy for productivity. Three different sets of performance tasks were selected from those used in previous research studies. They are designed to represent tasks typical of those conducted in the case-study office: *Numerical tests* (to solve simple mathematical questions), *Proof reading* (to identify spelling errors in a paragraph of text) and *Stroop test* (an interference test, differentiating between the colour of the text and the word). Both the test score and time taken to complete the task were recorded.

4. BASELINE PERIOD: RESULTS

Physical monitoring from March 2017 to August 2017 showed that during occupied hours (8am-6pm, Monday-Friday) indoor temperatures were relatively warm, staying within 22-24°C for the majority of the time (Fig. 1). During the non-heating months (May-August) the range of temperatures increased.

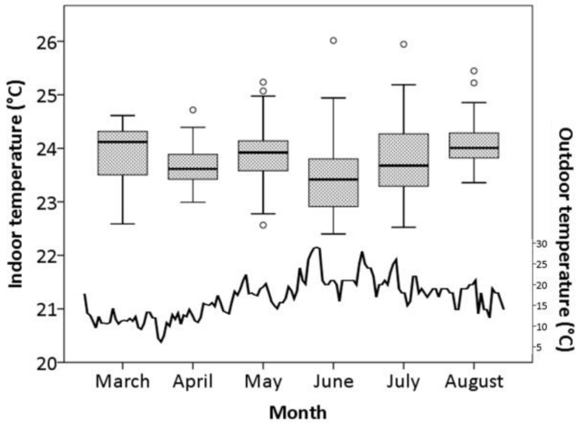

Figure 1: Boxplot of monthly indoor air temperatures (with daily average outdoor temperatures shown on secondary y-axis)

As the windows within the working area were not openable, CO_2 concentrations were not affected by windows being opened in warmer weather. Median CO_2 levels remained fairly stable (around 800 ppm) throughout the baseline period. RH within the office was close to the low end of the recommended range (40-60%) throughout both the baseline and intervention periods. RH levels increased in the summer months when indoor heating was used less.

4.1 Perceived productivity

The BUS survey (n: 69) provided a snapshot of occupant perception of their working environment during summer and winter and self-reported change in productivity. Occupants were asked "Please estimate how you think your productivity at work is decreased or increased by the environmental conditions in the building?", with responses on a scale from "-40% or less" to "+40% or more" in 10% increments. Occupants estimated that their productivity decreased by a mean of 5% due to the indoor environmental conditions. Interestingly when occupants perceived the environment to be uncomfortable (air quality, thermal comfort), their perceived productivity decreased (e.g. stuffy smelly air results in a decrease in perceived productivity).

The first round of the online (longitudinal) survey was conducted from 11 May to 24 May 2017 and the second round was from 11 July to 17 July 2017 (total n: 950). In both rounds, a link to the questionnaire was sent to the occupants three times a day. The responses were time stamped so concurrent indoor environmental measures could be identified. Thermal sensation votes, thermal preference votes, perceived air quality votes and overall comfort votes all received close to normal distributions. Notably, perceived air quality was slightly skewed toward stuffy rather than fresh, whereas overall comfort was slightly skewed towards comfortable rather than uncomfortable. As these surveys were investigating occupants' experience at a particular moment in time, the wording of the productivity question was adapted to "At present, please estimate how you think your productivity has decreased or increase by the environmental conditions in the building". The response scale was also adapted to be from "-20% or less" to "+20% or more" in 5% increments.

The following boxplots show visually the correlations between occupant perceptions of their environment and changes in their perceived productivity. About 73% of the responses were thermally comfortable (scoring 3-5 on the thermal sensation vote). When thermally comfortable, occupants perceived their productivity to be neutral (Fig. 2). At both ends of the scale, though more so at the warm end, occupants perceive their productivity to be reduced. Notably, occupants perceived their productivity to be more positively affected when they were comfortably cool than neutrally comfortable or comfortably warm.

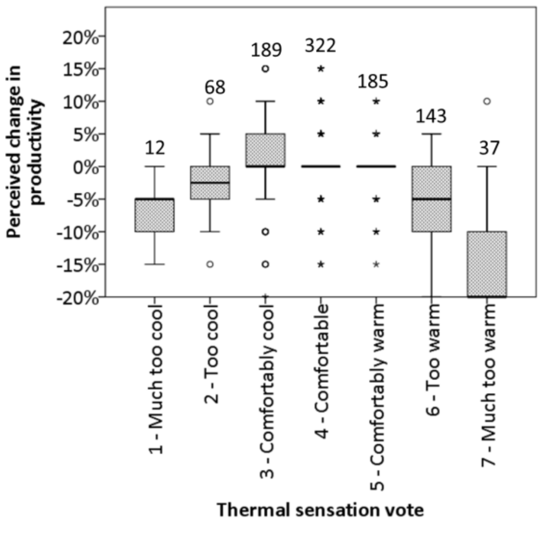

Figure 2: Baseline distribution of perceived change in productivity grouped by thermal sensation vote (with N shown). Note: Upper and lower quartiles for '4-Comfortable' and '5-Comfortably warm' were 0%

Similarly, the distribution of results for different thermal preference votes indicates that when occupants would prefer to be much warmer or cooler, they perceive their productivity to be negatively affected (Fig. 3). 92% of responses voted neutral (a bit cooler, no change or a bit warmer).

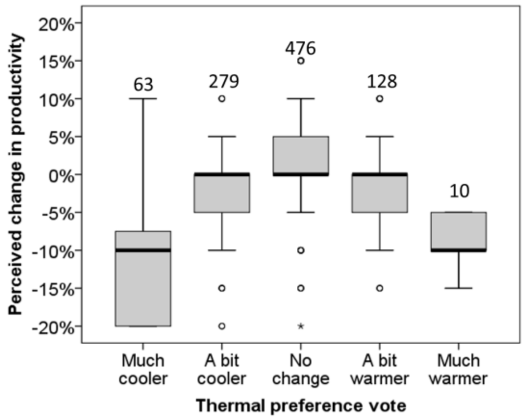

Figure 3: Baseline distribution of perceived change in productivity grouped by thermal preference vote (N shown for each vote)

Interestingly, occupants' perceived change in productivity had a stronger correlation with their thermal sensation votes (fig. 4) than with the measured indoor temperature. Indeed, statistical analysis of variance (comparing perceived change in productivity with measured temperature) indicated no statistical difference at the $p<0.05$ level: the subjective thermal comfort of the occupants was more important in terms of perceived productivity than the objective temperature in which they were working. A temperature of 23°C, for example, was perceived by some occupants as being too warm and by others as being too cool. Thermal comfort depends on a combination of factors in addition to temperature, including RH and air movement. However, neither RH or air movement showed any statistically significant correlation with either thermal sensation votes or occupants' perceived change in productivity.

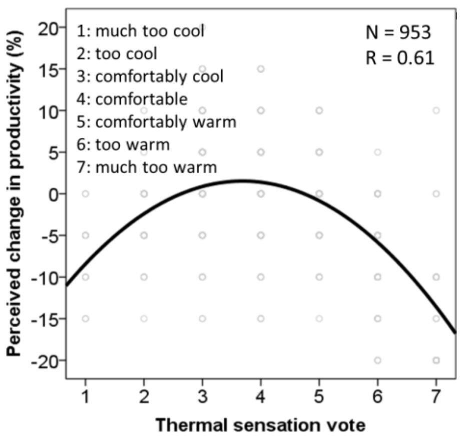

Figure 4: Scatter plot with quadratic trend line showing correlation between perceived change in productivity and thermal sensation vote.

The distribution of perceived change in productivity for different overall comfort votes (Fig. 5) showed that when respondents felt comfortable overall (voting 6 or 7) they perceived their productivity to be positively affected. A neutral perception of their change in productivity correlated with an overall comfort vote of 5. Overall comfort votes of 4 or lower correlated with an increasingly negative perception of change in productivity.

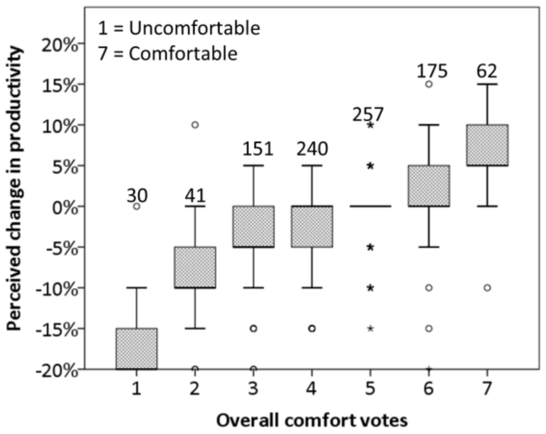

Figure 5: Baseline distribution of perceived change in productivity grouped by overall comfort vote (N shown for each vote) Note: Upper and lower quartiles for 5 were 0%

4.2 Measured productivity

The first round of the performance tasks was conducted from 5 June - 9 June, 2017 and the second round from 24 July - 28 July 2017 (total n: 285). As the tasks were time stamped, concurrent indoor conditions were recorded.

Indoor temperatures when tasks were conducted fell within a narrow band (predominantly 22-25°C), making it difficult to identify significant correlations. The direction of the trendline indicated that as indoor temperature increased, the proportion of correct answers decreased (Fig. 6). However, statistical analysis indicates this correlation is very weak and not statistically significant (p>0.05).

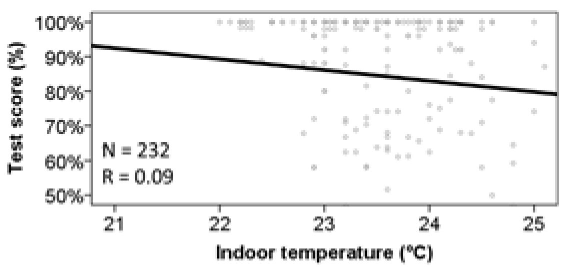

Figure 6: Scatterplot and linear trendline comparing scores from all baseline tests to concurrent indoor temperatures.

5. INTERVENTION PERIOD: RESULTS

Based on the findings from the baseline period, the BMS was used to control the temperature set-points (21.5°C, 22.0°C, 22.5°C and 23.0°C for each week) over a 4-week intervention period (23 Oct to 17 Nov 2017). During this period, online survey and performance tasks were repeated and time stamped.

5.1 Perceived productivity

The online (longitudinal) surveys were conducted three times a day on Mondays and Tuesdays. Responses indicated that the occupants were fairly satisfied with their thermal sensation (70% of thermal comfort responses voting neutral: 3-5) and with their thermal preference (91% of responses voting neutral: A bit warmer, no change or a bit cooler). Interestingly, these figures were slightly lower than the neutral responses at baseline (73% and 92% respectively).

When occupants were thermally comfortable, they perceived their productivity to be unaffected, but when they were too cool or (more significantly) too warm, they perceived their productivity to be negatively affected. These results concurred with findings from the baseline study (Fig. 7).

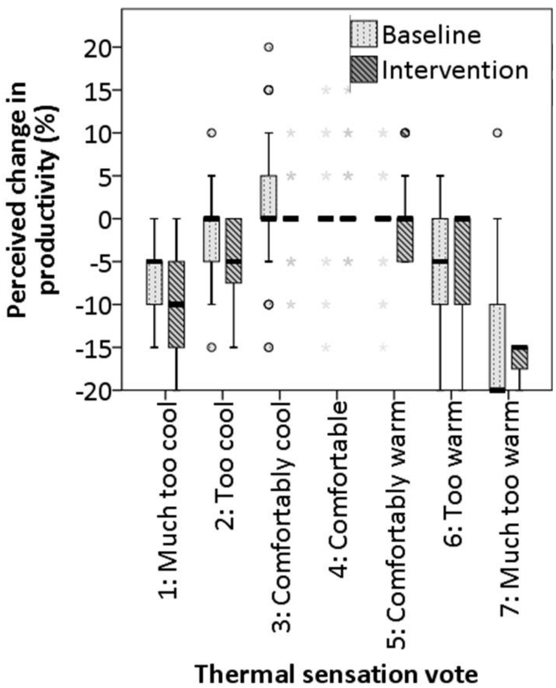

Figure 7: Baseline and intervention period distribution of perceived change in productivity grouped by thermal sensation vote (N shown for each vote). Note: Upper and lower quartiles for '3-Comfortably cool' and '4-Comfortable' were 0%.

Furthermore as thermal preference gets further from the neutral "no change", the perceived change in productivity decreases. Again, these results concur with those in the baseline (Fig. 8).

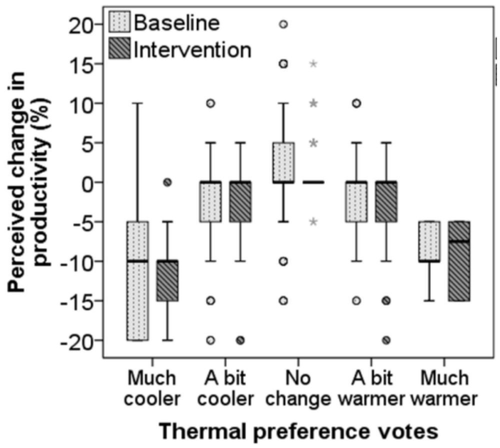

Figure 8: Baseline and intervention period distribution of perceived change in productivity grouped by thermal preference vote. Note: Upper and lower quartiles for intervention 'No change' were 0%

In summary, when comparing survey responses and the correlations between perceived change in productivity and the different environmental perceptions, the trends are very similar during the baseline and intervention periods.

5.2 Measured productivity

Online tasks were conducted twice daily from Wednesday to Friday during the intervention period, and were scheduled so that each type of task was conducted an equal number of times in the morning and afternoon to reduce any unintentional bias.

As with the baseline, the indoor temperatures concurrent with the times the tasks were conducted covered a fairly narrow band (21-25°C). However, the intervention gave a more even spread of temperatures within this band. Again, the correlation between test scores and corresponding indoor temperatures was very weak (R = 0.09) and not statistically significant ($p>0.05$). A stronger and more significant correlation was found between perceived productivity and thermal sensation vote (Fig. 9).

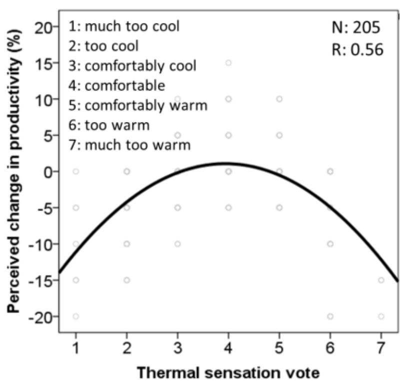

Figure 9: Scatterplot and quadratic trendline comparing perceived change in productivity to thermal sensation votes

Furthermore, when comparing test scores grouped by the concurrent levels of CO_2, it was evident that higher levels of CO_2 correlated with lower test scores, with the median score in the '1000-1200 ppm' grouping 16% lower than the median score in the 'less than 800 ppm' grouping (Fig. 10 and table 1). Somers' D test was run to determine the association between CO_2 concentration and test scores. The correlation was weak (d=-0.16) but statistically significant ($p=0.03$). Although the recommended upper limit of CO_2 in offices is 1500 ppm in the UK, results from the study indicate that there may be productivity benefits to having CO_2 concentrations significantly lower than this.

Table 1: Descriptive statistics for intervention period test scores grouped by concurrent CO_2 concentrations

Statistic	Less than 800 ppm	800-1000 ppm	1000-1200 ppm
N	49	39	10
MEAN (%)	88	76	66
MEDIAN (%)	92	83	76
SD (%)	12	26	26
Q1 (%)	82	63	58
Q3 (%)	100	96	80

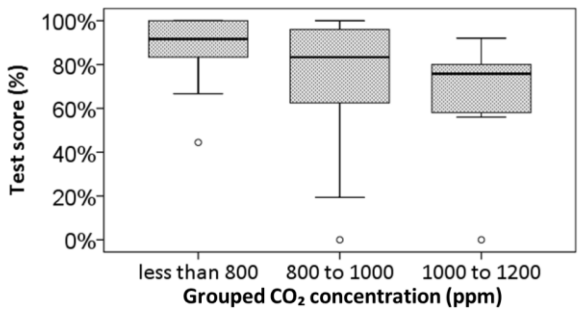

Figure 10: Boxplot showing intervention period distribution of test scores conducted within three bands of CO_2 concentration.

6. DISCUSSION

The present study has discovered interesting results through monitoring, surveys and tests in the case study, during the baseline and intervention periods. The workplace operated within fairly narrow bands of temperature (22-25 °C), RH (40-60 %) and CO_2 concentration (below 1200 ppm) for the majority of working hours. Consequently, correlations between measured indoor environment (particularly temperature and RH) and both perceived and measured productivity were very week and not statistically significant.

Occupant feedback indicated that the majority of occupants were content with their indoor environment (thermal comfort, air quality, overall comfort). However, a significant proportion of occupants expressed discomfort due to feeling too cool, too warm, or the air feeling too stuffy. These responses corresponded to perceptions of productivity being decreased.

Stronger correlations were found between perceived changes in productivity and thermal sensation than actual measured temperature. Likewise, stronger correlations were found between perceived changes in productivity and perceived air quality than either measured RH or measured CO_2 concentration. These results indicate that how an occupant subjectively feels can have a greater impact on their perceived productivity than the objective environment they are in.

In addition to the perceived changes in productivity, measured changes in test score (used as a proxy for productivity) were observed which correlated with changes in the indoor environment. Both higher temperatures and higher CO_2 concentrations correlated with a decrease in average test score. Throughout the study, no statistically significant differences were found between gender (all surveys and tasks) or for respondents in different age categories (BUS survey).

7. CONCLUSION

This study has provided interesting results through continuous physical monitoring, surveys and performance tasks in a case-study working environment in the south of England.

Conducting this research in a real-world working office environment posed a number of challenges, particularly in terms of occupant engagement and data gathering. It also allows a great deal of 'noise' in the data, as a myriad of mitigating factors may influence the results.

Nevertheless, despite these challenges, this study has found empirical evidence that suggests elements of indoor environment (specifically CO_2 concentration) are related to workplace productivity, suggesting that by managing the indoor environment effectively, there is potential to improve productivity.

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