Use of adaptive control and its effects on human comfort in a naturally ventilated office in Alameda, California[1]

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Abstract
Naturally ventilated buildings have been found to be comfortable over a wider range of indoor temperatures than in air-conditioned buildings, while using less energy. The mechanisms underlying this are not well understood. Through a longitudinal field study of a naturally ventilated office in Alameda, CA, we obtained insights into how occupants exercise various adaptive control opportunities to meet their comfort needs in the absence of a mechanical HVAC system. Continuous measurements were made of adaptive behaviors such as window state, ceiling fan usage, heater usage, and indoor and outdoor climate (dry-bulb air temperature, relative humidity, CO2, outdoor temperature). Over 1400 thermal comfort survey responses were collected, which showed that the building provided acceptable thermal conditions for 98% of the survey period, covering an indoor temperature range of 16–28°C. Occupants wore clothing between 0.5 and 0.6 clo in summer, and 0.7–0.8 in winter. Occupants opened windows when the outdoor temperature was above 15°C, with window opening often occurring at the occupant's arrival and proportional to outdoor temperature. Fan use was best explained by indoor temperature, typically being turned on during summer at indoor temperatures above 25°C. Heaters were turned on in winter more than an hour after arrival and commencement of sedentary activity. With these adaptive control behaviors, occupants were thermally neutral and satisfied from 18 to 27°C. Their satisfaction exceeded that predicted by ASHRAE Standard 55 or PMV-based ISO standards. Overall, our findings provide empirical support for adopting adaptive comfort model in office buildings.

Keywords: Adaptive actions, Thermal comfort, Natural ventilation, Air movement

1. Introduction

Commercial buildings housing desk-based office work are often sealed and air-conditioned even if they are located in mild climates such as coastal California. Overall, almost 90% of the office area in the US is air-conditioned. This imparts a huge financial and energy consequence: 14% of

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the electricity in office buildings is used for cooling [1]. Natural ventilation with operable windows helps reduce non-essential conditioning of indoor air. Buildings with passive design strategies such as natural ventilation have been found to use 25−75% less energy than air-conditioned buildings [2].
In naturally ventilated (NV) buildings with operable windows, equally acceptable thermal comfort has been found to occur over a wider range of indoor temperatures than in air-conditioned buildings [3]. This wider range of acceptable indoor temperature allows the building to be conditioned less intensely and less often, with major reductions to its energy use. In parallel with such comfort and energy benefits, it has been found that sick building syndrome (SBS) symptoms are substantially reduced in office buildings with natural ventilation compared to buildings with air conditioning [4].

The ASHRAE database [5] compiles data from previous thermal comfort studies that used "right now" surveys matched with simultaneous physical measurements of the environment at the occupant's workspace. Both AC and NV buildings are included. The measured air speed in NV buildings was found to be two to three times higher than in AC buildings, but is still a fairly low value, averaging 0.3 m/s. This airspeed over the occupant's skin and clothing produces the equivalent of 2°C cooling. The air movement seen in the studies was primarily due to flow through windows, and was probably less than optimal in warm conditions. The database shows that in both NV buildings and AC buildings, when occupants feel neutral or warm, the great majority are split between preferring more air movement or no change, and very few want less [6].

Fans are one way to satisfy the desire for increased air movement. They can act as backup to the less predictable wind-driven flows through windows in NV buildings. In climates with large daily temperature swings, they provide fast-acting comfort when indoor air temperature is warm, and allow the windows to be closed during the hotter times of day while maintaining air movement for convective cooling. Fans can cool the occupants from above (ceiling fans [7]) or from the side (stand and desktop fans [8], and via local air jets from personal systems [9]). Laboratory studies of comfort under ceiling fans and desk fans have shown that people can be comfortable at temperatures as high as 30°C at airspeed levels below 1 m/s [10], [11]. Studies of head-level air flow show similar levels of comfortable air movement and temperature [12].

The combination of NV and fans is very energy-efficient. A modern ceiling fan provides 1.2 m/s air movement at occupant level using only 8 W [10], and a personal fan at desk or head level provides 1.5 m/s on the upper part of the body with only 3 W [11]. The equivalent cooling for these is over 3°C. Per occupant, HVAC requires two orders of magnitude more power for this level of cooling. Buildings cooled by NV together with fans are feasible in many climates, limited primarily by whether the system provides an acceptable level of comfort. The acceptable climatic range can be expanded with 'mixed-mode' designs that stage AC to come on after windows or fans at high temperatures, or that employ AC locally in warmer parts of the building.

Responding to such considerations, ASHRAE Standard 55 was modified in 2009 to expand the allowable airspeed range in neutral to warm conditions [12], [13]. The changes enabled new opportunities to use air movement in buildings to improve both energy and comfort performance; these opportunities have been widely embraced in recent design practice [14].

In addition to enhancing air movement with fans in NV buildings, occupants have control over windows and may also have control over doors, blinds, and personal heaters. Ability to access these controls is one reason why occupants accept a wider range of indoor temperatures. Although the details of the methods and results vary, studies investigating window and fan behavior have consistently found that windows are used more frequently at lower temperatures than fans, and that there is a strong correlation between their usage and indoor and outdoor temperature [15], [16], [17], [18]. Raja et al. [15] found that the temperature threshold for opening windows was 20°C indoors, with a steep rise in the frequency of opening at 27°C. This is similar to the use of fans, which started being used at 20°C indoor and 15°C outdoor. Employing a different metric, Haldi and Robinson [17] found that there was a 50% probability of a window being open at 26°C indoors and 23°C outdoors compared to 28°C indoors and 26°C outdoors for fans. Liu et al. [18] found that the sequence of window and fan usage was part of a pattern of using no-energy controls (windows, doors, curtains) before using low-energy alternatives (fans, air conditioners (for heating)). In addition to temperature, the subjective measures air movement preference and thermal sensation are seen to influence window opening behavior [15], [16].

Adaptive control has also been analyzed by researchers mainly with an aim of identifying the effect of personal control on occupant perceptions. Comparing the thermal sensation of occupants who had and had not taken adaptive actions (windows, cold drinks, and fans), Haldi and Robinson [19] found that those who had taken action had lower thermal sensations at high temperatures than those who had not. The perception of control influences an occupant's thermal comfort and overall satisfaction with the workplace [20].

Occupants also change their clothing level to maintain comfort. By analyzing the ASHRAE RP-884 and RP-921 database, Schiavon and Lee [21] found that the median clo values were similar in AC and NV buildings in California. During summer, it was 0.58 in AC buildings and 0.55 in NV buildings. During winter, the median clo value was 0.66 in AC and 0.69 in NV buildings. Clothing was related highest with outdoor temperature [18]. Carli and Olesen evaluated data from AC and NV buildings from 30 cities worldwide and found good correlations ($R2 = 0.72$) between clo value and outdoor temperature in NV buildings, and poor correlation for AC buildings ($R2 = 0.07$) [22].

In the current study we consider multiple ways with which occupants control their indoor environment: clothing, ceiling fan and window adjustment behavior and their interactions, particularly windows and fans. The adaptive theory predicts that occupants will accept a wider range of temperature when given the opportunity to dress freely and have access to adaptive opportunities in their surroundings. We use occupants' thermal comfort responses and physical parameters to evaluate whether the predictions of the adaptive theory are supported.

Specifically, the aims of this study are to:
1) Understand adaptive actions, such as clothing choice and occupants' interaction with windows and fans, in relation to the physical environment;
2) Understand how adaptive opportunities and actions affect comfort;
3) Understand how occupants' perceptions about air quality, temperature, and air movement relate to measured environmental conditions;
4) Examine comfort ranges in naturally ventilated buildings when adaptive options are available and compare them with the adaptive comfort standard ASHRAE 55.

2. Methods

Like most field studies, this study used "right now" surveys while simultaneously monitoring the physical environmental conditions of the space. The study is unusual in that it observed the same occupants in the same building for a full year, allowing us to capture the seasonal variation of environmental parameters as well as individual occupant behavior and comfort responses. The field test and survey procedures were reviewed and approved by UC Berkeley's Committee for the Protection of Human Subjects (CPHS). Subjects consented to the study, knowing their participation was voluntary and their identities and individual responses would be confidential.

2.1 Location and climate

The case study building is in Alameda, CA at 37° N and 122° W. It has relatively cool winters and mild summers. The average temperature for the year in Alameda is 15.7°C. The warmest month on average is September, with an average temperature of 19.2°C. The coolest month on average is January, with an average temperature of 11.3°C [23].

2.2 Occupancy and building

The building is the office of an architectural/engineering firm with primarily desk-based work. The 14 occupants are a mixture of architects and engineers doing both computer design work and manual assembly of electronic and mechanical controls. They are each knowledgeable about sustainable building principles. They therefore represent an appropriately aware occupancy for inhabiting a building whose operation requires occupant involvement. They may not be a typical occupancy at this time, but if NV buildings were to become common, one might expect NV occupancies to attain similar levels of awareness and expertise as this one.

There are high internal loads from the 14 occupants, desktop computers, printers, copiers, and a server. The building is oriented northeast - southwest on its long axis, divided into two rooms. Eight occupants work in the front room with windows on three sides, and six in the back room with windows on opposite sides. Large openings connect the two rooms. The southwest wall has no openings; a mirrored office lies beyond. The construction material is well-insulated lightweight wood frame, and the exposed facades are about 15% glazed with double-pane glass.

There is no central cooling or heating, and the building is cooled only by natural ventilation in summer and heated mainly by solar and internal heat gain during the winter. There are five windows in the front room and four windows in the back room. All windows have automated sunshades. Each window has two single-hung parts that could be open/close vertically. There are six ceiling fans in the front room, but no ceiling fans in the back room due to the lower ceiling heights. Of the six ceiling fans, four of them are directly above the occupied zone, cooling all the 8 occupants in the front room, and were therefore monitored. Two ceiling fans were located in the corridor, were rarely used, and were therefore not monitored. Five occupants had personal electric heaters which were also monitored.

2.3 Data collection

Outdoor/indoor temperature, humidity, CO2 concentration, outdoor air velocity were continuously monitored every 5 min from Oct 2011 to Oct 2012. The positions for monitoring equipment are shown in Fig. 1c. Outdoor temperature, humidity (Onset U-12 hobo data loggers, temperature accuracy ±0.35°C, RH ± 2.5%), and CO2 (Onset Telaire 7001 CO2 sensor, accuracy ±50 ppm) were monitored in a well-ventilated box outside of the building. The same Hobo data loggers were distributed at every workstation, recording temperature and relative humidity at 5 min intervals at the workstation of each occupant. CO2 levels were recorded in both the front and back rooms also with Telaire 7001 CO2 sensors.

Four time-lapse fish-eye cameras (Fig. 1c) modified from A570 Canon power shot cameras, took pictures of the window open/close actions and status. The two cameras in the front room were mounted on a ceiling joist, and the two in the back room were mounted on a bookshelf, such that all window positions were captured. The camera's software was scripted to take pictures every 5 min [24].

The settings of the ceiling fans and five personal heaters were monitored by voltage recorder.

Fig. 1. (a) Building exterior and the weather station, (b) Building interior (notice the ceiling fans), and (c) Floor plan with monitoring equipment positioning.

2.4 Occupancy survey

Occupants were surveyed throughout the year for their “right now” opinions about the indoor environment, using a web-based survey tool shown in the Appendix. The web survey link was sent to the occupants three times a day (10:00 a.m., 1:00 p.m. and 3:30 p.m.) for 2 weeks each month except for February, April, or August in 2012. They were asked to rate 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.

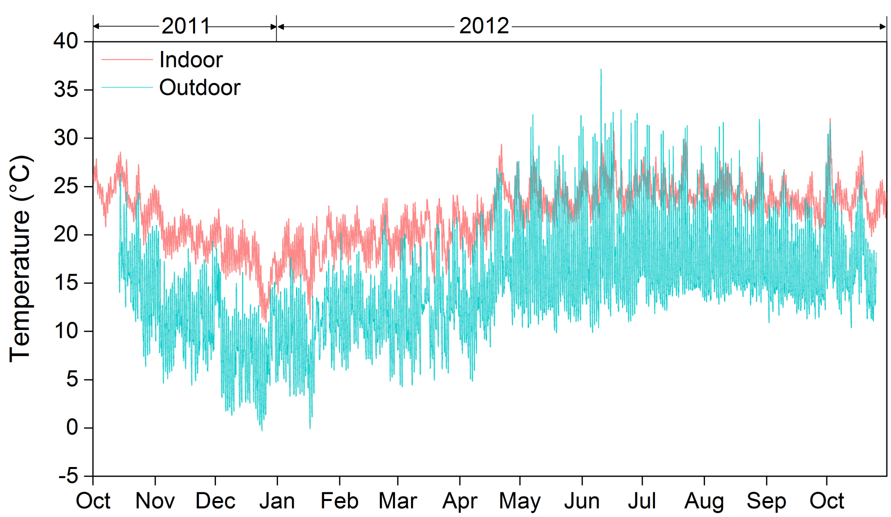
2.5 Data processing

The final database required careful quality assurance because it was based on matching and merging time-sequence data from five different sources (repetitive survey, indoor physical measurements, outdoor weather data, window open/close data from cameras, and fan and heater use data from voltage meters). Over the test year, some data were lost for various reasons. In the case of temperature and humidity, where multiple sensors were monitoring these parameters throughout the space, holes in the data from a missing sensor location were filled by data from a nearby datalogger. For window status, the periods without data were excluded from analysis. There were no missing data for fans.

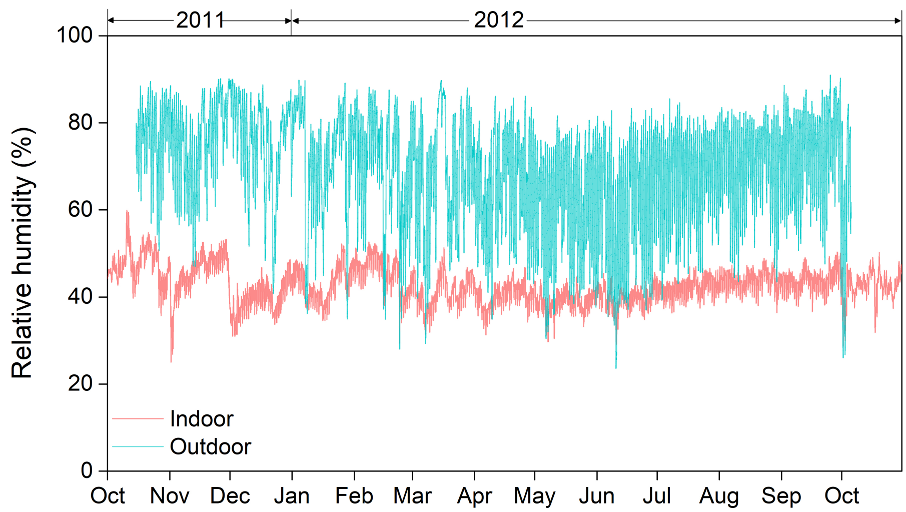
3. Results and discussion

3.1 Physical measurement

Fig. 2 shows the outdoor and indoor temperature during the test. The indoor temperature is the mean of the front and back rooms, and is seen to be warmer than the outdoors for most of the year. We divided the year into three seasons - summer (June–October), winter (December–February), and swing (November, March–May) based on the measured outdoor temperature. Outdoor temperature ranged from 15°C to 26°C during summer, 5°C to 18°C during winter and 10°C to 25°C during swing seasons. Indoor temperatures were comparatively warm in the range of 22–28°C in summer, 16–25°C in winter and 19–28°C during the swing. The outdoors began getting warmer from March, and relative warmer summer occurred in June–July, when indoor air temperatures were around 25–28°C. Relative humidity was relatively stable (40–50%) throughout the year (Fig. 2b), less than the variation in outdoor humidity (20–80%).



(a) Indoor and outdoor temperature



(b) Indoor and outdoor relative humidity

Fig. 2. Indoor and outdoor temperatures (a) and relative humidity (b) during the test period

Fig. 3 shows the indoor and outdoor CO2 concentration during the test period. The mean outdoor concentration is relatively constant at around 400 ppm, whereas the indoor concentration fluctuates at both weekly and monthly time scales. In particular, there are high indoor concentrations up to 600 and 700 ppm from November to March when the windows mostly remain closed. During the rest of the year, the CO2 concentration in both rooms has much less variation and is closer to outdoor levels. Although the concentrations in the front and back rooms are more similar to each other than to the outside, the back room generally has about 100 ppm more CO2 than the front room throughout the year. Perhaps the difference comes from the front door and the bathroom exhaust fan in the front room that caused outdoor air infiltration even in winter.

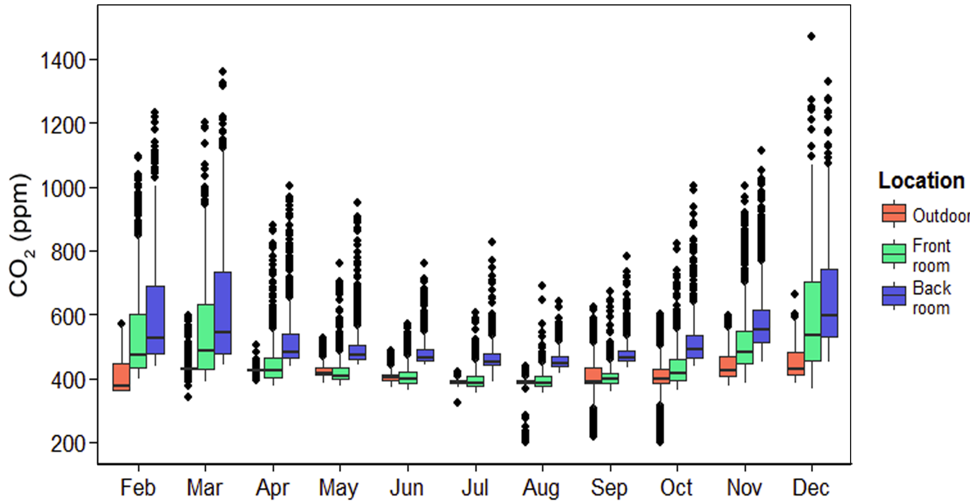


Fig. 3. Monthly CO_2 concentration

3.2 Occupancy adaptive behaviors

Occupancy state

Fig. 4 shows the occupancy percentage throughout the year, obtained by using the camera data to count the occupants present during each day. There was no seasonal difference in daily occupancy rate. The occupancy rate is clearly defined by the routine working schedule, namely, 9 a.m.–5 p.m. However, there were individuals who came earlier, around 6 am, and left later than 8 pm.

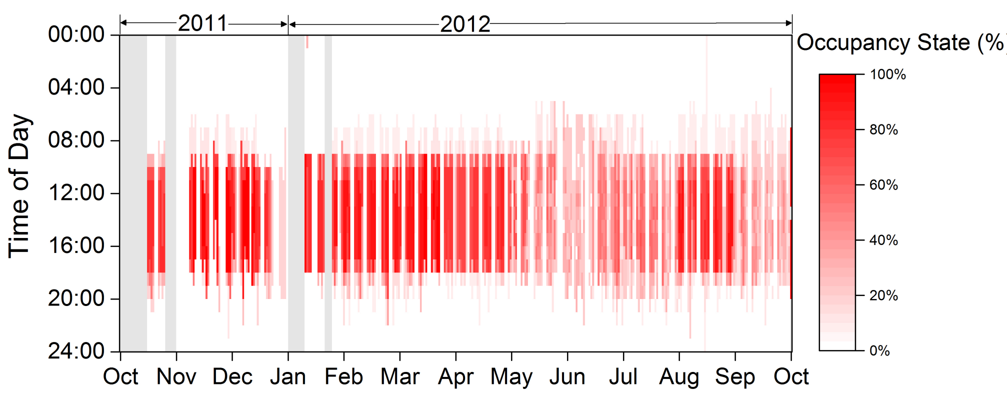
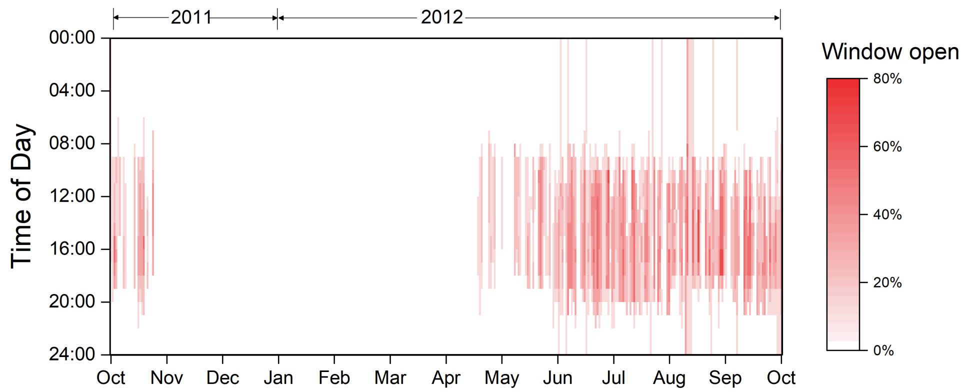


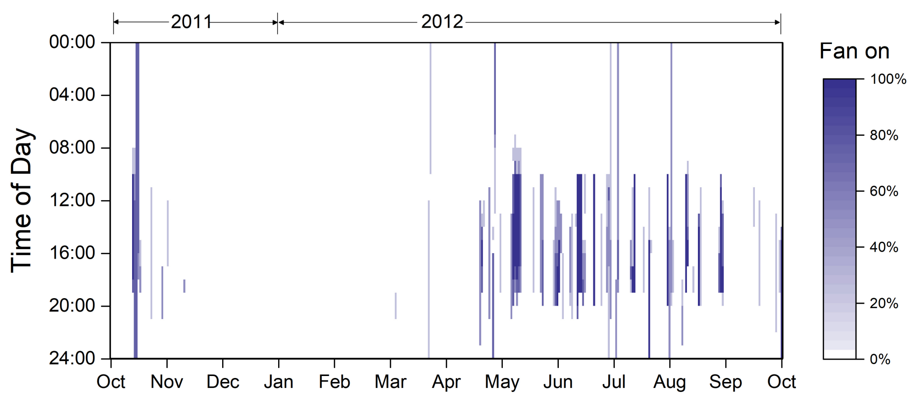
Fig. 4. Yearly occupancy rate (shade in grey means missing data)

Windows and fans

The patterns of using the windows and ceiling fans in the office show a strong temporal dependence on both monthly and daily timescales (Fig. 5). Compared to windows (Fig. 5a), fans are used much less frequently (Fig. 5b), almost entirely during April through October. Both windows and fans are most often opened or turned on in the morning between 9 and 10 a.m. and closed or turned off in the evening between 6and 8 p.m. This illustrates that occupant arrival and departure influences window and fan adjustment (Fig. 4). Although all of the fans are used a similar amount, about half the time only one fan is on at a time.



(a) Percentage window open (shade in grey means missing data)



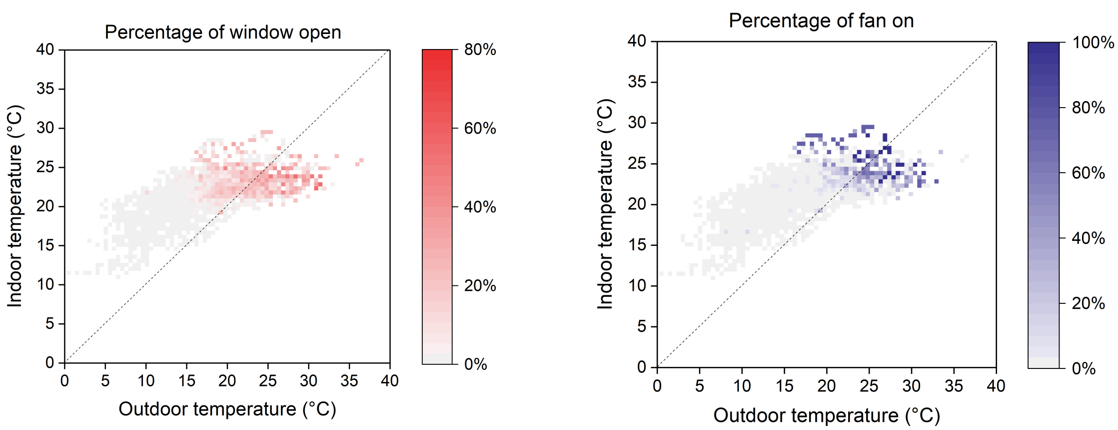
(b) Percentage of fans in use

Fig. 5. Window and fan usage frequency by month

Also shown in Fig. 5 is that windows and fans were occasionally left open over night during warm seasons. Therefore, for the following analysis on windows and fan use behaviors, only data with occupancy time were used.

Fig. 6a shows the average number of windows open for various combinations of indoor and outdoor temperature. The equal temperature contour is overlaid on the data for reference. Only work hours are shown. Graphically, the percentage of windows open appears to be related to both indoor and outdoor temperature. While the number of fans on appears to be more related to the indoor than outdoor temperature (Fig. 6b). It was expected that fans would be on almost all the time when the outdoor temperature is warmer than indoors because air movement is then the best way of achieving thermal comfort.

Occupants started opening the windows frequently at an indoor temperature of 21–22°C and a concurrent outdoor temperature of 15°C. While people turned on fans at indoor temperatures above 24–25°C and outdoor temperatures above 20°C. When the fans are on, the windows were also very likely to be open. Of the 18% of work hours when the fans were on, the windows were also open 47% of the time.

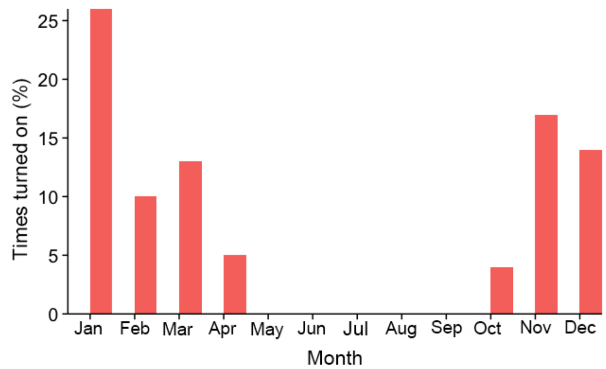


a. Windows b. Fans

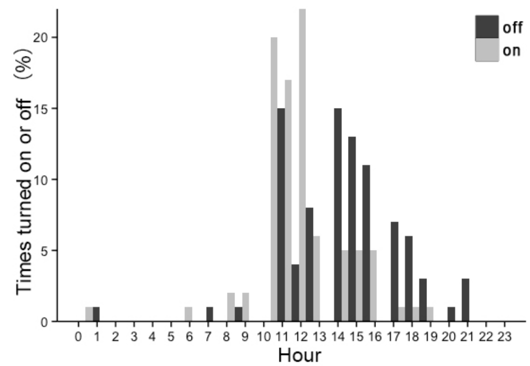
Fig. 6. Window opening and fan on vs. indoor and running mean outdoor temperatures

Heaters

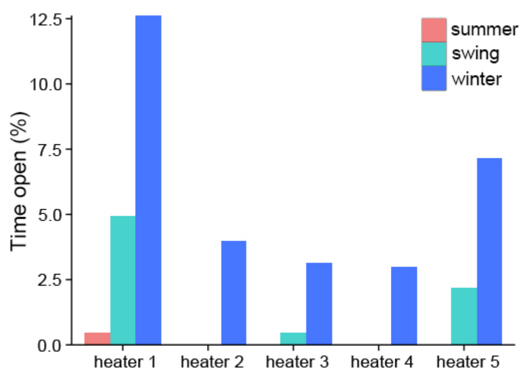
The settings of the five personal heaters were monitored via a voltage recorder. The portable heaters are turned on very infrequently—only 89 times for a total of 210 h in all of 2012. They were used from October to April (Fig. 7a). Surprisingly they are not usually turned on until the period 10:30 to 12 noon (Fig. 7b), rather than around 9am upon arrival, this is probably related to the higher metabolic rate that occupants experience during their commute, and the time required for body heat to dissipate [25]. Like the windows, there are large differences in usage frequency between the different heaters (Fig. 7c). Considering only those times when the state of the heater changed from off to on or vice versa shows that the heaters tended to be turned on at lower temperatures and off at higher ones, although there was overlap (Fig. 7d). The heaters were used only in a narrow range of indoor and outdoor temperatures: less than 25°C indoors and 20°C outdoor running mean. But even in these ranges, the heaters were off the majority of the time (Fig. 7e and 7f).



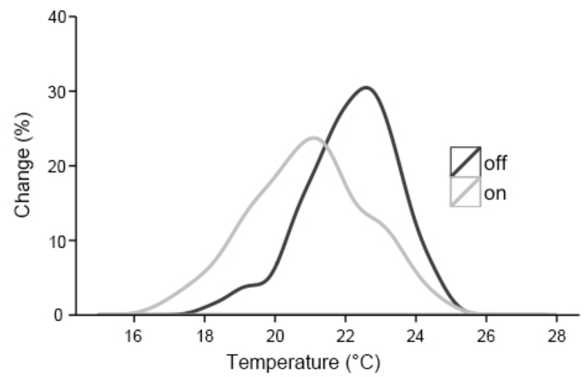
(a) Heater use by month



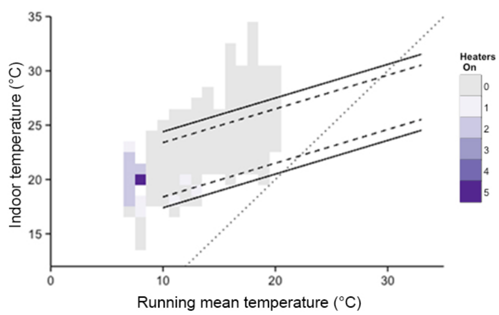
(b) Heater daily adjustment patterns



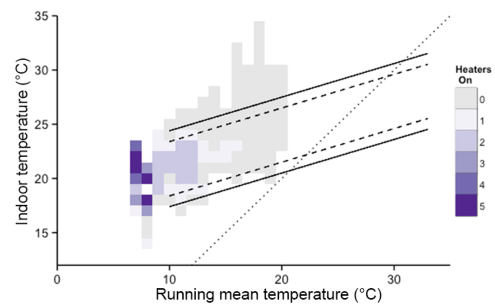
(c) Heater usage frequency



(d) Temperature when adjusted



(e) Average number heaters on



(f) Maximum number heaters on

Fig. 7. Heater usage patterns

Clothing

Occupants changed their clothing levels significantly through the year (Fig. 8, $p < 0.001$-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 [21] and is similar to what has been found in Japan [26]. Even so, the winter range is substantially different than the "typical winter indoor" value of 1.0 clo.

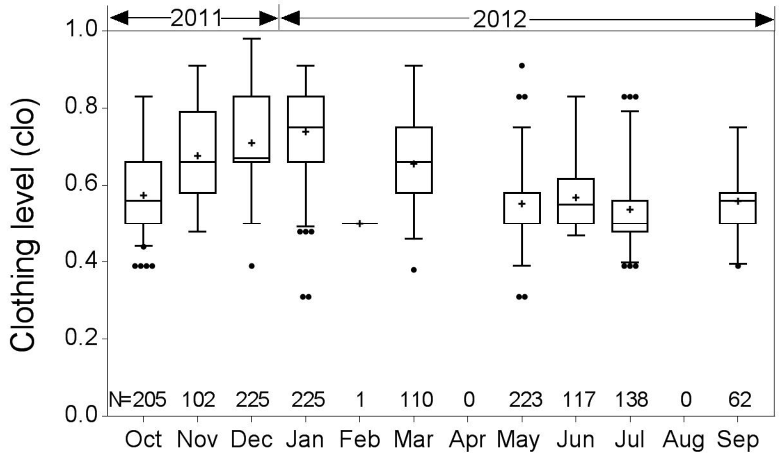


Fig. 8. Monthly clothing levels

Our data show a running mean outdoor temperature with α = 0.66 [27] to be the best temperature metric for explaining clothing variation (R2 = 0.35, $p < 0.001$). Multiple linear regressions (show in Table 1) including both outdoor and indoor temperature found indoor temperature to be an insignificant predictor variable ($p = 0.468$), implying that occupants' wardrobe decisions were made independent of indoor temperature. The occupants of this building clearly took 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 such climatically suitable design more difficult [28].

Table 1 Coefficients of linear regression between clothing and explanatory variables - indoor temperature and running mean temperature

Coefficient	Value	Std Error	p value	R^2
Intercept	0.914	0.027	< 0.001	0.35
T_{indoor}	~0	0.002	0.468	
$T_{running\ mean}$	-0.019	0.001	< 0.001	

Thermal sensation

Fig. 9a shows monthly thermal sensation votes. Majority votes were in the neutral zone between −1 and 1, indicating that occupants could adapt to their thermal environment effectively throughout the year, despite the large yearly variation in outdoor and indoor temperatures (Fig. 2a).

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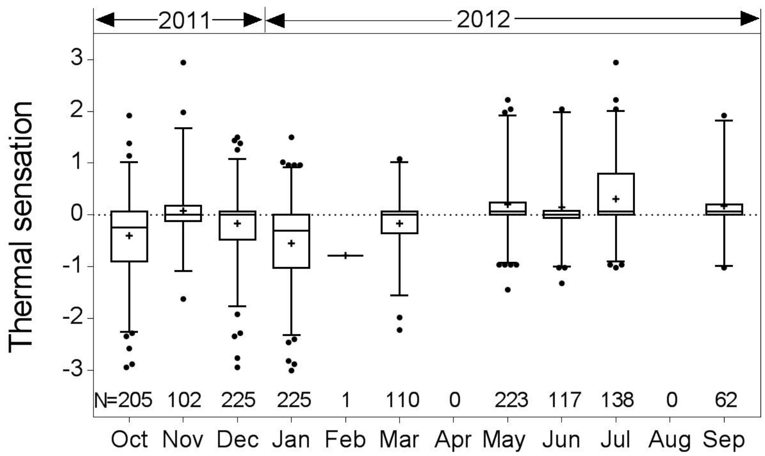
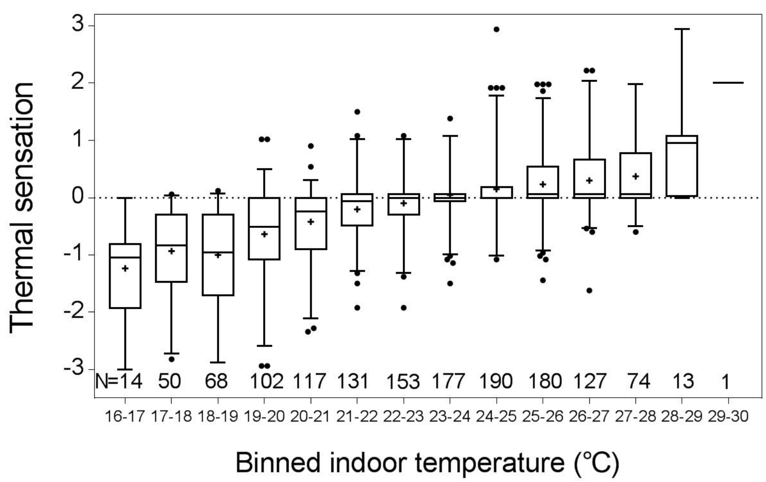
Fig. 9b shows the relationship between thermal sensation and indoor air temperature. From cold to neutral, thermal sensation increases with temperature as expected. However, it is interesting that after about 20°C the curve flattens out. The thermal sensation votes were well within the neutral zone from 20 to 28°C. These results explain the lack of monthly variation in thermal sensation votes. The occupants were no longer sensitive to indoor temperature changes due to their adjustment of clothing insulation, and the use of windows and fans to enhance convective cooling.



a. Monthly thermal sensation votes



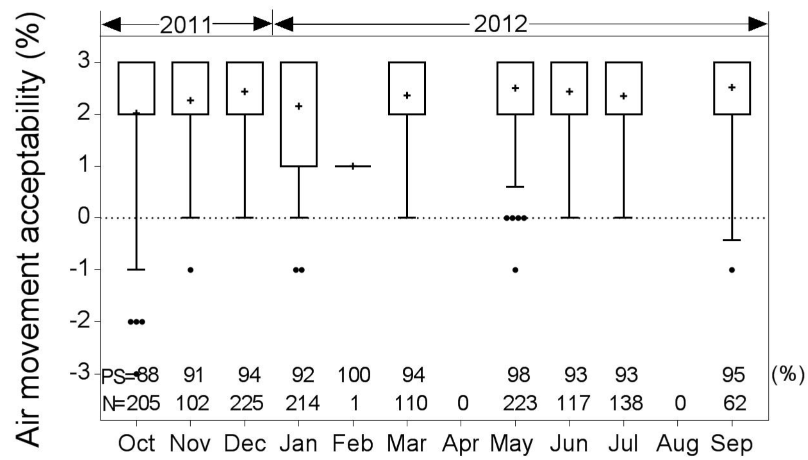
b. Thermal sensation vs. indoor temperature

Fig. 9. Thermal sensation votes: (a) monthly, and (b) thermal sensation against indoor temperature

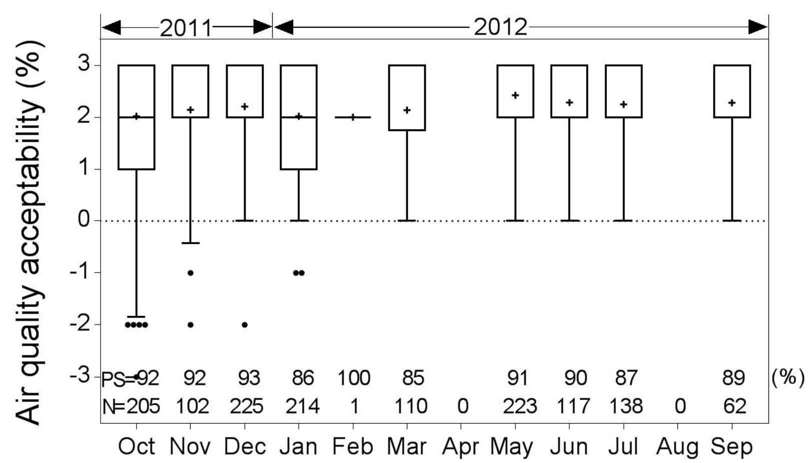
Running separate linear regressions between thermal sensation and indoor temperature for the three seasons and the whole year gives such similar results that the neutral indoor temperature varies by less than 2°C between the seasons (23–24.6°C), while the whole-year neutral temperature was 23.7°C. These differences are 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. Perhaps this is due to the mild climate of Alameda and the variable weather patterns that intersperse hot and cold days during most of the year (Fig. 2).

Air movement and air quality acceptability

For the whole year there were not issues on air movement (Fig. 10a) or air quality (Fig. 10b) acceptability, with monthly satisfaction rate all well above 80%.



a. Air movement acceptability



b. Air quality acceptability

Fig. 10 Monthly air movement and air quality acceptability

Table 2 shows the results of single variable regressions of air quality acceptability with the subjective survey responses (in the blue rows: thermal acceptability, thermal sensation, thermal preference, air movement acceptability, air movement preference) and physical measurements. The most important predictor of perceived air quality is air movement satisfaction—it accounts for nearly half of the variation in air quality acceptability. The next most important parameter is thermal acceptability. It is interesting that both these parameters are subjective assessments rather than physical measurements and that their most closely associated physical measurements (number of windows open, number of fans on, thermal sensation) are not correlated with air quality acceptability.

Some studies in climate chambers have found that air quality is perceived to be worse at higher temperatures [29], but this result is not seen in the current study or another study carried out by this group [30]. Other previous studies have shown that increased air movement increases perceived air quality [31]. Because occupants can open windows or turn on fans to increase air movement when they feel hot or are dissatisfied with the air quality, it is possible that changes in air movement explain the lack of temperature dependence.

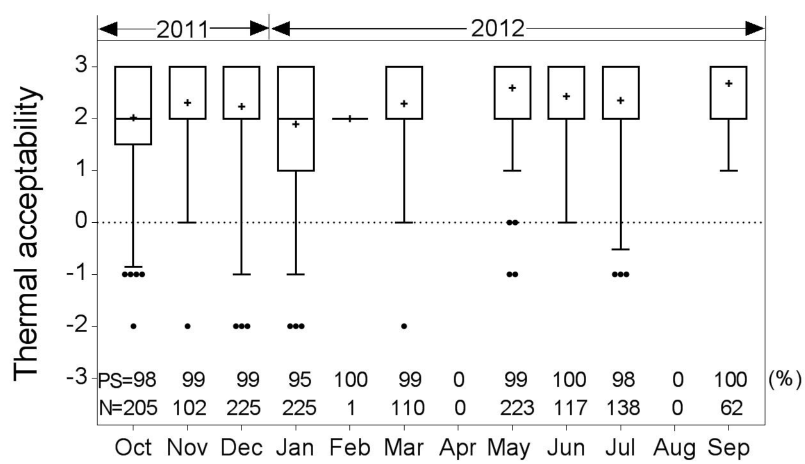
Table 2 Linear regressions with air quality acceptability

	slope	intercept	R^2
Air movement acceptability	0.72	0.51	0.46
Thermal acceptability	0.45	1.16	0.18
Relative humidity	-0.07	5.00	0.07
CO2 concentration	0.00	3.44	0.07
Air movement preference	-0.54	2.25	0.04
Number of fans on*	0.06	2.64	0.02
Indoor temperature	0.03	1.49	0.01
Outdoor temperature	0.01	2.01	0.00
Number of windows open†	0.03	2.15	0.00
Temperature preference	0.10	2.17	0.00
Thermal sensation	0.04	2.18	0.00

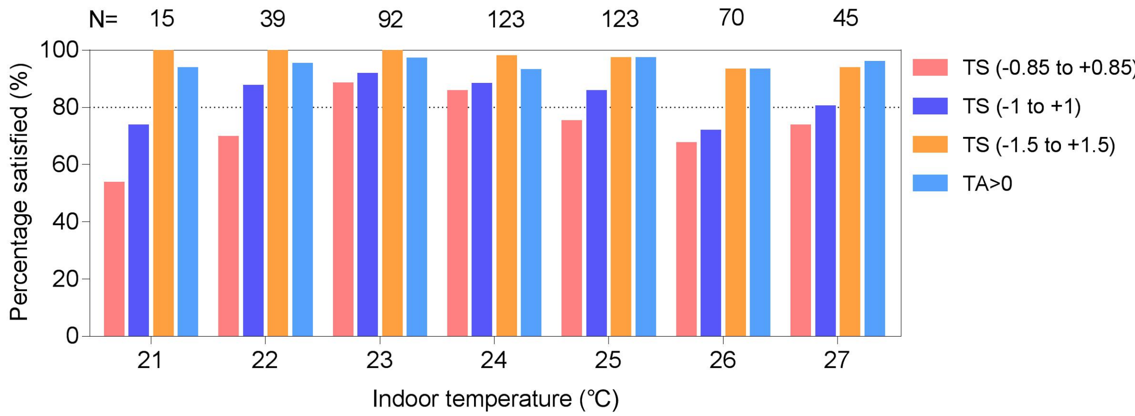
*Only front room results because there are no ceiling fans in the back room.
†Number of windows open in the same room as the occupant whose vote is being considered.

Acceptable temperature range
Defining the comfort zone remains a current issue in standards committees such as ASHRAE SSPC 55 [13]. There is great intra- and interpersonal variability in occupants' neutral temperatures and in the ranges of temperature above and below these neutrals that occupants find acceptable. The ASHRAE Standard 55 comfort zone is based on prediction of a population's mean thermal sensation or predicted mean vote (PMV) and the predicted percent dissatisfied (PPD) associated with PMV deviations from neutral. The Standard recommends a PMV range of ±0.5. This corresponds to 10% dissatisfied (90% satisfied) by the PPD curve, but hypothesized local thermal discomfort effects reduce the satisfaction to 80%, which is close to the best satisfaction value found in comfort field studies. The adaptive comfort zone for NV buildings is also set to provide 80% satisfied, but it encompasses a wider range of temperatures. The adaptive zone is based on field study data, and dispenses with both the PMV model and with the local thermal discomfort hypothesis [3].

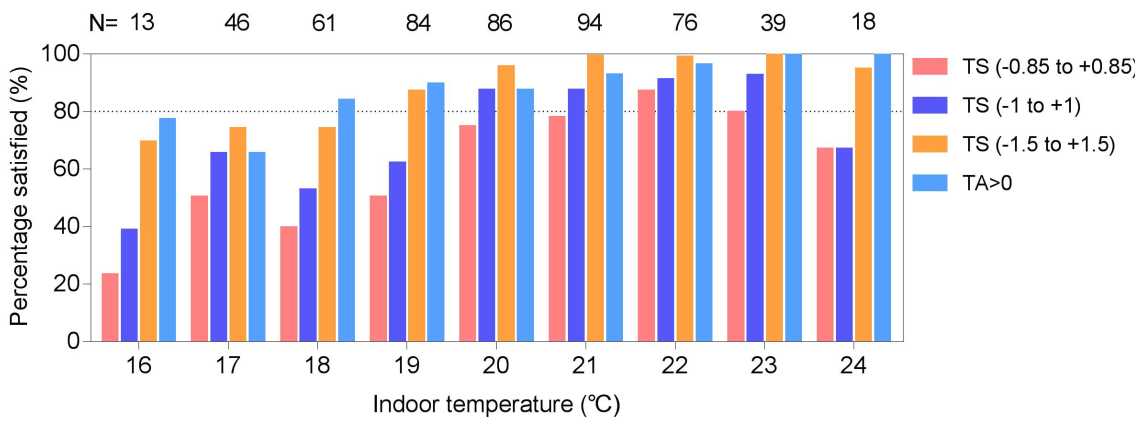
Field surveys have increasingly added a question about *thermal acceptability* to supplement the thermal sensation question. The thermal acceptability metric can be used directly to determine the range of thermal sensation values that provides the most relevant aspect of 'satisfaction' for building occupants. Fig. 11a shows that thermal acceptability votes remain constant over the year, with the great majority of the votes are 95% to 100% satisfied in the range 27 to 21°C, and above 80% satisfied from 20 to 18°C. The percentage of people satisfied in a particular indoor temperature bin, as defined by three thermal sensation ranges: ±0.85, ±1, and ±1.5 are compared in Fig. 11b and c, for the summer and winter seasons. With the threshold defined as the temperature at which 80% occupants are satisfied, the ±1.5 range matches most closely with the thermal acceptability ratings. Note that each of these thermal sensation vote ranges is significantly wider than the PMV ranges defined for 'recommended criteria categories I, II, or III' in standards ISO 17772 [32] and EN 16798 [33] (in which PMV ranges are ±0.2, ±0.5, ±0.7). The ISO categories fit these measured results very poorly. Given that occupant acceptability for all the temperatures in the figure approaches or exceeds 80%, the narrow 'category I' classification is particularly inapplicable [34], [35].



a. Thermal acceptability votes for each month



b. Summer (June-October). TS-Thermal sensation votes, TA-Thermal acceptability votes. Only bins with at least 5 votes are shown.



c. Winter (December-February). TS-Thermal sensation votes, TA-Thermal acceptability votes. Only bins with at least 5 votes are shown.

Fig. 11. Thermal acceptability

This study's results can be compared with the thresholds for the ASHRAE 884 database [36]. The summer threshold (temperature at which 80% occupants vote "acceptable") for the Alameda building is 21–27°C while for the ASHRAE database (for NV buildings) is 22–30°C. The winter threshold range for the Alameda building is 18–24°C while it is 19–27°C for the ASHRAE database. The lower threshold ranges from the current study are due to the mild climate in Alameda, because the indoor temperature rarely gets warmer than 28°C.

Comparison with the adaptive model

Fig. 12 shows the thermal sensation votes plotted on an indoor temperature vs. outdoor running mean temperature graph. The parallel lines represent the 90% (dotted) and 80% (solid) acceptable ranges defined by the adaptive model in ASHRAE 55. In the section above, we have demonstrated that thermal sensation votes between −1.5 and +1.5 (slightly cool to slightly warm) are considered satisfied. The distribution of green points shows that a majority of occupants do not feel warm/hot or cool/cold even at temperatures lying outside the comfort zone defined by the adaptive standard. Hot and cold discomfort votes are distributed sparsely at the extreme end of the outdoor running mean temperature scale. Also many votes were cast at running mean outdoor temperatures of less than 10°C, which is not covered by the adaptive standard. Overall, our results show that the adaptive model is generally effective in predicting thermal comfort in naturally ventilated office buildings, but its comfort zone could be wider for occupants in mild climates like in north California.

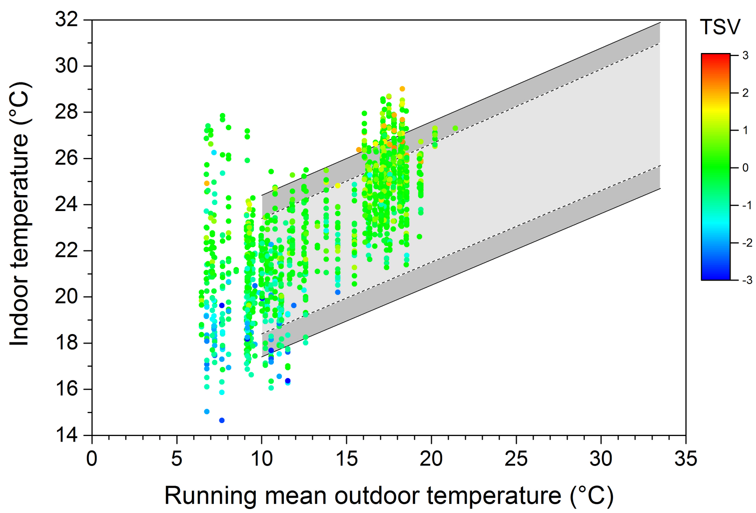


Fig. 12 Comparison with ASHRAE adaptive comfort model

4. Conclusion

In the Alameda building, a knowledge-worker occupancy aware of naturally ventilated design principles uses windows and fans very effectively to achieve thermal comfort throughout the year in a building with no HVAC. Windows are used most often: they are open 67% of the time during summer work hours. Fans are only used 21% of summer work hours, and for 75% of this time, the windows are also open. Windows also start being opened at lower indoor air temperatures than fans: around 21–22°C compared with 24–25°C.

The window opening/closing patterns are heavily driven by occupancy. In the warm season, people are likely to open their windows when they arrive and close them when they leave at the end of the day. Because of this, it makes sense that window opening is more closely related to outdoor temperature than indoor. Fans, on the other hand, are not routinely turned on when occupants arrive, and their use is more closely related to indoor temperature.

The occupants of this building are comfortable over a broad range of temperatures, from 18 to 27°C with neutral temperature at 23.7°C. Although there is variation in satisfaction as defined by thermal sensation inside and outside the ASHRAE 55 80% satisfaction zone, there are still many regions outside the 80% satisfaction zone with high satisfaction.

Comparing acceptability and sensation votes reveals that a sensation range of ±1.5 most closely matches the 80% acceptable limit. Its associated temperature range is wider than the three 'recommended categories' in ISO Standard 17772 and EN 16798 (in which PMV ranges are ±0.2, ±0.5, ±0.7). The measured acceptability results from this study provide evidence that PMV-based classification system, and particularly the narrow 'class I' classification, is inappropriate for the adaptive comfort design and operation in this building.

The detailed study of a single NV building used innovative techniques for examining adaptive comfort. A profitable direction for future work would be to apply these techniques to larger datasets, such as the new ASHRAE thermal comfort field study database [37]. For example, it would be interesting to divide the buildings in the database by climate, creating adaptive models for different climates that could be compared. Another goal would be developing a window-opening model for estimating the opening/closing of a window, allowing improvement to the operation algorithms and schedules in energy simulation software like EnergyPlus. Another interesting direction would be to compare the effectiveness of using fans and windows in pure naturally ventilated buildings (like the one in this study) to their use in conjunction with AC in mixed-mode buildings. Such evidence is needed for the important decision whether the ASHRAE adaptive comfort chart may be applied beyond NV buildings alone, but rather to occupant-controlled NV zones in mixed-mode buildings.

Declaration of Competing Interest

The authors declared that they have NO conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Acknowledgments

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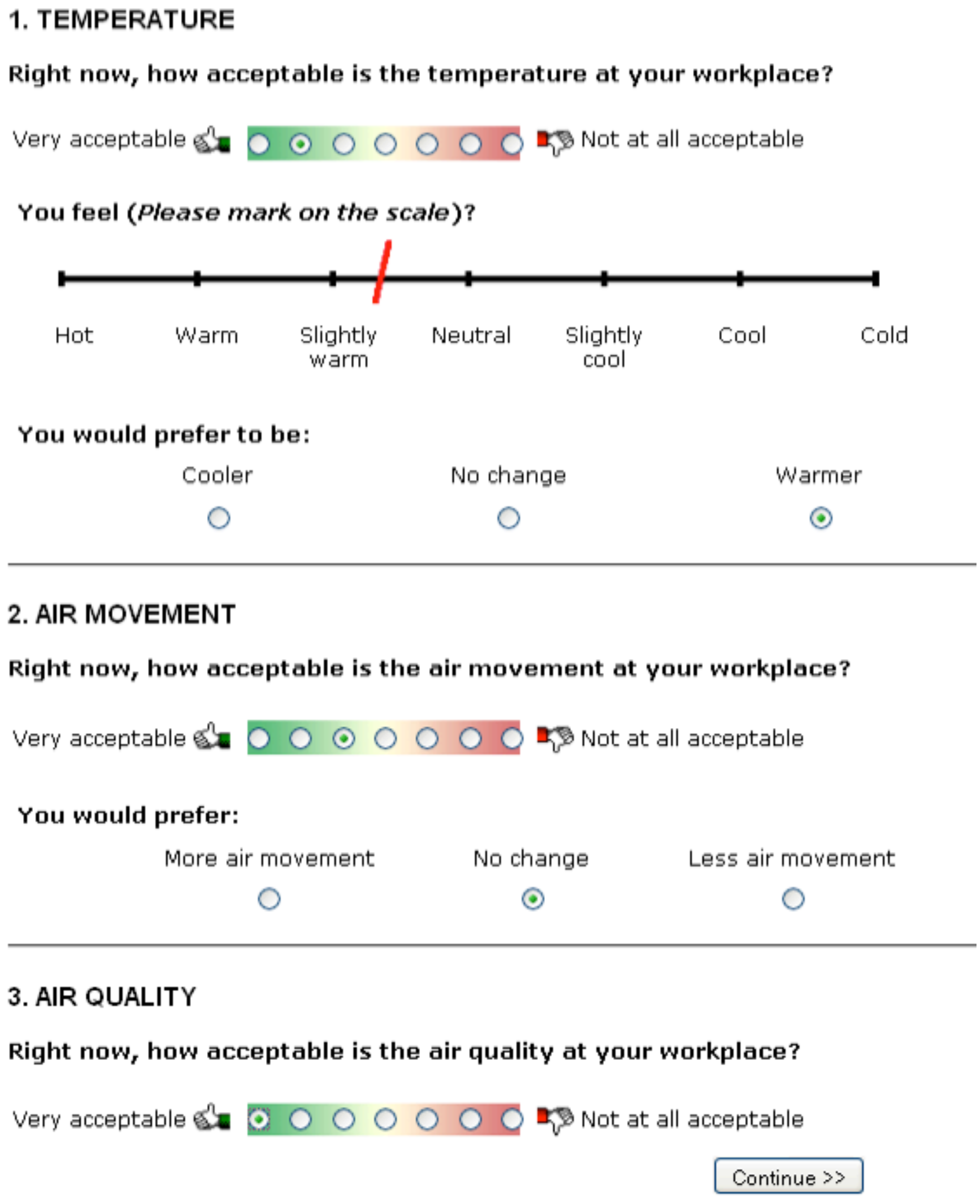
Appendix: Right now Survey


1. TEMPERATURE

Right now, how acceptable is the temperature at your workplace?

Very acceptable … Not at all acceptable

You feel (*Please mark on the scale*)?

Hot
Warm
Slightly warm
Neutral
Slightly cool
Cool
Cold

You would prefer to be:

Cooler
No change
Warmer

2. AIR MOVEMENT

Right now, how acceptable is the air movement at your workplace?

Very acceptable … Not at all acceptable

You would prefer:

More air movement
No change
Less air movement

3. AIR QUALITY

Right now, how acceptable is the air quality at your workplace?

Very acceptable … Not at all acceptable

Continue >>

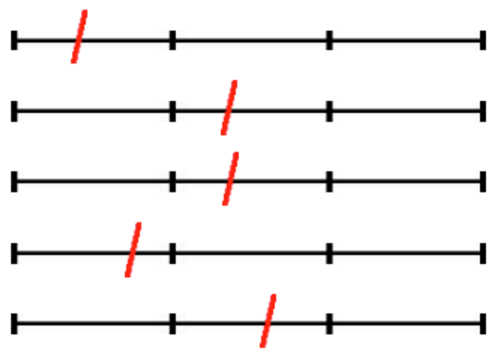
4. NOISE LEVEL

Right now, how acceptable is the noise level at your workplace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

Please rate the noise from.....

	Not disturbing	Slightly disturbing	Moderately disturbing	Very disturbing
...people's conversations, phones, etc.				
...ceiling or desk fans				
...office equipment				
...outside				
...other				



Please specify

If you have additional comments, click here

5. CLOTHING

Please mark in the list below all the garments you are wearing now.

☐ Short-sleeved shirt or blouse

☐ Sweater or jacket

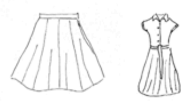
☐ Long-sleeved shirt or blouse

☐ Tie

☐ Shorts

☐ Trousers, pants

☐ Skirt or dress



☐ Sandals or open-toed shoes

☐ Shoes, sneakers, or boots

Continue >>