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

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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 (NV) and one mechanically ventilated (MV) located in southeast England. Environmental parameters (indoor and outdoor relative humidity (RH), CO₂ and indoor and outdoor temperature) were continuously monitored at 5 minute intervals over a period of 19 months (March 2017 to September 2018). During the monitoring period, occupant satisfaction surveys (snapshot and longitudinal) were conducted to record occupant perceptions of their working environment, including thermal comfort, resulting in approximately 2600 survey responses from each case study.

In the NV office, CO₂ levels were high (>2000ppm) and indoor temperature was both high (>27°C) and variable (up to 8°C change). The MV office environment was found to operate within much narrower indoor temperature, RH and CO₂ bands. This was evident in the little seasonal variation observed in the indoor CO₂ levels in the MV office; whereas in the NV office, CO₂ concentrations were over 1400 ppm for 20% of the working hours during the heating seasons and decreasing to 3% in the non-heating seasons, when windows were frequently opened. Occupants were found to have different levels of tolerance to measured indoor temperatures - neutral thermal sensation votes corresponded to a higher indoor temperature in the NV building, indicating the role of adaptation. Insights from the study can help in improving indoor environments of NV and MV offices.

1. Introduction

A number of studies have investigated occupant perception of their working environment – particularly relating to thermal comfort – and its relationship with measured environmental conditions [1-3]. Thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment. The Predicted Mean Vote (PMV) model, developed by Fanger [4] is amongst the most recognised models. This has been the basis for several standards including EN ISO 7730 [5] and ASHRAE Standard 55 [6]. However, a key assumption in this model is steady state conditions: temperatures, RH levels, CO₂ concentrations remaining stable. This is why field studies of thermal comfort assess the dynamic state of the indoor environment by cross-relating subjective responses of occupants with measured indoor environmental conditions to determine acceptable ranges of indoor temperature.

Many modern office buildings strive to achieve this acceptable environment using mechanical ventilation and air conditioning. However, many office buildings do not have the ‘luxury’ of mechanical ventilation and/or air conditioning and rely on natural ventilation and conventional heating and cooling systems such as fan coil units (FCUs). In these buildings, environmental conditions can be much more variable both seasonally and even over the course of a single working day.



Some studies have considered the differences in occupant perception between naturally ventilated (NV) buildings and mechanically ventilated (MV) buildings [7, 8]. Other studies have taken a simulation approach, using models and/or climate chambers to investigate subjective perception of the environment under different, controlled static conditions [3, 9, 10]. These have found evidence that there is an interaction between different environmental parameters that can affect occupant perception. Geng et al. [3] found that occupants perceived changes not only in their thermal comfort levels, but also in other IEQ-related comfort factors, when indoor temperatures were varied.

Many studies have taken a field-study approach, combining subjective occupant surveys with objective environmental monitoring, and have found that thermal sensation votes and overall comfort show correlations with indoor temperatures, but that the results agree more closely with adaptive comfort models than with the static PMV model [2, 11, 12]. 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 [2]. Meta-studies such as Hellwig et al. [7] have further supported this finding, suggesting that the ability of occupants to control aspects of their environment can positively affect how accepting they are of their working environment.

This paper builds on the existing body of research by conducting continuous monitoring of indoor environment and occupant surveys in two contrasting office buildings located in the south of England: one naturally ventilated, the other a mechanically ventilated. Environmental monitoring was conducted for nineteen months, during which time occupants provided feedback on their perception of their working environment through a questionnaire and surveys. The results of these data streams provide insight into how occupants perceive their environment, and whether or not the more stable, mechanically ventilated office space provided more favourable working conditions than the variable naturally ventilated office space.

2. Methods and overview of case study buildings

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). For the physical monitoring, the case study work areas were divided into zones, with Hobo data loggers (range and accuracy: $-20-70^{\circ}\text{C} \pm 0.21^{\circ}\text{C}$ and $15-95\% \text{ RH} \pm 3.5\%$) in each zone recording indoor and outdoor temperature, indoor and outdoor relative humidity (RH) and TinyTag data loggers (range and accuracy: $0-5000\text{ppm} \pm 50\text{ppm}+3\%$ of reading) in each zone recording CO_2 concentration at five-minute intervals.

The naturally ventilated case study building was located in central London. It was owner-occupied and owner managed with heating and cooling provided by FCUs. The case study offices were on the seventh floor of nine, and consisted of two open-plan areas with 120 workstations. The mechanically ventilated case study building was a modern office building in southern England. Built in 2006, its facilities were managed by an on-site external facilities management company, with mechanical ventilation and non-openable windows. Two open-plan workspaces were selected as the case study environments, one on the second (top) floor, one on the first floor, with a total of 260 workstations.

In both case-study buildings, occupants completed a Building User Studies (BUS) survey 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. Over the course of 19 months, each case study office underwent a baseline period when online surveys were delivered three times a day every (working) day for two weeks, and two 'intervention' periods when an element of the indoor environment (temperature or CO_2 concentration) was controlled and surveys were delivered three times a day on Mondays and Tuesdays over four weeks. Respondents indicated their desk numbers, which allowed responses to be cross-related with concurrent indoor environmental conditions in their zone. As the baseline and intervention periods took place 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.

3. Results

3.1 Measured indoor environmental conditions

The measured indoor environmental parameters (temperature, RH and CO₂ concentration) alongside outdoor temperature and RH provided valuable insight into the similarities and differences between the two case study working environments. As shown in Figure 1(left), it is evident that the temperature ranges during working hours each month were much greater in the NV offices than in the MV offices, particularly during the heating season.

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 the MV building compared to 11% of working hours in the NV building. During the non-heating season, temperatures exceeded the recommended 24°C for 60% of working hours in the NV case study buildings and 41% of working hours in the MV case study building. However, temperatures exceeded 26°C for only 1% of working hours in the MV case study compared to 15% of working hours in the NV case study.

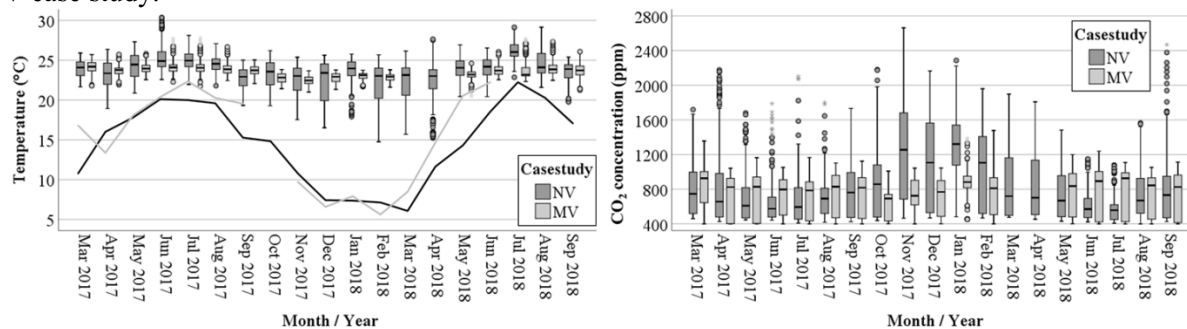


Figure 1. Distribution of hourly averaged temperatures (left) and CO₂ concentrations (right) during working hours for each month of the monitoring period in the naturally ventilated (NV) and mechanically ventilated (MV) offices, with lines showing monthly average outdoor temperatures during working hours.

The range of indoor RH during working hours was more similar between the two case study buildings. Measured CO₂ concentration provided the most significant contrast between the two buildings (Figure 1, right). The MV building was able to keep peak concentrations below 1200 ppm for the vast majority of working hours throughout both seasons. In the NV building, during the non-heating season, CO₂ concentrations were similar to those in the MV building, with median levels significantly lower. However, during the heating season, with windows closed for the majority of the time, CO₂ levels increased dramatically, with median levels exceeding 1200 ppm and peaks in excess of 2800 ppm.

3.2 Transverse survey responses: BUS survey

BUS survey provided an overview of occupant perception of their working environment. The key questions relevant for this study 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).

Despite the measured differences in environmental conditions in the two buildings, the only winter-related questions which gave a statistically significantly different distribution of responses between the two buildings were 'Air in winter (still/draughty)' (more skewed towards 'still' in the NV building than in the MV building) and 'Air in winter (odourless/smelly)' (more skewed towards 'smelly' in the NV building than in the MV building).

By comparison, six of the eight summer conditions questions produced results that were significantly different between the two case studies. Overall temperatures in the NV building were viewed less favourably than those in the MV building and skewed much more towards 'hot' than 'cold'. The air in summer was perceived to be stuffy in both buildings.

It is also worth noting that in the BUS questionnaire the occupants were asked about the level of control they felt they had over their working environment in terms of heating, cooling, ventilation,

lighting and noise. The occupants of the MV building felt that they had much less control than their NV counterparts, particularly in terms of heating, cooling and ventilation. Control has been linked to perceptions of thermal comfort in several studies [1, 7, 9, 11].

3.3 Longitudinal survey responses: Online survey

3.3.1 Thermal comfort and preference vs. measured temperature. Thermal sensation votes were given on a seven-point scale from ‘Much too cold’ to ‘Much too warm’. Despite the differences in temperature profiles in both buildings, the distribution of thermal sensation votes was remarkably similar (Figure 2, left). Perhaps most surprising is that during the non-heating season a higher proportion of survey responses were on the warm end of the scale in the MV building than in the NV building, despite median indoor temperatures being 0.5°C higher and maximum indoor temperature being almost 2.5°C higher in the NV building compared to the MV building.

Cross-relating the thermal sensation votes with the concurrent indoor temperatures showed a significant distinction between the two case-study buildings, particularly during the heating season (Figure 2, right). The range of indoor temperatures experienced by the occupants was much greater in the NV building, and yet they were much more tolerant, particularly at higher temperatures. The median temperature when NV occupants voted ‘Comfortably cool’/‘Comfortable’/‘Comfortably warm’ was around 24°C, compared to 22-23°C for MV occupants. Indeed, 24°C in the MV building was the median temperature for thermal comfort votes of ‘Much too warm’. During the non-heating season, there was more overlap between buildings in the distribution of temperatures for each thermal comfort vote, and median temperatures were much closer. Nevertheless, other than at the ‘Cool’ and ‘Much too cool’ end of the scale, median temperatures were higher from NV occupants than from MV occupants for each thermal comfort vote.

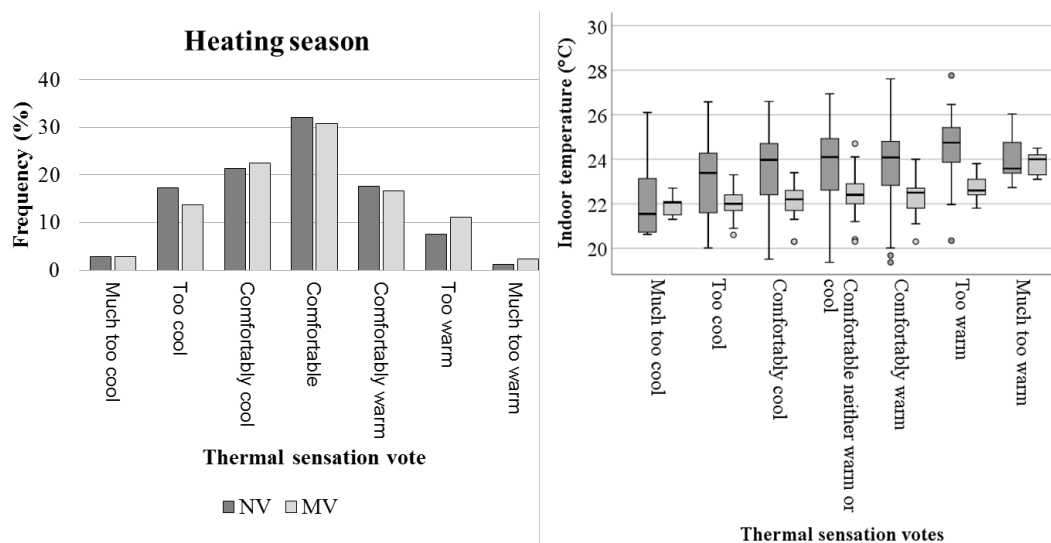


Figure 2. Distribution of survey responses to thermal sensation (left) and distribution of concurrent temperatures for each thermal sensation vote (right) during the heating season.

A similar pattern was found for the thermal preference votes. The distribution of votes was similar in both buildings during both seasons and a higher proportion of occupants of the MV building expressed a preference to be cooler than those in the NV building. Plotting thermal preference votes against concurrent indoor temperatures showed that during the heating season, NV occupants were fairly content with temperatures of 24°C (the median score for the almost 50% of responses wanting ‘no change’), whereas MV occupants much preferred temperatures nearer 22-23°C. During the non-heating season, there was more overlap in the distribution of boxplots between both buildings, and it was notable how similar the boxplot distributions were for each of the thermal preference responses in the MV building.

3.3.2 Perceived air quality vs. measured RH levels and CO₂ concentration. 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. 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 the NV building was very similar in both seasons, whereas MV 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. Plotting perceived air quality votes against measured RH levels or CO₂ concentrations showed no significant correlation in either building in either the heating or non-heating seasons, suggesting that the perception of air quality is a more subjective sensation.

In summary, the survey responses showed similar distributions of votes for the perception of the environment (thermal sensation, thermal preference, air quality and overall comfort), despite the significantly different environmental conditions (indoor temperature, RH levels and CO₂ concentrations) experienced by the occupants.

4. Discussion

The differences between the two case study buildings were evident in the environmental profiles produced from nineteen months of monitoring. The NV building experienced a wide range of indoor temperatures both seasonally and over the course of a day. By comparison, the MV building’s temperatures were much more stable, remaining within the 22-24°C range for the vast majority of working hours, and rarely varying by more than 1 or 2°C over the course of a working day. In the NV building during the heating season, median CO₂ concentrations during the working day were around 1200 ppm, and exceeded 2000 ppm regularly, whereas during the non-heating season, with open windows, concentrations were much lower, significantly lower than in the MV building. By comparison, CO₂ concentrations in the MV building remained consistently below 1200 ppm throughout the year, with little seasonal variation.

Responses to the BUS survey reflected this, with NV occupants perceiving the air in winter to be more still and the air in summer and winter more smelly than their MV counterparts. The temperature in summer was considered more hot and uncomfortable overall by NV occupants. The distinctions between the buildings became much less clear in the longitudinal surveys. Occupants of the NV building showed much greater levels of tolerance for both lower and higher temperatures which occupants of the MV building would have found unacceptable. Despite experiencing much higher CO₂ concentrations during the heating season, the NV occupants’ level of satisfaction with the indoor air quality was on a par with that of the MV occupants, and during the non-heating season, the NV occupants were more satisfied with the indoor air quality than their MV counterparts.

It is possible that by completing the BUS survey in the spring, respondents’ memories of summer conditions were biased by extreme cases (for example, remembering unusually high temperatures being more common than they actually were). The longitudinal surveys were able to provide a series of snapshot perceptions of the environment which provided occupant feedback over a more representative range of indoor environmental conditions.

Occupants of the NV building appeared to be more adaptable and have a wider range of acceptable indoor environmental conditions compared to the occupants of the MV building. The degree to which occupants feel they have control over their environment may also have contributed to the range of acceptable indoor environmental conditions.

5. Conclusions

Although the NV building experienced a wider range of temperatures, both seasonally and over the course of a working day, and experienced much higher CO₂ concentrations throughout the heating season, its occupants expressed similar levels of acceptance of their environment as their counterparts in the much more tightly controlled environment of the MV building. The role of adaptation and perception of control may well have contributed to this increased tolerance of objectively uncomfortable/unsatisfactory conditions.

The BUS questionnaire provided useful insights into the buildings' performances overall, but was unable to identify the specific indoor environmental conditions which occupants found thermally comfortable and preferable. The longitudinal surveys therefore provided complementary evidence, as they were able to give an indication of the range of acceptable conditions for the occupants.

The implications for these findings are interesting, particularly in terms of energy. Levels of energy use were not measured during this project, so it was not appropriate to speculate on the comparative amounts of energy used in each building for heating, cooling and ventilation. However, the MV building inherently expended a significant amount of energy to control its indoor environment. It is successful in doing so, but the levels of satisfaction the occupants have expressed in both the BUS questionnaire and surveys suggests that they are not much more satisfied, if at all, than their counterparts in the NV building.

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