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USE OF ADAPTIVE ACTIONS AND THERMAL COMFORT IN A NATURALLY VENTILATED OFFICE

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SUMMARY

A naturally ventilated office building in Alameda, CA with operable windows and ceiling fans was monitored from Oct 2011 to Oct 2012. Physical environmental parameters such as dry-bulb air temperature, humidity, CO_2 levels, outdoor wind speed, hourly window positions, heater settings and fan settings were recorded. Occupants were surveyed regularly over a period of one year about their current thermal comfort, thermal acceptability, air movement satisfaction, clothing and noise satisfaction. Occupants wore clothing with a clo value of between 0.5 – 0.6 during summer, and 0.7 – 0.8 during winter. The clo value of the occupants clothing was most closely correlated with the outdoor running mean temperature. Occupants start opening windows when the outdoor is at 16 °C. Window opening was strongly related with occupant's arrival and outdoor temperature. Fans use was best explained by indoor temperature. Fans were typically turned on during the summer at indoor temperatures above 26 °C. Occupants voted that the thermal environments in the building were acceptable 98% of the time during the year-long survey period.

INTRODUCTION

Commercial buildings with desk-based office work are often sealed and air conditioned even if they are located in regions with a mild climate. Overall, almost 90% of the office area in the US is air conditioned. This imparts a huge financial and energy consequence: 14% of the electricity in office building is used for cooling (US EIA, 2008). Natural ventilation (NV) with operable windows helps reduce non-essential conditioning of indoor air. Buildings with passive design strategies including natural ventilation were found to use 25%-75% less energy than ASHRAE 90.1 code compliant buildings (Torcellini et al. 2006). In NV buildings with operable windows, equally acceptable thermal comfort occurs over a wider range of indoor temperatures than in air conditioned buildings (de Dear and Brager, 1998). One of the reasons why these buildings are comfortable at higher temperatures is the convective cooling of the occupants achieved by air movement through operable windows. However, outdoor environmental conditions are not always conducive to providing sufficient air movement using natural ventilation alone. Indoor fans may provide the additional air movement; studies have found that they are used at higher indoor temperatures than windows (Haldi and Robinson, 2008, Nicol, 2001, Liu et al., 2012).

Prior studies have modelled occupant window adjustment behaviour (Haldi and Robinson, 2008, Nicol, 2001, Haldi and Robinson, 2009, Yun and Steemers, 2008, Herkel et al., 2008, Dutton and Shao, 2010). In these studies, indoor and outdoor temperatures were used as predictors of window intervention. One hypothesis is that occupants open windows when it is uncomfortably warm inside and close them when the outdoor temperature is too hot. However, indoor and outdoor temperatures are correlated in a NV building, at least during the summer, and so distinguishing their individual contributions towards window adjustment behaviour is difficult. Other studies also found that CO_2 concentration and time of the day influence window adjustment (Herkel et al., 2008, Dutton and Shao, 2010, Andersen et al., 2013). If outdoor temperatures have been warm, occupants open their windows on arrival and close them on departure (Herkel et al., 2008). In addition to these physical parameters, window opening is also influenced by context-specific latent factors such as access to window, type of window (e.g. awning and sliding) and local culture (Bahadur Rijal et al., 2012).

We consider multiple ways occupants control their indoor environment: clothing, ceiling fan and window adjustment behaviour and their interactions, particularly windows and fans. The adaptive theory predicts that occupants will accept a wider range of temperature if given an opportunity to dress freely and have access to adaptive opportunities in their surroundings (de Dear and Brager, 1998, Nicol and Humphreys, 2002). We analyse thermal comfort responses of occupants to evaluate whether the predictions of the adaptive theory are supported.

Specifically, the aims of this study are to

1) Understand the behavioural adjustment such as clothing in a NV building and their relationship with temperature.
2) Understand the operation of windows and fans and characterise the physical conditions under which they are used.
3) Examine comfort ranges in naturally ventilated buildings when adaptive options are available (ceiling fans in particular) and compare it to the ASHRAE Standard 55 adaptive model.

METHODOLOGIES

Building description

The case study building is located in Alameda, CA at 37° N and 122° W. As the office of an architectural firm with primarily desk-based work, it has high internal loads from computers, printers, copiers, and a server. The building is oriented northeast - southwest on its long axis and has two rooms. Seven occupants work in the front (northeast) room and six in the back (southwest) room. The construction material is well insulated light weight wood frame and the facade is about 15 % glazed with double pane glass on all sides except the southwest.

There are ten windows and four ceiling fans in the front room and seven windows in the back room. All of the windows have automated sun shades. There is no central heating, and the building is heated mainly by solar and internal heat gain during the winter. However, there are five personal electric heaters.

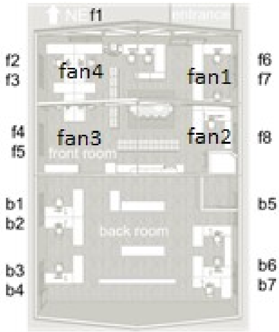


Figure : Fan and window positions

Data collection

Outdoor/indoor temperature, humidity, CO_2 concentration, outdoor air velocity were continuously monitored every five minutes from Oct 2011 to Oct 2012. 17 Onset hobo temperature/humidity data loggers were used: 10 in the front room, 6 in the back room, and one outside. Four time-lapse fish eye cameras took pictures of the double hung windows every five minutes. These pictures were then read hourly to record the percentage opening. Settings of the four ceiling fans were monitored via a voltage recorder.

Occupants were also surveyed three times a day in selected weeks throughout the year for their “right now” opinions about the indoor environment. They were asked to rank their thermal sensation and the acceptability of the temperature, air movement, air quality, and noise. These responses were all given on a 7-point Likert scale from -3 (“cold” or “not at all acceptable”) to +3 (“hot” or “very acceptable”). Temperature and air movement preference votes were collected on a 3-point scale with -1 (“prefer cooler” or “prefer less air movement”), 0 (“prefer no change”) and +1 (“prefer warmer” or “prefer more air movement”). The occupants also indicated what clothing items they were wearing to allow us to estimate clo value.

Most field studies employ a similar method of conducting “right now” surveys while simultaneously monitoring the physical environmental conditions of the space. A unique feature of our study is that it covers the same occupants in the same building for a full year, which allowed us to capture seasonal variation of environmental parameters as well as individual occupant behavior and comfort responses.

RESULTS

Temperature distribution

Figure shows the daily mean outdoor and indoor temperature distributions during occupied hours (8am- 7pm). The indoor temperature is the mean of the front and back rooms. We divide the year into three seasons: summer (June-October), winter (December-February), and swing (November, March-May). Outdoor temperature ranges from 15 °C to 26 °C during summer, 5 °C to 18 °C during winter and 10 °C to 25 °C during swing. Indoor temperature stays comparatively warm in the range of 22 °C – 28 °C in summer, 16 °C – 25 °C in winter and 19 °C – 28 °C during swing. While indoor temperature is warmer than the outdoors for a majority of the year, it is cooler than the outdoors during summer mornings.

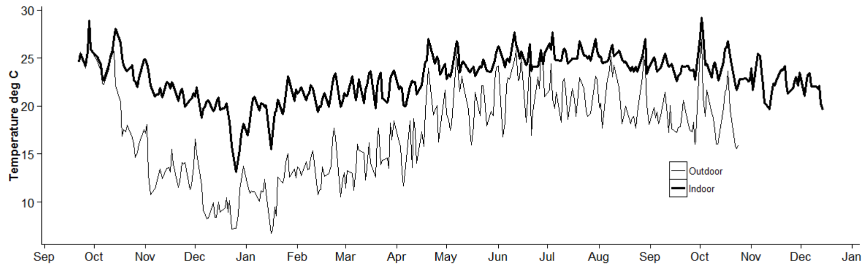


Figure Daily mean indoor and outdoor temperatures

Clothing

Occupants changed their clothing levels significantly through the year (p<0.001- ANOVA test). In summer, occupants wore a clothing range of 0.5-0.6 clo (0.55 median), which is 0.2 clo units less than the winter range of 0.7- 0.8 clo (0.75 median). This seasonal difference is wider than the 0.07 difference found in the ASHRAE RP-884 and RP-921 databases and similar to what has been found in Japan (Schiavon and Lee, 2012, Goto et al., 2007).

Our data shows a running mean outdoor temperature with α = 0.66 (Nicol and Humphreys, 2002) to be the best temperature metric for explaining clothing variation (R^2 = 0.35, p< 0.001). Multiple linear regressions including both outdoor and indoor temperature found indoor temperature to be an insignificant predictor variable (p = 0.814), which implies that occupants' wardrobe decisions are independent of indoor temperature.

Window and fan use

The patterns of using the windows and ceiling fans in the office show a strong temporal dependence on both monthly and daily timescales. Compared to windows, fans are used much less frequently, almost entirely during April through October (Figure). Both windows and fans are most often opened or turned on in the morning between 9-10 am and closed or turned off in the evening between 6-8 pm (Figure). This illustrates that occupant arrival and departure influences window and fan adjustment. Figure shows the usage frequencies for windows and fans by seasons. When windows are right next to each other (e.g. f2 and f3), often only one window is opened (Figure). Although all of the fans are used a similar amount, about half the time only one fan is on at a time.

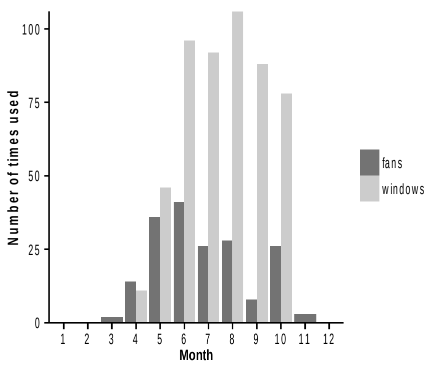


Figure Window/fan monthly use

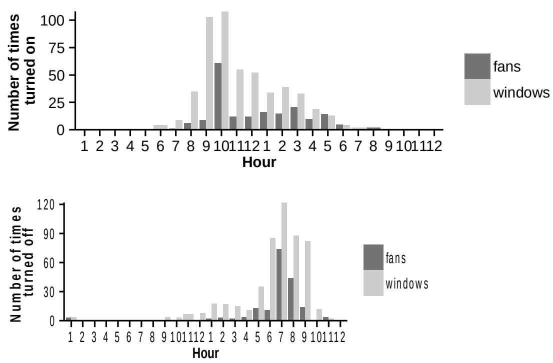
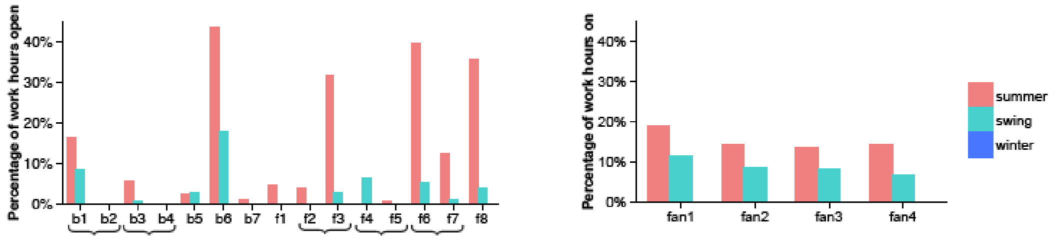


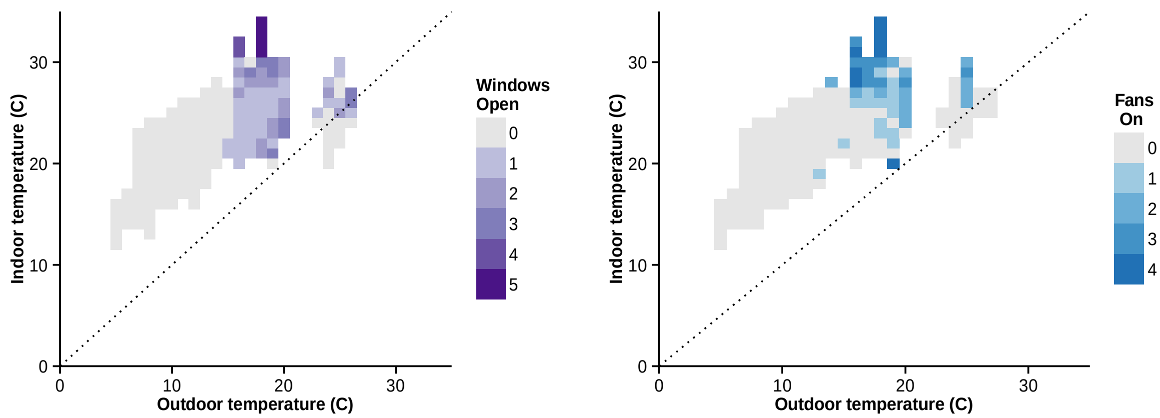
Figure Windows/fan daily adjustments



a. Windows b. Fans

Figure Usage frequency by season

Figure shows the average number of windows and fans deployed for various combinations of indoor and running mean outdoor temperature. Only work hours are shown. Graphically, whether or not a window is open appears to be more strongly related to running mean outdoor than indoor temperature because there is a distinct vertical dividing line at 16 °C below which windows are not open, but there is not a similar horizontal line. Although there is a similar line for fans at 16 °C outdoor, the division is not as consistent because the fans aren't always on above 16 or always off below 16 °C. For fans, the pattern is less clear because there is not a distinct horizontal or vertical dividing line.



a. Windows b. Fans

Figure : Window and fan opening vs. indoor and running mean outdoor temperatures

Occupants started opening the windows frequently at an indoor temperature of 21-22 °C and a concurrent outdoor temperature of 16 °C. While people turned on fans at lower temperatures, they only used them frequently at indoor temperatures above 18 °C and outdoor temperatures above 24 °C (Figure).

When the fans are on, the windows are very likely to also be open. When at least one fan is on, at least one window is also open 47% of the time. Conversely, if at least one window is open, at least one fan is also on only 29% of the time (Figure).

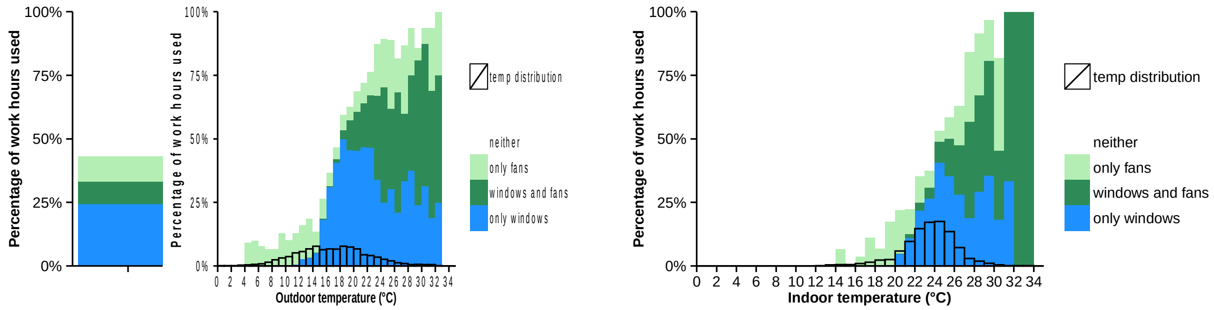


Figure : Combinations of windows and fans vs. temperature

Thermal comfort

Overall, occupants recorded thermal sensation votes between ± 1 in 82% of observations throughout the year. Although this sensation is also correlated with outdoor running mean temperature (R=0.4) and clothing (R=-0.32), it is most strongly correlated with indoor temperature (R=0.54). Figure shows this relationship between thermal sensation and indoor temperature. Interestingly, the rising slope of thermal sensation votes seems to flatten out above 23 °C, which is likely due to opening of windows and turning on fans at higher temperatures.

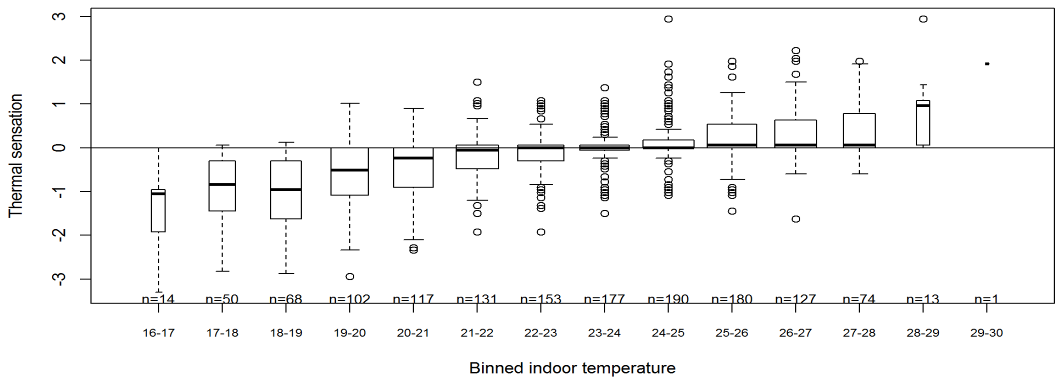


Figure Thermal sensation and indoor temperature

The neutral indoor temperature, calculated by linear regression, varies by less than 2 K between the seasons (23-24.6 °C), which is well within the standard error of the fits. The adaptive model predicts that the neutral temperature will vary depending on the outdoor conditions, but we saw a very small difference between seasons. This may be due to the mild climate of Alameda and the lack of distinct seasons (Figure).

At least 80% of occupants voted the temperature at their workplace to be acceptable in indoor temperatures between 16 – 28 ˚C. This wide range supports the view that occupants in naturally ventilated buildings with adaptive opportunities accept wider deviations from the neutral temperature.

We also conducted pair-wise correlations between thermal sensation, thermal acceptability, indoor temperature, running mean temperature, clothing, air movement satisfaction, noise satisfaction and perceived air quality. Thermal sensation was correlated with indoor temperature (R = 0.5), running mean temperature (R = 0.4) and clo (R = -0.32). Including all three predicted variables did not improve the fit over a single variable fit with indoor temperature. Interestingly, the variables that were not correlated with thermal sensation, i.e. air movement satisfaction, noise satisfaction and perceived air quality were correlated with thermal acceptability (R = 0.6; 0.42; 0.45 respectively).

DISCUSSION

Temperature inside the building was warmer than the outdoors except during summer mornings following nighttime cooling (Figure .

The occupants of this building clearly take advantage of the flexible dress code to adjust their clothing based on season and outdoor temperature. Rigid clothing norms that exist in much of the corporate world do not provide this adaptive opportunity and make climactically intelligent design more difficult (Fountain et al., 1996)

In addition to clothing, windows were the primary adaptive mechanism that the occupants used: they were opened more frequently and for longer periods of time than fans. Also, when the fans are on, the windows were very likely to also be open. Perhaps the windows were the preferred adaptive mechanism because they can provide a noticeable drop in temperature, or perceived sense of fresh air, as they provide air movement. If the air movement is sufficient without fans then they don't have to be turned on very often. Our results also reveal an interesting pattern of fan use; fans start getting turned on in the swing season between April-May while windows are not yet opened. The temperature during the swing season is transient, i.e. not as cold as winter and not as warm as summer. Perhaps the outdoor air is cool enough to be uncomfortable to bring in, so the occupants achieve adequate air movement by turning on fans.

Occupants did not feel overly warm even when the indoor temperature was between 26 – 28 ˚C. In addition to suggesting that air conditioning may not be required in a relatively mild climate, our results also call for moving away from the narrow temperature based PMV-PPD approach of modeling comfort for NV buildings. Interestingly, the statistically significant predictor variables of thermal sensation and acceptability were different: indoor and outdoor temperature and clothing for thermal sensation; air movement and noise acceptability and perceived air quality for thermal acceptability. This suggests that acceptability is influenced by variables that aren't directly related to sensation. Moreover, whether or not the indoor temperature is acceptable might be determined by the difference between indoor and outdoor temperature and not the absolute value of either one of them.

CONCLUSIONS

This naturally ventilated office building in Alameda is providing excellent thermal comfort: the occupants voted that the conditions were acceptable 98% of the time year round. These acceptable votes encompassed a wide range of indoor temperature: 16 ˚C – 30 ˚C. The occupants of this building had two main ways of adjusting their indoor environment: windows and ceiling fans. Windows were used the most commonly: they were opened more times and left open for longer periods of time than fans. In the summer, people start opening windows at higher indoor and outdoor temperatures than they turn on fans, and the windows are usually open when the fans are on.

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