Title
The Impact of Cooling Strategy and Personal Control on Thermal Comfort

Author
Pigman, Margaret

Publication Date
2014-05-01

The Impact of Cooling Strategy and Personal Control on Thermal Comfort

By

Margaret Celeste Pigman

A thesis submitted in partial satisfaction of the

requirements for the degree of

Master of Science

in

Architecture

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Gail S. Brager, Chair
Professor Edward Arens
Professor Joan Walker

Spring 2014

Table of contents

List of figures

List of tables

Acknowledgements

I would like to thank Hui Zhang and Ed Arens for their insightful questions, curiosity, and passion for thermal comfort; Gail Brager for her mentorship, encouragement, and perceptive comments; Joan Walker and Stephanie Kolvachik for their statistical guidance; and Anoop Honnekeri, research partner extraordinaire, for his optimism and for being the first sounding board for my ideas and road blocks.

This project was supported by funding from the California Energy Commission project 500-10-025, Natural ventilation for energy saving in California commercial buildings and ASHRAE URP-1656, Development of ASHRAE database II.

1 Introduction

The most fundamental purpose of buildings is to protect people from the elements and provide a comfortable and productive environment for them to live and work in. Currently many of our office buildings are failing at this simple task: only 11% of buildings provide satisfactory thermal comfort to at least 80% of their occupants, which is the goal of thermal comfort standards (Huizenga et al., 2006).

But while they are not providing comfort, our buildings are using a lot of energy. In 2010, buildings accounted for 41% of primary energy consumption, 78% of electricity consumption, and 40% of carbon dioxide emissions in the US (US Department of Energy, 2011). Space heating and cooling are responsible for 36% of the primary energy use and carbon dioxide emissions from buildings or 14% of the US total.

All in all, a better understanding of thermal comfort can help us make better environments for building occupants and find ways of reducing this substantial contribution to energy use and carbon emissions.

2 Literature review

2.1 Thermal comfort models

2.1.1 Heat balance

The fundamental idea of the heat balance comfort model is that in steady state conditions a person is comfortable when the net heat flow to and from their body is zero. This means that only the parameters that influence production, gain, or loss of heat are included in the model. The six key ones are air temperature, radiant temperature, air speed, relative humidity, clothing insulation (clo), and metabolic rate (met). Using these parameters one can compute the predicted mean thermal sensation vote (PMV) of a group of occupants in a given set of conditions (Fanger, 1970).

Derivation

In deriving the PMV model, Fanger started with a heat balance equation of the human body, quantifying the sources and sinks of heat, including, for example, metabolism, radiation from the skin, and evaporation of sweat. Since someone can keep themselves in heat balance by shivering or excessive sweating, zero net heat flux is not enough by itself to guarantee comfort. So Fanger imposed another condition for comfort, namely that skin temperature and sweat secretion levels must be in comfortable ranges. He determined those ranges in a series of experiments where he monitored subjects' skin temperature and sweat secretion levels at different metabolic rates and asked them if they were comfortable or not. From these two components, he derived a comfort equation that allows one to calculate the comfortable combinations of the environmental parameters for given a clothing level and metabolic rate.

The comfort equation by itself only describes comfortable conditions; it does not predict how people will feel in a particular set of conditions. To do that, Fanger took the data from climate chamber tests in which participants doing standard tasks in standard clothing at standard conditions rated their thermal sensation on a seven-point integer scale from very cold (-3) to very hot (+3). He then related the conditions under which the votes were taken to a thermal load on the body and the votes to that thermal load. From that he derived the PMV equation.

Then he further derived a relation between PMV and predicted percentage of occupants dissatisfied (PPD) using the same chamber data. For each experimental condition, he calculated the percentage of subjects who were dissatisfied, with the assumption that only those with sensation votes of -1, 0, and +1 were satisfied. He used probit analysis to derive a curve from this data and relate PMV directly to PPD (Figure 1). This curve is now included in many comfort standards, including ASHRAE 55 and EN 15251 (ANSI/ASHRAE, 2013; CEN, 2007).

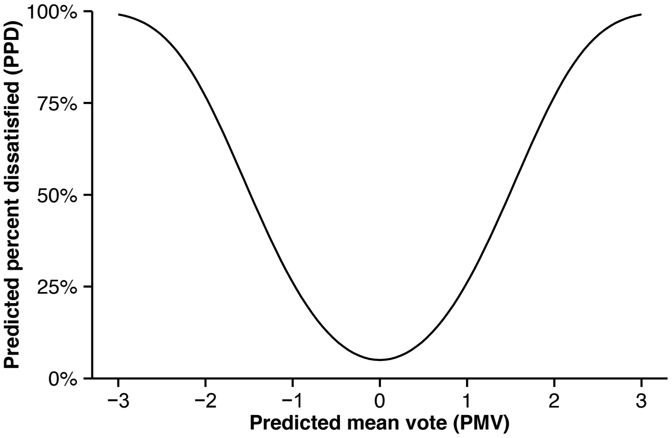


Figure 1 PMV-PPD curve

The PMV model has been very successful in predicting comfort in air conditioned buildings and very influential in standards. Some of its limitations include its high sensitivity to met and clo, which are hard to measure in the field, and the possibility that met is different for the same activities depending on climate (Humphreys and Nicol, 2002). It also tends to overestimate discomfort at warm temperatures in naturally ventilated buildings.

Implementation in standards

The PMV model is at the core of the major international comfort standards, although a few modifications and qualifications have been added to Fanger's original model

(Figure 2). In both ASHRAE 55 and ISO 7730, thermal comfort is described as having general and local contributions, with the PMV model predicting the general contribution (ANSI/ASHRAE, 2013; ISO, 2005). Although the two standards differ in how they treat them, they both consider draft, vertical temperature stratification, and floor temperature as potential sources of local discomfort. In ASHRAE 55, the environmental conditions are supposed to result in a PMV between -0.5 and +0.5 (10% PPD) so that a hypothesized 10% local discomfort will still result in 80% satisfaction.

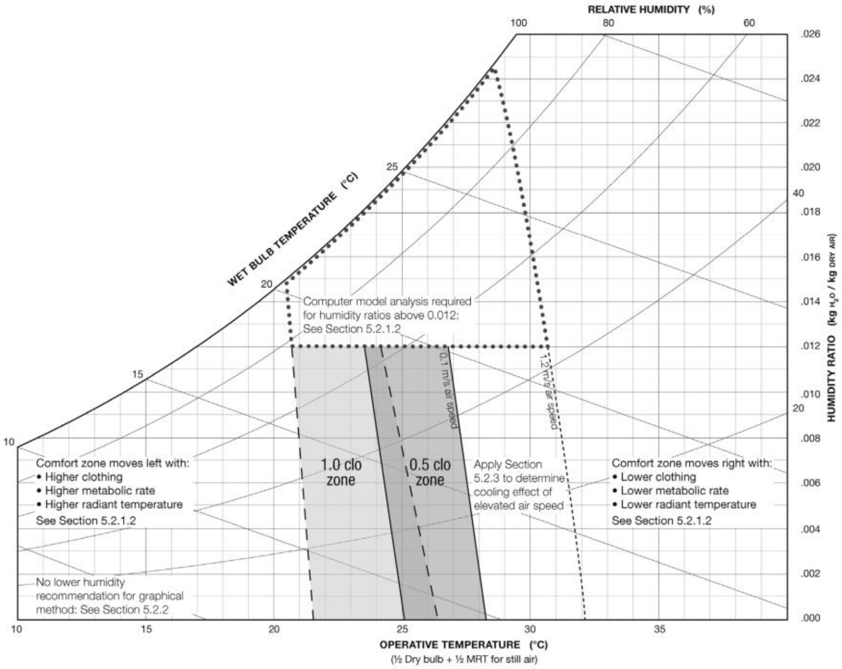
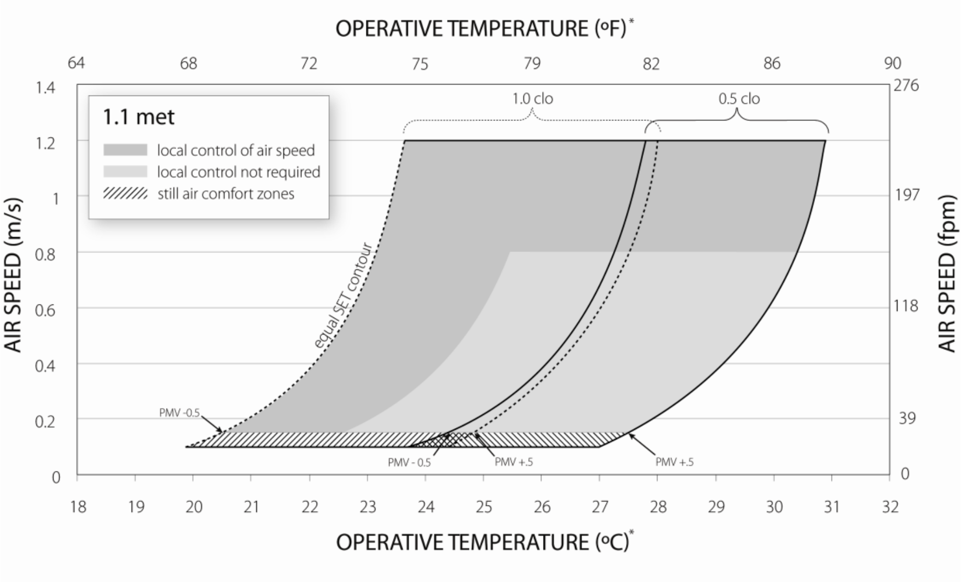


Figure 2 ASHRAE 55 PMV-based comfort standard

The elevated air movement provision in ASHRAE 55 has the opposite effect. Based on field data showing that occupants often prefer to have more air movement than allowed by previous standards even at neutral or slightly cool thermal sensations, ASHRAE 55-2009 increased the air movement limits and allowed higher operative temperatures when air movement is present (Arens et al., 2009).



* In determining operative temperature, use the lowest air temperature in the occupied zone

In this Figure, $t_r = t_a$

Figure 3 Elevated air movement provision in ASHRAE 55

2.1.2 Adaptive

Adaptive theory

Adaptive thermal comfort theory acknowledges that people react to their thermal environment in behavioral, psychological, and physiological ways, so Fanger's six physical parameters cannot be the whole story (Brager and de Dear, 1998).

Physiological adaptation changes the way that individuals respond to the same environment. Someone who is acclimatized to a hot environment may feel cooler at high temperatures than she would when she is acclimatized to a cold one. The physical changes that account for this difference include a decreased metabolic rate, starting to sweat at a lower core temperature, and increased peripheral blood flow (de Dear and Brager, 1998).

Behavioral adaptations allow people to respond quickly to their environment. For example, they can adjust windows and fans, add or remove clothing, drink hot or cold liquids, and move to a different location (Nicol and Humphreys, 1973). The first two are accounted for to some extent in the PMV model through the air movement and clothing insulation parameters, but the fact of individual control allows people to achieve conditions that are comfortable for them personally instead of just for people in general.

Psychological factors can also influence thermal comfort. Having control, and particularly perceiving that control, changes the way that people assess their environment. This is in addition to the added behavioral possibilities afforded by these controls (Brager et al., 2004; de Dear and Brager, 1998; Leaman and Bordass, 2013; Paciuk, 1990). Expectation due to cultural norms as well as current and recent experience can also influence thermal sensation and comfort (Bischof et al., 2002; de Dear and Brager, 1998; Fanger and Toftum, 2002). For example someone who has a more variable thermal history connected to natural outdoor temperature swings might expect the indoor conditions to be less constant.

Some current research is aimed at separating the effects of these three types of adaptation, but to date there are no conclusive results (Liu et al., 2012a; Schweiker et al., 2012).

Derivation methods

ASHRAE RP-884

In 1997 de Dear and Brager compiled the raw data from 46 previous thermal comfort field experiments into a single database (RP-884) (de Dear and Brager, 1998; de Dear, 1998). The data was collected from 121 buildings[1] in nine countries on four continents and contained 20,693 unique observations, 10,155 from air conditioned (AC) buildings, 10,069 from naturally ventilated (NV) buildings, and 2,818 from mixed-mode (MM) buildings. This data was compiled into a standard format with metrics calculated in a standardized way, and only data collected with sufficiently good equipment and methodology was included.

de Dear and Brager used the building as the unit of analysis, rather than an individual person or a whole field study, because it allows some consistency in factors such as daily temperature fluctuations, personal control, and job satisfaction. For each building in each season, they calculated the neutral temperature by running a linear regression through the average thermal sensation vote in each 0.5 K bin of indoor operative temperature. The temperature bins were weighted by the number of votes they represented. Only those buildings achieving a model with $p<0.05$ were included in the analysis. To be able to compare with the predictions from Fanger's heat balance model, they calculated the predicted neutral operative temperature of each building using that building's average RH, air speed, clothing level, and metabolic rate.

They also calculated preferred temperature for the 55 buildings in which respondents were asked about their preferences. For each building, they used indoor temperature to predict preference in two probit models: one for "want warmer" votes and one for "want cooler" votes. They assumed that the intersection between the two models indicates preferred temperature. Comparing preferred temperature to neutral temperature, they found a statistically significant regression between the two parameters for AC but not NV buildings. In colder outdoor conditions, people in AC buildings preferred to be "slightly warm", and in warmer

---

[1] For the purposes of analysis, de Dear and Brager considered a building where surveys were administered in two different seasons to be two "buildings." Here I consider it to be the same building.

outdoor conditions they preferred to be "slightly cool". Because not every building in the database asked a question to elicit thermal preference, they calculated a linear regression between neutral and preferred temperatures for AC buildings and then used the results to find the "comfort temperature" for each AC building. The difference was so small for NV buildings that they considered the comfort temperature to be equal to the neutral temperature.

After they calculated the comfort temperature for each building during each season, de Dear and Brager ran a linear regression between comfort temperature and mean monthly outdoor effective temperature. A compilation thermal comfort index, effective temperature, ET*, is the air temperature at 50% relative humidity with no air movement that would have equivalent comfort effects as the actual conditions (Fobelets and Gagge, 1988). They found a significant difference in the slopes of the regressions for AC and NV buildings, as shown in Equation (1). In AC buildings, the comfort temperature's dependence on outdoor temperature was easily explained by variations in clothing insulation, as demonstrated using PMV values. But for NV buildings, the neutral temperature was more dependent on outdoor temperature than predicted by the PMV model, which indicates that the occupants of these buildings were using more than just clothing to adapt to their environments.

$$\begin{aligned} T_C &= 0.255 * ET^*_{out} + 18.9 \quad \text{for NV buildings} \\ T_c &= 0.04 * ET^*_{out} + 22.6 \quad \text{for AC buildings} \end{aligned} \tag{1}$$

To determine the acceptable range of operative temperatures around the comfort temperature, they solved the linear regressions between thermal sensation and operative temperature obtained in the first step for sensations of ±0.85. This corresponds to the 80% acceptability limits from Fanger's PMV-PPD curve and contains the assumption that the variance (width) of the PMV-PPD curve is accurate even if its predicted neutral temperature (PMV) is not. They found that the range of the 80% acceptable temperatures is larger for NV than AC buildings and argue that this supports the adaptive hypothesis's prediction that expectations play a large role in comfort.

SCATs

The Smart Controls and Thermal Comfort (SCATs) project was conducted by a team of researchers in Europe with the goal of experimentally finding the relationship between outdoor temperature and indoor comfort temperature (McCartney and Nicol, 2002).

Unlike the RP-884 database, which was compiled after the fact from existing field studies, the SCATs database was assembled all at the same time from uniform studies in 26 NV, AC, and MM buildings in 5 European countries. Two different types of data were collected: transverse and longitudinal. Occupants answered the transverse survey once a month, and a subset of these respondents also answered the longitudinal survey up to four times a day. This combination of surveys allowed for a large sample size as well as information with a very large time resolution. The researchers collected 4,655 responses to the transverse questionnaire and 27,284 responses to the longitudinal one for a total of 31,939 responses (Nicol and McCartney, 2000).

McCartney and Nicol chose to use the exponentially decreasing running mean temperature as the metric for outdoor conditions. From previous studies, they knew that running mean outdoor and comfort temperatures were linearly related in some ranges, but they assumed that comfort temperature is a constant below a certain running mean. The form of the model they were fitting for comfort temperature is shown in Equation (2).

$$T_{RM}{}^{n} = c * T_{RM}{}^{n-1} + (1-c) * T_{DM}{}^{n-1}$$

$$T_C = \begin{cases} d * \ T_{RM}{}^{n} + e & \text{for } T_{RM} > f \\ g & \text{for } T_{RM} \leq f \end{cases} \tag{2}$$

c, d, e, f, and g are constants to be determined, T_C is the comfort temperature, $T_{RM}{}^{n}$ and $T_{DM}{}^{n}$ are the running and daily mean outdoor temperatures on day n.

In order to be able to run a regression between the running mean and comfort temperatures, it was first necessary to calculate the comfort temperatures from the recorded thermal comfort votes. Rather than deriving a relationship between comfort votes and globe temperature (proxy for operative temperature), McCartney and Nicol "inspected" the RP-884 database and assumed that a two degree change in temperature corresponded to a one unit change on the thermal sensation scale (Nicol and McCartney, 2000).

The constant c determines the half life of the influence of the average temperature of any particular day. To calculate it, McCartney and Nicol ran regressions between the running mean and the comfort temperatures for several values of c using the longitudinal data. They found that the models were not very sensitive to c. They chose a value of 0.8, which results in a half life of about 3.5 days.

The next step was to determine the value of f, which is the running mean temperature below which the comfort temperature is constant. By plotting comfort temperature vs. running mean temperature and using a loess regression to see the general shape of the relationship, they found the inflection point to be 10°C. Running a regression between comfort temperature and running mean for values above 10°C gave the final equation for the comfort temperature:

$$T_C = \begin{cases} 0.302 * \ T_{RM}{}^{n} + 19.39 & \text{for } T_{RM} > 10°C \\ 22.88 & \text{for } T_{RM} \leq 10°C \end{cases} \tag{3}$$

Although this method only includes one independent variable (outdoor running mean), it had better predictive power than Fanger's PMV model with six independent variables for the SCATs database.

Comparison between RP-884 and SCATs

The calculation methods used in ASHRAE RP-884 and the SCATs project were very similar in their general approach, even though some of the statistical details differed. In both cases, the researchers calculated a neutral temperature from sensation votes and operative temperature and then added prevailing outdoor temperature into the final model. Still, there were significant differences in their methods:

	ASHRAE RP-884	**SCATs**
Data source	Compilation from previous studies	All new studies
Unit of analysis	One building per season	Individual votes
Relationship between sensation and operative temperature	Calculated per building per season using binned votes	Assumed
Comfort temperature	Preferred temperature in AC buildings, neutral temperature in NV buildings	Neutral temperature
Outdoor temperature metric	Monthly mean effective temperature (ET*)	Exponentially weighted running mean temperature
Cooling strategy	Separate analysis for each strategy	Combined analysis for all strategies
Comfort result	Range of 80% acceptability	Single comfort line

Table 1 Differences in RP-884 and SCATs adaptive comfort calculation methods

Modifications to PMV

Recognizing that field data consistently overpredicts deviations from thermal neutrality, Fanger revised his PMV model for naturally ventilated buildings in warm climates. He and Toftum added a multiplier to the standard PMV, called the expectancy factor, that depends on the length of the warm season and the prevalence of air conditioned buildings in the region. It varies from 0.5-1 and brings the PMV into the range of actual mean votes from field studies (Fanger and Toftum, 2002).

Yao et al. also based their adaptive model on PMV, but their modification is rooted in adaptive theory. As discussed above, adaptation is seen as a creating a feedback loop between the physical stimulus and the subjective response. Using that as the theoretical basis, Yao et al. derived an equation for aPMV:

$$\text{aPMV} = \frac{PMV}{1 + \lambda * PMV} \tag{4}$$

Summer and winter adaptive coefficients (λ), were determined empirically for Chongqing from field studies (Yao et al., 2009).

This model forms the basis of the adaptive standard in China. Additional field studies were conducted in other regions of China to determine the appropriate adaptive coefficients (National standard of the People's Republic of China, 2012).

Implementation in standards

The findings of the RP-884 and SCATs projects were implemented in ASHRAE 55 and EN 15251 respectively. Minor alterations, such as replacing monthly mean effective temperature with monthly mean air temperature in ASHRAE 55, were made. Table 2 describes these current standards (ANSI/ASHRAE, 2013; CEN, 2007).

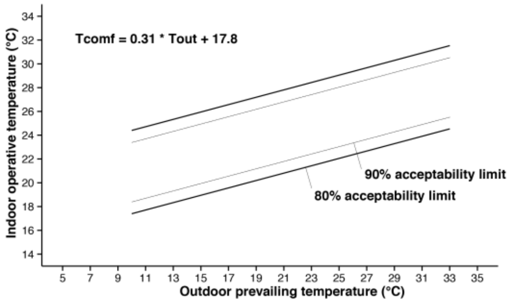
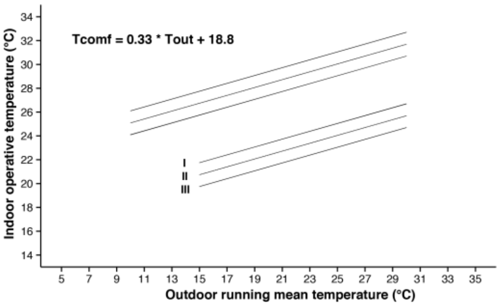
ASHRAE 55-2013	EN 15251-2007
Applies to NV buildings with no mechanical cooling installed	Applies to buildings that are free running (i.e. no mechanical cooling is operating)
Occupants must be free to adapt their clothing	Occupants must be free to adapt their clothing
Operable windows are required	Occupants must have easy access to operable windows
Applies to prevailing outdoor temperatures of 10-33.5°C—running, weekly, or monthly mean	Applies to running mean outdoor temperatures of 10-30°C
Defines limits on operable temperature for 80% and 90% satisfaction	Defines limits on operable temperature for class I, II, III comfort
	Upper temperature limits can be raised a few degrees when occupants can control the air speed
	

Table 2 Comparison of the ASHRAE 55 and EN 15251 adaptive models

2.2 Effects of personal control

Access to personal control is one of the most widely cited reasons for the differences in comfortable thermal conditions in air conditioned and naturally ventilated buildings. Multiple small scale studies have supported this idea.

Brager et al. (2004) conducted a field study in a naturally ventilated office building in which some occupants had easy access to a window and others had low or no access. The people with a higher level of personal control had neutral temperatures that were closer to the mean temperature of the preceding hour than those with less access, indicating that they had adapted to the conditions. In particular, the high control group's neutral temperature was 1.3K higher than the low control group's in the summer, but virtually identical in the winter. This is consistent with the hypothesis of personal control influencing adaptation because access to a window does not give the occupants useful thermal control during the winter.

Paciuk (1990) looked at how available, perceived, and exercised control influence thermal sensation and comfort. The study included measurements and survey responses from occupants of ten office buildings in Israel during the winter season. She found that thermal sensation and deviation from neutral temperature accounted for about 25% of the variance in thermal comfort and that the measures of control accounted for another 25%. The model including all of the predictors accounted for 44% of the variance, which indicates that there is little overlap between the two classes of predictors. While perceived control and access to thermal controls were positively correlated with satisfaction, exercised control was negatively correlated. She also found that the perception of control is related to but not determined by the availability of controls.

Haghighat and Donnini (1999) surveyed occupants in 12 mechanically ventilated buildings about their thermal comfort and their level of control over their thermal conditions. They found a moderate positive correlation ($0.16 < r < 0.22$) between perceived control and overall thermal satisfaction.

Bauman et al. (1998) conducted a field experiment in three office buildings in San Francisco. In each building they gave some occupants a task/ambient conditioning system (TAC), which allowed the occupants to control the air movement and air temperature at their desk as well as the setting of a radiant heating panel at leg height. Other occupants in the same building did not receive a TAC and served as the control group. They then varied the set point of the buildings while surveying the two groups about their thermal comfort. Comparing the thermal satisfaction of participants before and after receiving a TAC showed a significant increase in satisfaction. This increase was also significantly larger than the minor increase in satisfaction in the control group. In addition, the control group was about twice as sensitive to changes in temperature than the group that received TACs.

Although these studies in one or a few buildings support the idea that personal control allows occupants to be thermally comfortable in a wider range of conditions, the analysis of the RP-884 database does not. In the studies in Montreal and Townsville (~10% of observations in the database), the occupants rated their level of control over their environment. By correlating these responses with the controls are available to each occupant, de Dear et al. (1997) developed an index of perceived control. They then compared the likelihood of wanting no change in temperature, thermal acceptability votes, and thermal sensitivity to this index and found no statistically significant relationships.

Langevin et al. (2012) reanalyzed the data from the three datasets (Kalgoolrie, Montreal, and Townsville) included in RP-884 that have the most complete information about perceived control and comfort. All of the buildings considered had HVAC systems. Using these self-assessed, rather than calculated, ratings of control and control satisfaction revealed a statistically significant correlation between perceived control and thermal comfort votes. In particular, including these ratings of control in addition to physical measurements increased the predictive power of linear models. It is important to note that perceived control was more closely correlated with thermal comfort than simply having access to controls.

However, a field study conducted in an office building in China did not find a significant effect. In addition to answering the standard questions about thermal sensation, participants rated their level of control over their environment. The seasonal average sensation votes were closer to thermal neutrality for people with higher levels of perceived control than those with lower levels, but this difference was not statistically significant (Liu et al., 2012b).

Using the CBE indoor environmental quality survey (see below), Kim and de Dear (2012) analyzed the effect of having access to operable windows and/or individual HVAC controls on satisfaction with temperature. They found that temperature satisfaction ratings were very close to neutral for all of the groups and that access to controls was not a significant predictor of temperature satisfaction. In terms of overall satisfaction, the differences between the four levels of control were statistically significant. People with access to HVAC controls and operable windows were the most satisfied, followed by those with access only to windows, those with access only to HVAC controls, and those without access to either type of control.

2.3 General IEQ satisfaction

Since 2002, the Center for the Built Environment (CBE) has administered an online indoor environmental quality (IEQ) survey that asks about occupants' satisfaction in areas such as thermal comfort, light, indoor air quality, acoustics, and noise (Huizenga et al., 2003). Because of its standardized form and longstanding use, this survey provides an excellent benchmarking database that has been analyzed in many ways over the years.

The first large-scale analysis of the database was in 2006 when the survey had been administered in 215 buildings. Huizenga et al. (2006) examined the 20% dissatisfaction criterion of ASHRAE standard 55 and found that it was being achieved in only 11% of buildings in the database. Many of the other buildings were nowhere near the 20% mark: fully half of the buildings surveyed had more than 40% thermal dissatisfaction. Overall, 43% were dissatisfied with the temperature. Considering occupants with and without access to thermostats, operable windows, portable heaters, and portable fans, they found significantly lower dissatisfaction ratings for those with access to thermostats (24%) and operable windows (33%) but higher dissatisfaction rates for those with access to portable fans (56%) and portable heaters (49%). In all cases, there were many more people without a particular control than with it; perhaps they were occupant-supplied. Surprisingly, season had very little to do with whether people were too hot or too cold: occupants were slightly more likely to be too cold in the summer than in the winter, but the proportions were remarkably constant across season.

The database has been used extensively to assess the differences in IEQ between green or LEED-certified buildings and the rest of the database. Studies from 2003, 2005, and 2006 when the database contained results from 45-215 buildings found a significantly higher mean satisfaction score in green or LEED buildings than in more conventional ones (Abbaszadeh et al., 2006; Huizenga et al., 2005, 2003). In one case, when the green buildings were compared to the same (newer) generation, the performance difference was no longer statistically significant (Abbaszadeh et al., 2006). More recently, Altomonte and Schiavon (2013) carefully chose a subset of a larger database to study to ensure comparability by program type, size, and year of completion or last renovation and a minimum 5% response rate. The final dataset contained 144 buildings of which 65 were LEED certified. They did not find a statistically significant difference in temperature satisfaction between LEED and non-LEED buildings.

Brager and Baker (2008) compared the IEQ satisfaction in 12 mixed-mode buildings to the other 370 buildings that were in the database at the time. They found that all of the mixed-mode buildings were in the top half of the percentile ranking for temperature satisfaction. Newer buildings and those in milder climates (fewer heating degree days) tended to have higher rates of temperature satisfaction. They did not indicate how the age of the MM buildings compared to the rest of the database.

Kim and de Dear (2012) also looked at the effect that cooling strategy has on IEQ satisfaction, including temperature. Since survey respondents indicate their satisfaction with the building as a whole in addition to the individual components of IEQ, they could divide the various categories of IEQ into basic, proportional, and bonus factors depending on whether dissatisfaction or satisfaction with each individual category had a larger impact on the overall satisfaction score. They found that in AC buildings dissatisfaction with temperature had a larger impact on overall satisfaction than satisfaction with temperature did, so they concluded that it is a basic factor—occupants expect to be satisfied with temperature and when they are not, it detracts from their overall satisfaction with the building. In NV buildings on the other hand, they found that being satisfied with the temperature had a stronger effect on overall satisfaction than being dissatisfied did, so they concluded that it is a bonus factor. This means that occupants in NV buildings have more forgiving expectations of temperature and consider temperature satisfaction to be a bonus rather than a basic requirement. They noted that the NV buildings in the sample tended to be older, so it's possible that the difference they found between NV and AC buildings would be reduced when controlling for the age of the building.

3 Problem statement, goals, and objectives

The driving question behind this thesis is "How do a building's cooling strategy and the occupants' access to personal controls influence thermal comfort?" I investigate this question at two levels: physical conditions that create comfort and general satisfaction with temperature.

The methods for analyzing adaptive comfort described above have been very successful in changing the comfort requirements in the standards. The results are easy to use by design professionals and allow a quick understanding of comfort in a specific climate. Nevertheless the methods have some drawbacks, so new methods that avoid them are very valuable.

The end result of the adaptive models implemented in ASHRAE 55 and EN 15251 is a relationship between indoor and outdoor temperature and levels of satisfaction, but these components are approached indirectly with many intermediate steps (Figure 4). Both de Dear and Brager (1998) and McCartney and Nicol (2010) first related indoor temperature to thermal sensation and only brought in outdoor temperature in a secondary step. Also, they both use the PMV/PPD relationship, either explicitly or implicitly, to determine the allowable ranges around the neutral temperature line. But this relationship was developed for air conditioned buildings based on a small dataset from chamber experiments and has not been demonstrated to be valid in the field or across building types (Fanger, 1970).

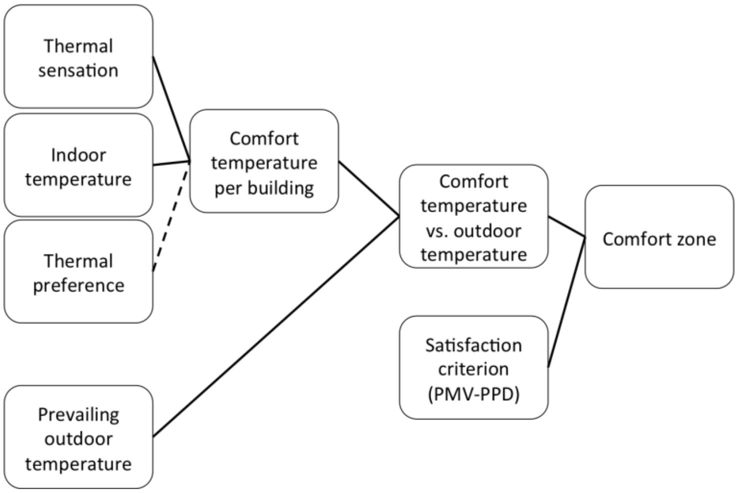


Figure 4 Schematic diagram of RP-884 calculation methodology

Two aspects of the way that de Dear and Brager ran the regressions between thermal sensation and indoor temperature lead to a loss of information. Before running the regressions, they averaged the thermal sensation votes by temperature bins, which leads to a loss of information about individual preferences and artificially raises the correlation coefficient of the fit (Humphreys et al. 2013). Then they ran separate regressions for each building during each season to account for differences between buildings due to factors such as daily temperature fluctuations, personal control, and job satisfaction. While it is valuable to account for these differences, this technique meant that several of the regressions were not statistically significant and therefore that data was not included in the rest of the analysis (de Dear and Brager, 1998).

The differences in comfortable conditions in NV and AC buildings have been studied extensively. Although the influence of personal control is one of the key factors that are cited as causing the differences between the two, this inference has not been well demonstrated in large datasets.

In order to investigate the effects that building cooling strategy and individual access to personal controls on thermal comfort, the specific goals of this thesis are to

- Develop methods of exploring the physical conditions under which people are thermally comfortable that reduce the loss of information, the number of assumptions, and the steps between the measured and desired variables.
    - Assess the strengths and weaknesses of these methods.
- Determine the relationship between thermal sensation and comfort, acceptability, and satisfaction.
- Use these new methods and relationship to describe the conditions that provide thermal comfort.
    - Compare the results across building cooling strategies and levels of access to personal controls.
    - Look at the conditions beyond the current outdoor temperature range covered by the adaptive standards (10-33°C).
- Create an interactive visualization tool to provide researchers and practitioners with easy and useful access to publically available thermal comfort field data, so they can conduct their own analysis.
- Investigate the effects of personal control on general temperature satisfaction in case study buildings in which occupants have access to operable windows and fans.

4 Defining comfortable conditions

4.1 Database description

4.1.1 Data collection methods

This project is based on thermal comfort field study data from the ASHRAE RP-884 and SCATs transverse databases as well as two separate studies in the San Francisco Bay Area (Brager et al., 2004; de Dear et al., 1997; de Dear, 1998; Arens et al., 2014; McCartney and Nicol, 2002; Nicol and McCartney, 2000; Zhang et al., 2007). The precise methods of data collection vary across studies from paper surveys and mobile measurement carts to automatic web-based surveys with continuous data logging. In some cases a transverse approach was taken in which many occupants were polled only once, and in other cases fewer occupants were polled multiple times. In all of these studies, subjective survey responses were collected along with simultaneous physical measurements.

The core survey response in all of the studies was thermal sensation rated on the 7-point ASHRAE scale from “cold” (-3) to “neutral” (0) to “hot” (+3). In some cases, occupants were presented with a continuous scale, but they were mostly limited to integer votes. The other questions on the surveys varied. Some occupants were asked to rate their thermal comfort on a 6-point scale from “very uncomfortable” to “very comfortable” with no “neutral” option in between. Others were asked about their thermal preference on a 3-point McIntyre preference scale of “cooler,” “no change,” and “warmer.” Finally, some occupants were asked whether their current temperature or thermal conditions were acceptable or not.[2] Sample wording of these questions along with the scale options can be found in Appendix A.

The surveys also included questions about physical parameters. To allow calculation of met and clo, occupants checked off their recent activities and the items of clothing they were wearing. These were then converted into clo values including the insulating effects of the desk chair. In some cases, occupants were asked whether or not they had access to an internal or external door, window, local fan, local heater, thermostat, or curtains/blinds.

The main physical parameters that were measured indoors were air temperature, operative temperature, relative humidity, and air speed. A metric of prevailing outdoor temperature was also recorded. Where all of the necessary inputs were available, PMV and PPD were calculated using the ASHRAE algorithm.

The metric for prevailing outdoor temperature varies considerably between the studies. In the RP-884 database, the metric is monthly mean outdoor temperature, which was calculated from daily measurements at 6am and 3pm. These were assumed to be the daily low and high temperatures. The overall monthly mean was calculated as the mean of the monthly mean high and monthly mean low. The source of the measurements varied from climatological data to measurements from nearby weather stations (e.g. airports) to measurements directly outside the test building (de Dear and Brager, 1998).

In the SCATs database, all of the outdoor temperature measurements were taken from nearby meteorological stations or outside the buildings themselves. The outdoor temperature metric that is reported is exponentially weighted daily running mean (McCartney and Nicol, 2002).

For the studies in Berkeley and Alameda that are not included in the other databases, the outdoor temperature was measured on site. The study in Berkeley

---

[2] The survey for the study in Alameda offered the choice of a 7-point scale from “very unacceptable” (-3) to “neutral” (0) to “very acceptable” (+3) (Arens et al., 2014). To allow comparison with the binary responses in the RP-884 database, acceptability votes of 0 or above were coded as “acceptable.”

reported monthly mean outdoor temperatures based on continuous measurements (Brager et al., 2004). For Alameda, the outdoor temperature metric is exponentially weighted daily running mean (Arens et al., 2014).

Other survey responses and physical measurements that are not discussed here are available in the database.

4.1.2 Contents of the database

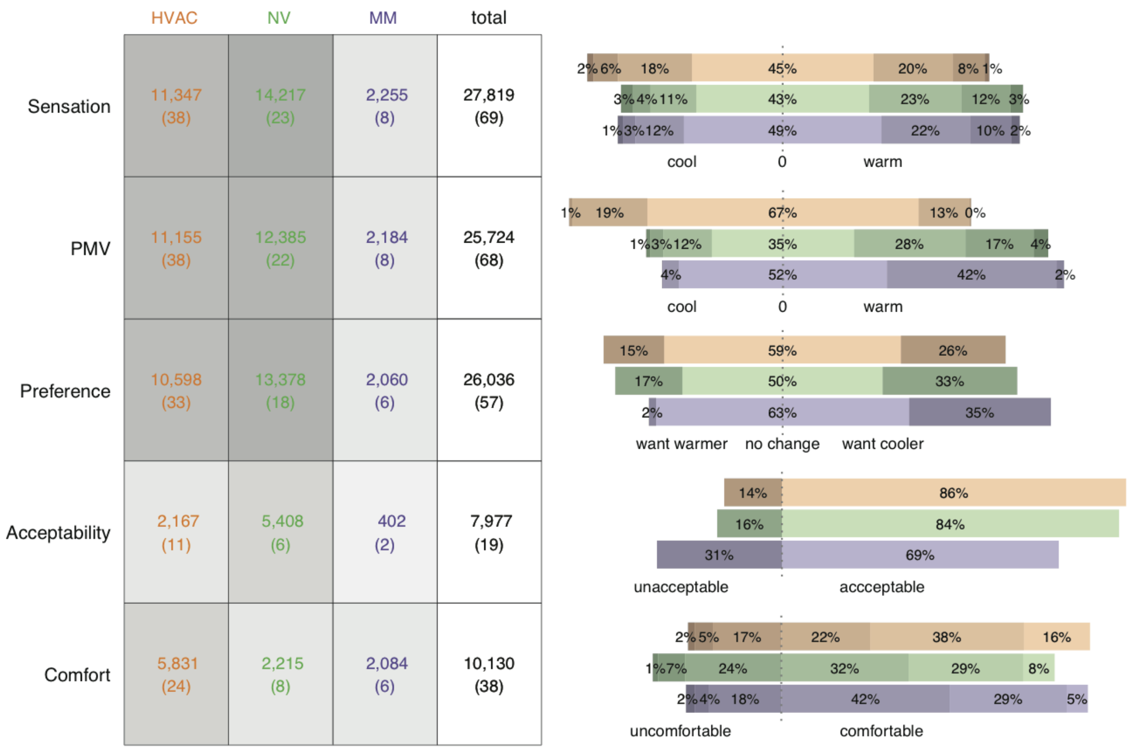
The aggregated database contains 32,055 observations from 167 buildings in 53 cities in 12 countries. The buildings are located in 11 climate zones ranging from continental subarctic to wet equatorial. 148 of the buildings are offices, and the others include houses, schools and factories. About half of the observations come from naturally ventilated (NV) buildings; the remaining half come predominantly from air conditioned (AC) buildings, but there are also some from mixed-mode (MM) buildings. For this analysis I exclude the data from Honolulu and Townsville because it does not include a metric of prevailing outdoor temperature and because the data from Honolulu comes from schools and school children, who may not be reliable survey takers (see p. 26). So what I consider here has a total of 27,819 observations (Table 3).

	AC	NV	MM	Total
Climates	9	9	5	11
Countries	10	10	7	12
Cities	37	23	8	51
Buildings	110	46	10	156
Respondents	5,769	2,766	475	8,770
Observations	11,347	14,217	2,255	27,819

Table 3 Database characteristics, excluding Honolulu and Townsville

Figures 5-7 show the number of observations for each of the variables considered in this study broken down by cooling strategy. To enable easy comparison between categories, the cells in the table are shaded according to the number of observations, with darker grey indicating more observations. The 100% bar plots or boxplots are shown for each variable to indicate the range and distribution of survey responses and measurements for each building cooling strategy.

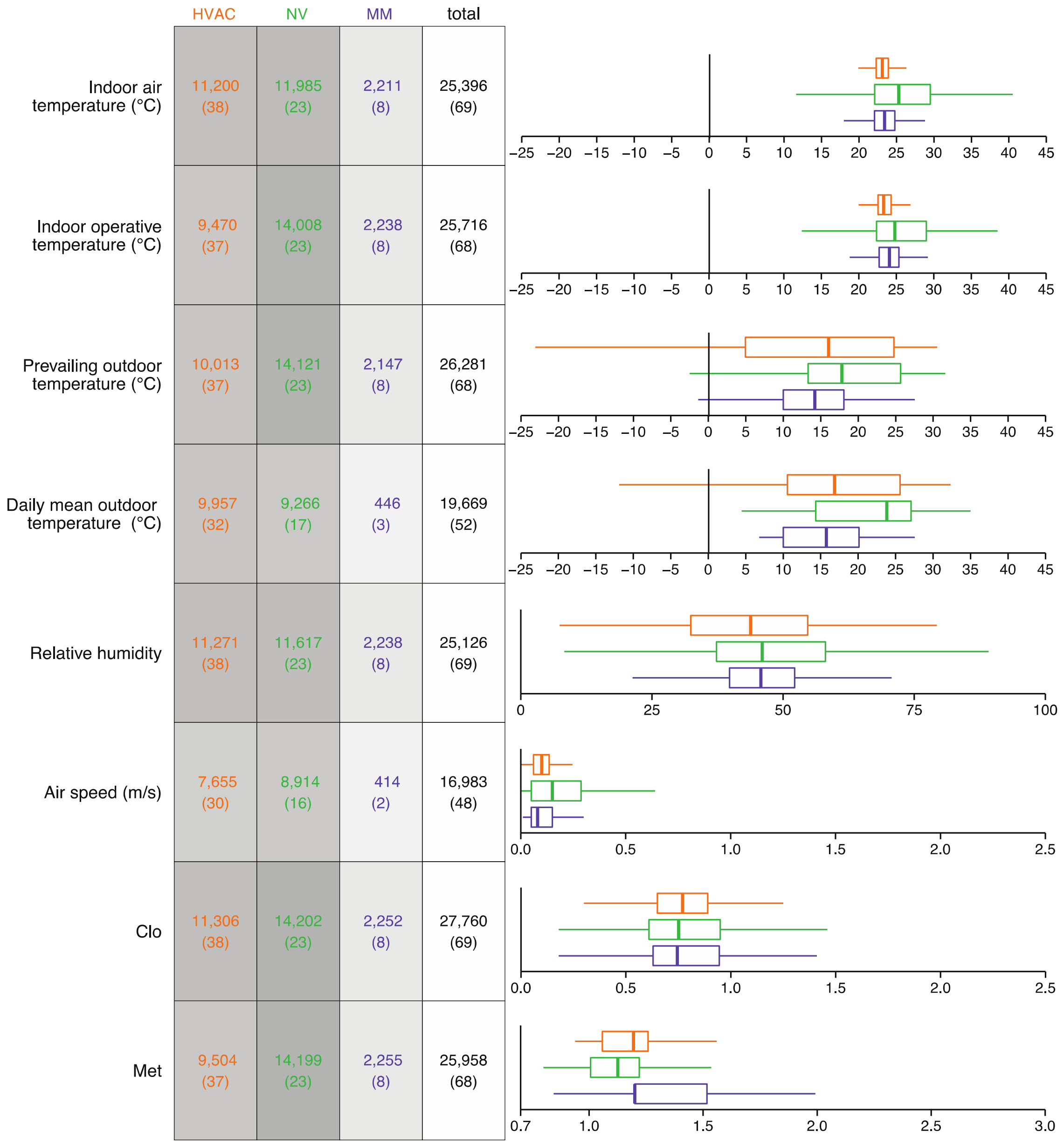
The sensation votes are very similar in all three building types; in particular, a similar percentage of respondents indicated that they felt neutral. The PMVs predict more neutral votes in AC buildings than occurred and fewer neutral votes in NV buildings than occurred. The percentage of “no change” votes was similar to the percentage of “neutral” votes for each building type. Although there were very fewer votes for acceptability, the ones that were collected were overwhelmingly “acceptable.” The result is similar for comfort (Figure 5).



	HVAC	NV	MM	total
Sensation	11,347 (38)	14,217 (23)	2,255 (8)	27,819 (69)
PMV	11,155 (38)	12,385 (22)	2,184 (8)	25,724 (68)
Preference	10,598 (33)	13,378 (18)	2,060 (6)	26,036 (57)
Acceptability	2,167 (11)	5,408 (6)	402 (2)	7,977 (19)
Comfort	5,831 (24)	2,215 (8)	2,084 (6)	10,130 (38)

Figure 5 Summary of survey responses and PMV by cooling strategy
NOTE: The number of observations of each type are indicated in the boxes with the number of cities involved shown in parentheses.

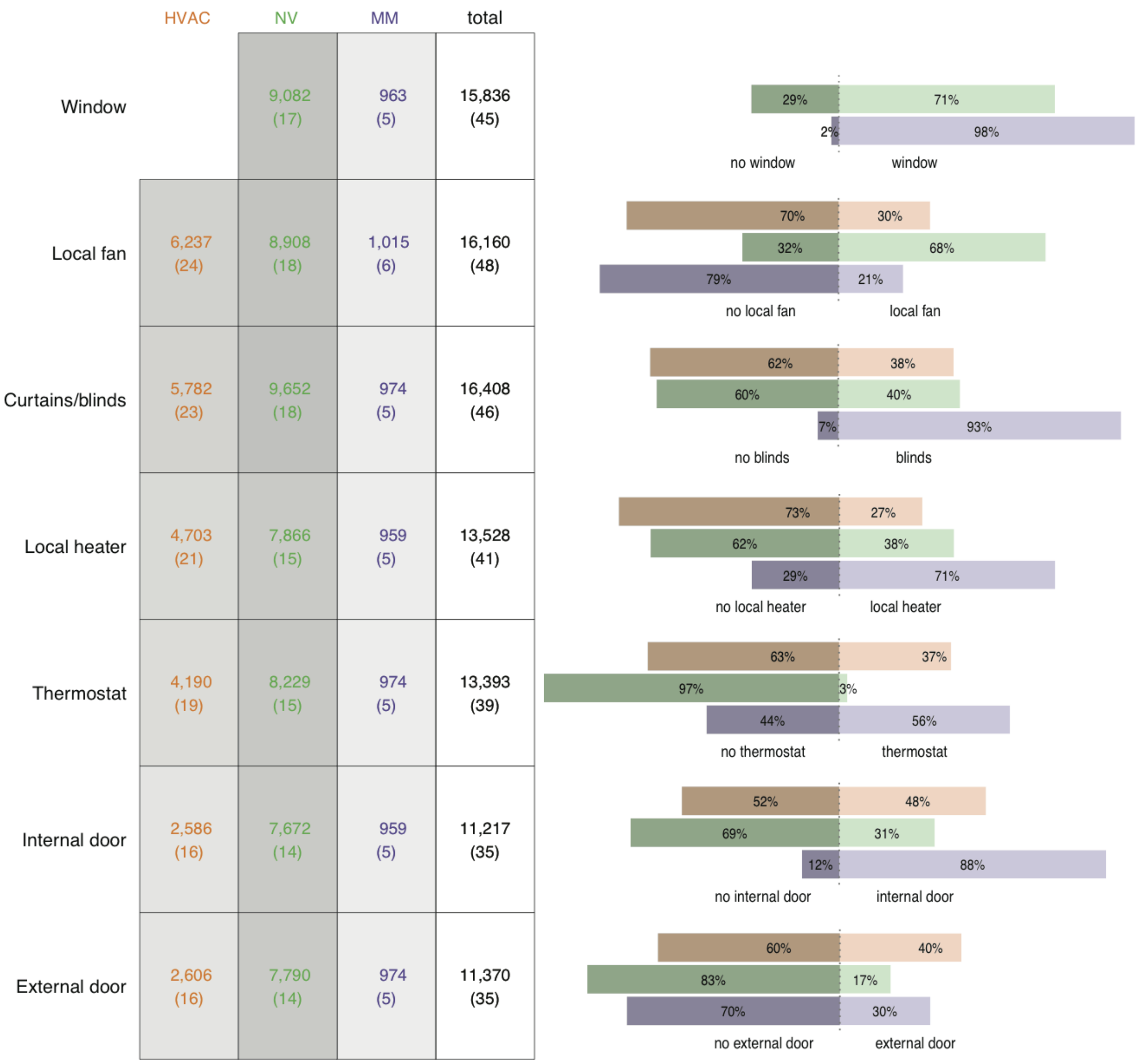
Figure 6 shows the summary statistics for the physical conditions under which the measurements were taken. As expected, NV buildings had a wider range and higher values of indoor air and operative temperatures as well as air speeds than the other building types. The outdoor temperatures varied the most in AC buildings; the observations from the coldest outdoor conditions were all taken in AC buildings. The MM buildings were in general similar to the AC ones, except with respect to met rate, where it is distinctly higher than for AC or NV buildings. Since all the MM buildings are offices, I do not know why the met rate is so high.



	HVAC	NV	MM	total
Indoor air temperature (°C)	11,200 (38)	11,985 (23)	2,211 (8)	25,396 (69)
Indoor operative temperature (°C)	9,470 (37)	14,008 (23)	2,238 (8)	25,716 (68)
Prevailing outdoor temperature (°C)	10,013 (37)	14,121 (23)	2,147 (8)	26,281 (68)
Daily mean outdoor temperature (°C)	9,957 (32)	9,266 (17)	446 (3)	19,669 (52)
Relative humidity	11,271 (38)	11,617 (23)	2,238 (8)	25,126 (69)
Air speed (m/s)	7,655 (30)	8,914 (16)	414 (2)	16,983 (48)
Clo	11,306 (38)	14,202 (23)	2,252 (8)	27,760 (69)
Met	9,504 (37)	14,199 (23)	2,255 (8)	25,958 (68)

Figure 6 Summary of physical conditions by cooling strategy

About half of the total observations were accompanied by information about the controls the respondents had access to (Figure 7). Surprisingly, for each of the six controls other than windows, 30-40% of the observations in AC buildings were given by people with access to that control. In NV buildings, on the other hand, access to controls varied substantially based on the type of control: about 80% of the time people had access to windows or local fans, but they only had access to thermostats 3% of the time. In general, the occupants of the MM buildings had the most controls.



	HVAC	NV	MM	total
Window		9,082 (17)	963 (5)	15,836 (45)
Local fan	6,237 (24)	8,908 (18)	1,015 (6)	16,160 (48)
Curtains/blinds	5,782 (23)	9,652 (18)	974 (5)	16,408 (46)
Local heater	4,703 (21)	7,866 (15)	959 (5)	13,528 (41)
Thermostat	4,190 (19)	8,229 (15)	974 (5)	13,393 (39)
Internal door	2,586 (16)	7,672 (14)	959 (5)	11,217 (35)
External door	2,606 (16)	7,790 (14)	974 (5)	11,370 (35)

Figure 7 Summary of available controls by cooling strategy

Although the data was collected in 11 climate zones, slightly more than a third of the observations are from Mediterranean climates, primarily the San Francisco Bay Area (Figure 8). Except for humid subtropical climates, the observations for the different cooling strategies in the same climate were taken under similar outdoor conditions.

	HVAC	NV	MM	total
wet equatorial	688 (2)	471 (2)	41 (1)	1,200 (2)
tropical savanna	3,022 (3)	390 (1)		3,412 (3)
humid subtropical	642 (2)	609 (1)	303 (1)	1,554 (2)
humid mid latitude	2,683 (5)		206 (1)	2,889 (5)
hot arid	1,222 (1)	1,743 (3)		2,965 (4)
semi arid mid latitude		964 (1)		964 (1)
semi arid high altitude		1,017 (1)		1,017 (1)
temperate marine	509 (1)	552 (1)		1,061 (1)
mediterranean	2,330 (7)	6,419 (7)	1,141 (2)	9,890 (12)
west coast marine	602 (9)	2,052 (6)	564 (3)	3,218 (13)
continental subarctic	869 (8)			869 (8)

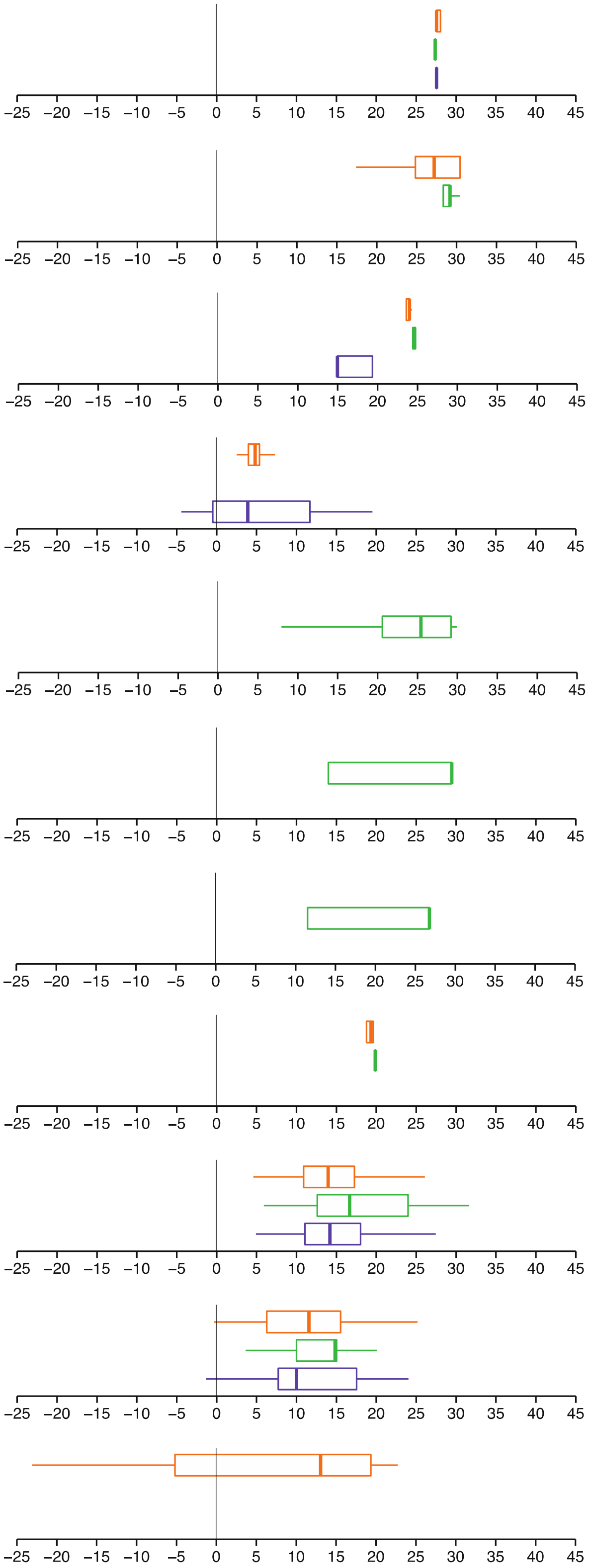


Figure 8 Prevailing outdoor temperature (°C) by climate zone

Summary statistics divided by city can be found in Appendix B.

4.2 Methods for defining the comfort zone

4.2.1 Probit

ASHRAE 55 defines thermal comfort as the “condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ANSI/ASHRAE, 2013). Since most field studies don’t ask directly about satisfaction with the thermal environment, researchers look to questions about thermal sensation, acceptability, preference, and comfort to assess satisfaction (Arens et al., 2010; Zhang et al., 2011). Thermal sensation is the most widely reported response, so it is a very useful metric to use. But it is not clear what range of sensation should be considered satisfied. Fanger assumed that individual thermal sensation votes of -1, 0, and 1 indicated satisfaction and used probit analysis to derive the PMV-PPD relationship from that (Fanger, 1970). Although de Dear and Brager did not explicitly define a satisfied range of thermal sensation for individual votes, they did so implicitly by calculating the 80% satisfaction limits based on an average thermal sensation of ±0.85. This value comes from the original PMV-PPD curve and has not been justified with field data by directly comparing thermal sensation and comfort or acceptability votes (de Dear and Brager, 1998). Others explicitly accept this assumption, and it is even included in ISO 7730 (Humphreys et al., 2013; ISO, 2005; Langevin et al., 2012; Nicol and Humphreys, 2010). Because the -1, 0, 1 criteria was developed using an integer scale, other researchers have adapted this to a range of -1.5 to 1.5 for continuous scales (de Dear and Brager, 1998).

I consider acceptability to be the best indicator of thermal comfort because it is what is used in both ASHRAE 55 and EN 15251 to talk about the actual recommended thermal conditions:

- “The purpose of this standard is to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space” (ANSI/ASHRAE, 2013).
- “Optimal” operative temperature is the “operative temperature where a maximum number of the occupants can be expected to feel the indoor temperature [is] acceptable” (CEN, 2007).

Because only about a third of the survey responses in the database include acceptability questions, I use the studies that have acceptability votes to develop a relationship between those votes and thermal sensation. I also consider other predictors, such as cooling strategy and climate information, which can be known without surveys. Following the methodology that Fanger (1970) used to develop the PMV-PPD curve, I use probit analysis to predict the percentage of dissatisfied votes. Because the raw acceptable votes are binary but there need to be three categories for the multinomial probit, I use thermal sensation to determine whether an unacceptable vote is caused by being hot or cold. 160 out of the 1,927 "unacceptable" votes had a simultaneous thermal sensation vote of 0, so they were not included in the analysis.

4.2.2 Mixed effects models

A basic assumption of linear, probit, and logit models is that the observations are independent. In the database of field studies, the sampling is clustered in a few buildings, so the observations are not independent. In other words, we might expect observations from the same building to be more similar to each other than to ones from different buildings because of factors such as culture, daily variability in indoor or outdoor temperature, and job satisfaction (de Dear and Brager, 1998). Mixed statistical models address this problem by dividing the variance in the dependent variable between fixed effects and random ones. The fixed effects are the standard modeling parameters that are being studied, while random effects account for differences between groups when those groups are not of interest or are a consequence of the sampling method (Pinheiro and Bates, 2000; UCLA statistical consulting group; Winter, 2013). In this case, the data is grouped by building, but since I am less interested in the building-specific results than the general results for different kinds of buildings, I consider the individual building to be a random effect.

In addition to the regression coefficients that are a result of simple linear models, mixed models also give estimates of the variance in these coefficients that can be expected due to variations in the random effects (Bates, 2010). For example, Figure 9 shows made up data from two people who were surveyed repeatedly about their thermal sensation at varying indoor temperatures. Person A is much more sensitive to the changes in indoor temperature than Person B. A simple linear model does not reveal this individual variation, but a mixed linear model gives an indication of how much variation you might expect in responses depending on which individuals you happen to survey. The fixed effects describe the overall behavior of the sample and are very similar to the model without the random effects. The random effects are a measure of how much variability to expect between different groups (Bates, 2010).

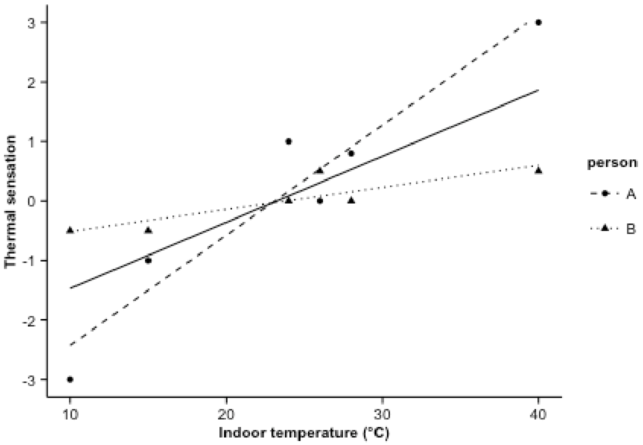


Figure 9 Example of linear mixed model

In order to visually show how much variation that is between groups, I use a bootstrapping approach to find the marginal differences (UCLA statistical consulting group,). For example, if I am predicting thermal sensation at an operative temperature of 20°C using building number as the random effect, there will be as many estimates of sensation as there are buildings. Rather than show all of the estimates, I take a random sample of 1,000 of the buildings and use the model to predict the sensation at each temperature for each of those buildings. The mean value of sensation for each operative temperature is the result of the fixed effects, so I also calculate the first and third quartile values to plot the range. This region contains the predicted values for half of the buildings. Because each building is equally likely to be drawn in the random sample, I am assuming that the overall sample of buildings is representative of the building stock.

I explore linear mixed models that predict calculated acceptability and thermal sensation based on indoor temperature, prevailing outdoor temperature, PMV, cooling strategy, climate zone, and access to personal controls. Depending on the model, I use the building, or the building and respondent as the random effect. The algorithm is from the “nlme” library of the statistical package R (Pinheiro et al., 2014; R Core Team, 2013)

Linear mixed models do not use the standard R^2 as a measure of the goodness of fit, so the relative success of two models must be judged another way. Because the sample size is so large, even small changes in the model are usually significant, so commonly used metrics such as Akaike’s Information Criterion (AIC) are not very informative. Therefore I use the standard deviation of the residuals, which does not depend on sample size, for evaluating the success of the models (Burnham and Anderson, 2002; Kovalchik, 2014). A lower standard deviation indicates that the residuals are more tightly clustered around zero and therefore that the model more accurately predicts the observed values.

In order to get a handle on how much variation there is between buildings with respect to the relationship between acceptability and sensation, I also use a mixed logit model. The shape of the logit function is very similar to that of a probit and the function is easier computationally, so it was preferable for the mixed effects model. I used the “lme4” library (Bates et al., 2014).

4.2.3 2D bin visualization

Adaptive comfort standards relate comfortable indoor temperatures to outdoor temperature (ANSI/ASHRAE, 2013; CEN, 2007). In order to visualize satisfaction in this framework, I bin thermal comfort votes according to the indoor and outdoor temperature conditions under which they were given. Then within each two-dimensional bin I calculate the percentage of satisfied votes. An accumulation of bins with at least 80% satisfaction delineates the comfort zone. For example, if the bin with an outdoor and indoor temperature of 20°C had 100 acceptability votes of which 80 were “acceptable”, then the (20°, 20°) bin would be colored green to mark it as having 80% satisfaction (Figure 10). Similarly, if there were 50 votes in a bin of

20°C outdoor and 30°C indoor temperature, and 10 of them were "acceptable," then the (20°, 30°) bin would colored red to mark it as having 20% satisfaction. When "calculated acceptability" is used as the satisfaction metric, the probability of an "acceptable" vote that was calculated using the probit analysis described above is averaged to determine the satisfaction percentage. I use the convention of ASHRAE 55 and EN 15251 and put indoor temperature (air or operative) on the y-axis and outdoor temperature (daily or prevailing mean) on the x-axis.

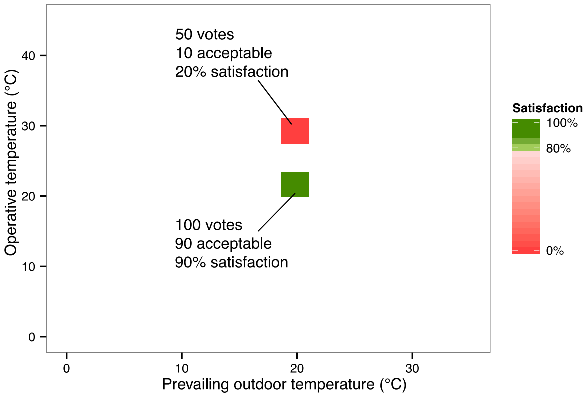
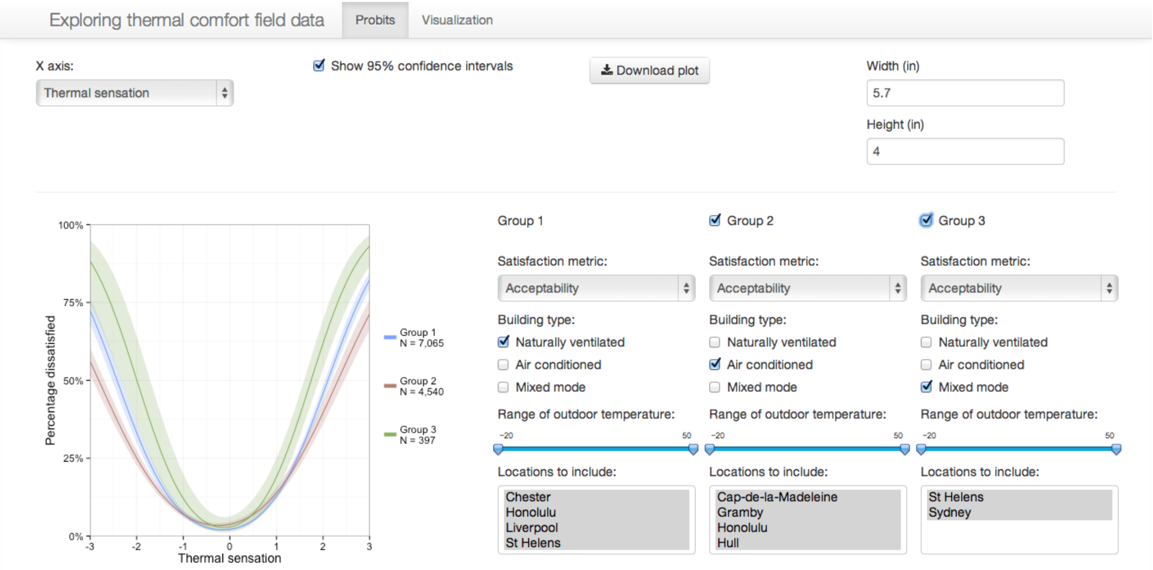


Figure 10 Illustration of 2D bin visualization

4.2.4 Interactive thermal comfort visualization tool

I developed an interactive visualization tool to give practitioners and researchers an easy way to explore the thermal comfort field study databases using some of the methods described above. The tool is built with the statistical package R, using the "ggplot2" library for visualization, the "ordinal" library for the probit analysis, and the "shiny" library as the interface between R and html (Christensen, 2013; R Core Team, 2013; RStudio and Inc, 2013; Wickham and Chang, 2013). The user interface has dropdown menus, sliders, and input fields that allow users to filter the overall database and choose the metrics to be plotted. The key database filters are cooling strategy, city, and available personal controls.

The tool is divided into two parts. The first uses probit analysis to display the percentage of dissatisfied votes as a function of a variety of variables (thermal sensation, PMV, or indoor temperature) and plots the corresponding curves (Figure 11). Users can then compare satisfaction calculations based on different metrics (acceptability, comfort, preference, sensation ±1.5) or subsets of the data. The screen gives immediate feedback, which makes the tool very useful for exploring the data.



X axis: Thermal sensation

☑ Show 95% confidence intervals

Width (in): 5.7

Height (in): 4

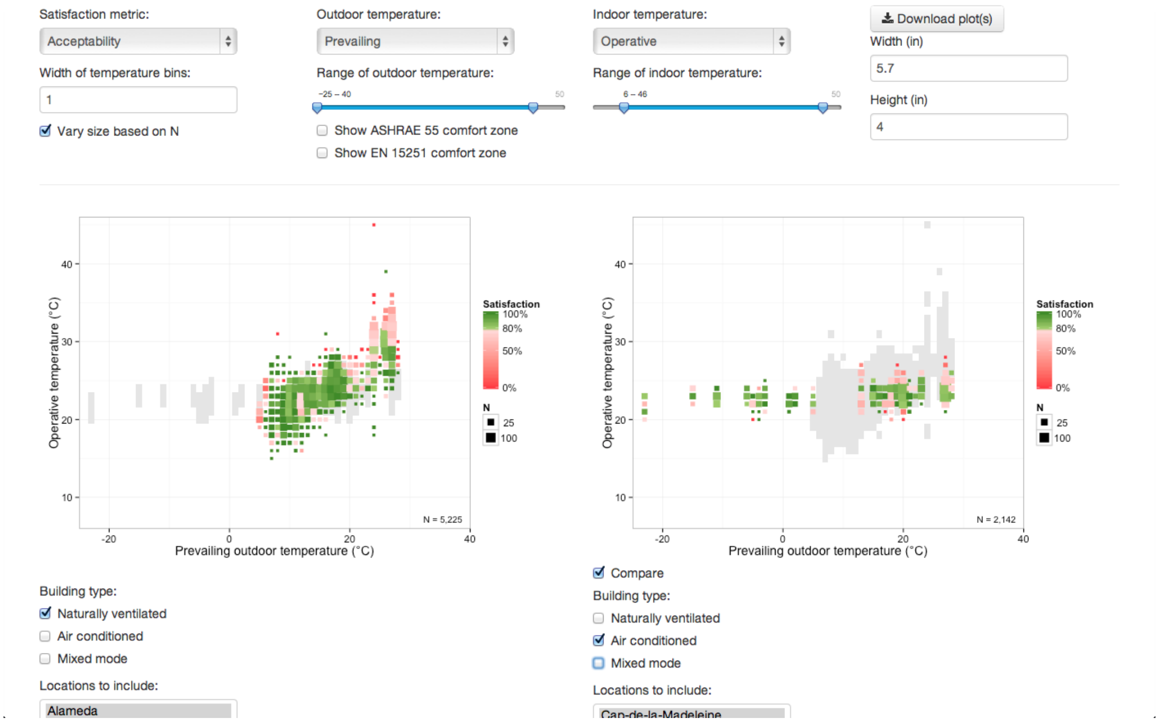
Group 1
Satisfaction metric: Acceptability
Building type:
☑ Naturally ventilated
☐ Air conditioned
☐ Mixed mode
Range of outdoor temperature: -20 to 50
Locations to include:
Chester
Honolulu
Liverpool
St Helens

☑ Group 2
Satisfaction metric: Acceptability
Building type:
☐ Naturally ventilated
☑ Air conditioned
☐ Mixed mode
Range of outdoor temperature: -20 to 50
Locations to include:
Cap-de-la-Madeleine
Gramby
Honolulu
Hull

☑ Group 3
Satisfaction metric: Acceptability
Building type:
☐ Naturally ventilated
☐ Air conditioned
☑ Mixed mode
Range of outdoor temperature: -20 to 50
Locations to include:
St Helens
Sydney

Figure 11 Screenshot of interactive thermal comfort database tool: probits

The second part of the tool produces the 2D bin visualizations described above. The user can choose the metrics for indoor and outdoor temperature as well as for satisfaction. There are four satisfaction metrics to choose from: acceptability, calculated acceptability, comfort, sensation ±1.5, and sensation ±2. Other options allow the user to control the granularity of the bins, scale the size of the rectangles according to how many votes they represent, and compare two datasets side by side. In the comparison mode, the light gray shadow of the comparison dataset is displayed behind the colored graph to register the two sets of results against each other (Figure 12).



Satisfaction metric: Acceptability

Width of temperature bins: 1

☑ Vary size based on N

Outdoor temperature: Prevailing

Range of outdoor temperature: -25 – 40

☐ Show ASHRAE 55 comfort zone

☐ Show EN 15251 comfort zone

Indoor temperature: Operative

Range of indoor temperature: 6 – 46

Width (in): 5.7

Height (in): 4

Building type:

☑ Naturally ventilated

☐ Air conditioned

☐ Mixed mode

Locations to include: Alameda

☑ Compare

Building type:

☐ Naturally ventilated

☑ Air conditioned

☐ Mixed mode

Locations to include: Cap-de-la-Madeleine

Figure 12 Screenshot of interactive thermal comfort database tool: visualization

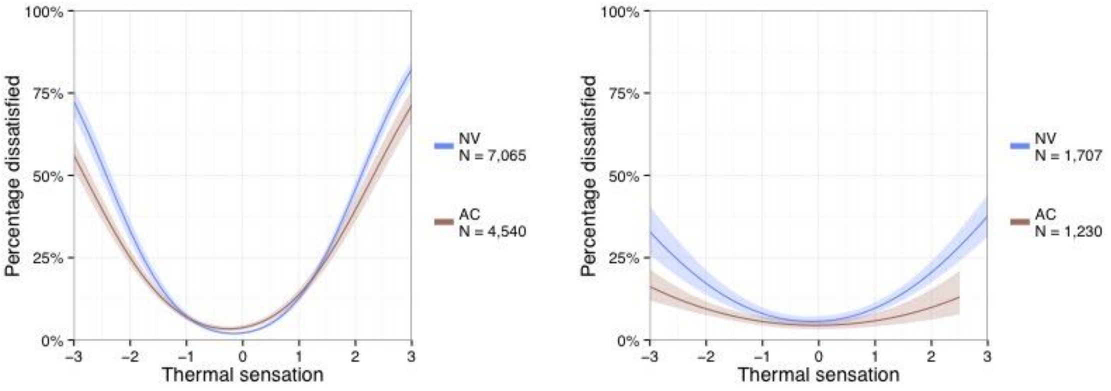
The capabilities of this tool are described further in the following sections as the results are being discussed.

4.3 Results

4.3.1 Relationship between sensation and acceptability

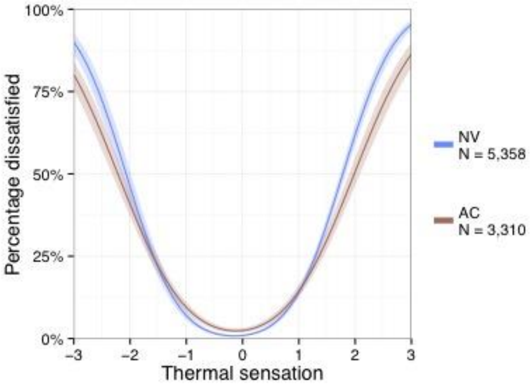
Interactive thermal comfort visualization tool, part I: probits

I used the interactive thermal comfort visualization tool to compare the acceptability probits based on thermal sensation for NV and AC buildings (Figure 13a). I was surprised by the prediction that almost 50% of people would find a sensation of -3 to be acceptable, so I looked through the probits for individual cities. I found that the predictions for Honolulu (Kwok, 1997) were even more extreme: 65-80% acceptance of a thermal sensation of -3 (Figure 13b). Since these results are unreasonable and come from schools where many of the participants were children, I excluded Honolulu from further analysis. Figure 13c shows the result without the buildings in Honolulu. 80-90% dissatisfaction at thermal sensations of -3 and +3 are much more expected. I describe these steps as an illustration of the benefits of this interactive tool, which makes all of these steps of the analysis quick and easy to do.



a. All NV & AC buildings

b. NV & AC buildings in Honolulu



c. NV & AC buildings outside of Honolulu

Figure 13 Dissatisfaction vs. thermal sensation including and excluding Honolulu

Another question that can be explored with this tool is whether acceptable sensations vary based on the outdoor conditions. Literature has suggested that someone might prefer to be slightly cool or even cool during hot months and slightly warm or warm during cold ones (de Dear et al., 1997; Humphreys and Nicol, 2004). Figure 14 shows that the cold side of the curve (sensation<0) is virtually identical for warm and cool outdoor conditions. For a given warm sensation, people tend to be slightly more accepting during cool than warm conditions.

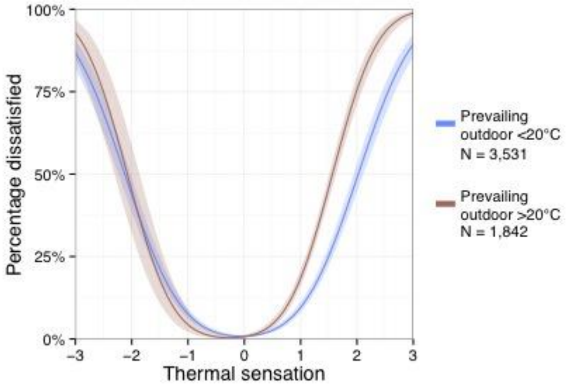


Figure 14 Dissatisfaction vs. thermal sensation for NV buildings based on outdoor conditions

Because subsetting the database can result in small amounts of data being analyzed, the tool draws 95% confidence intervals by default. As an example, Figure 15 adds a third curve for mixed mode buildings. The wider confidence interval (shaded area) reflects that there are many fewer mixed mode votes and that the curve cannot be distinguished from NV and AC buildings with the available data.

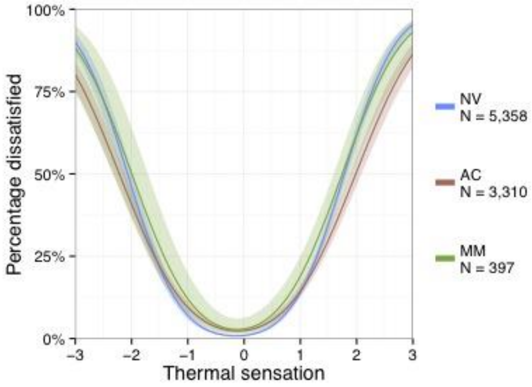


Figure 15 Dissatisfaction vs. thermal sensation for NV, AC, and MM buildings showing confidence intervals

Another way of quantifying the uncertainty is to use a mixed effects model that takes into account variation between buildings and individual respondents. I ran a mixed effects logit model and calculated the probability of an acceptable vote at each sensation for 100 randomly chosen buildings. Figure 16 shows the interquartile range of these estimates. Because this shaded area is wider than the confidence interval in Figure 15, we can see that there is more variation between buildings and people than uncertainty in the estimates. This is because the sample size is so large.

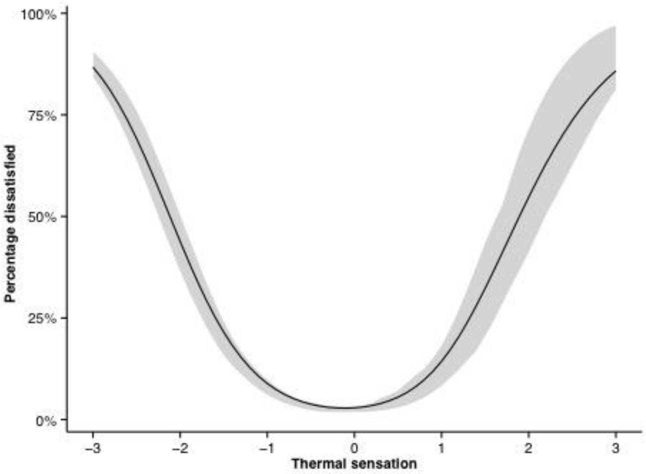


Figure 16 Dissatisfaction vs. thermal sensation using mixed logit model showing interquartile range of estimates

Statistical analysis

Acceptability is clearly related to sensation, but as explored above it may also be related to other parameters such as cooling strategy or climate. To test the relevance of these parameters statistically instead of visually, I built four different probit models to find the best one in terms of predictive power and parsimony. The base model uses sensation as the single predictor of acceptability. The second and third models add cooling strategy or prevailing outdoor temperature, and the fourth model includes all three predictors. In the multivariate models, I include additive as well as interactive terms. I use two standard performance measures for probabilistic models, the scaled Brier score and the difference in discrimination slope, to evaluate the performance of the models. Both measures are pseudo R^2 parameters which range from 0-1 and indicate the proportion of variance that is explained by the model. The scaled Brier score is a quadratic relation between Y_i, the actual outcomes, and p_i, the predicted probabilities as shown in Equation (5). The difference in discrimination slope is simply the difference in the mean predicted value for acceptable and unacceptable votes (Steyerberg et al., 2010).

$$\begin{aligned} Brier_{scaled} &= 1 - \frac{Brier}{Brier_{max}} \\ &= 1 - \frac{\frac{1}{n}\sum_{i=1}^{n} Y_i\,(1-p_i)^2 + (1-Y_i)p_i^2}{mean(p)(1-mean(p))} \end{aligned} \tag{5}$$

The performance measures for the four models are virtually identical (0.43-0.48), which indicates that adding the additional independent variables does not increase the predictive power of the model (Table 4, Figure 17). Therefore, to have the simplest adequate model, I consider sensation as the sole predictor of acceptability. This is statistical evidence supporting the conclusions from the visual exploration that cooling strategy and outdoor temperature do not change the relationship between sensation and acceptability very much.

Predictors	Brier score	Change in discrimination slope
Sensation	0.48	0.44
Sensation & cooling strategy	0.48	0.44
Sensation & prevailing outdoor temperature	0.46	0.43
Sensation, cooling strategy, & prevailing outdoor temperature	0.47	0.43

Table 4 Performance measures for probit models predicting acceptability

From Figure 17 it is clear that the model is much better at predicting acceptable votes than unacceptable ones: the mean probability of acceptability is about 0.9 for acceptable votes and 0.45 for unacceptable ones. In other words, true “acceptable” votes have an average predicted probability of being unacceptable of only 10% while true “unacceptable” votes have an average predicted probability of being acceptable of 45%.

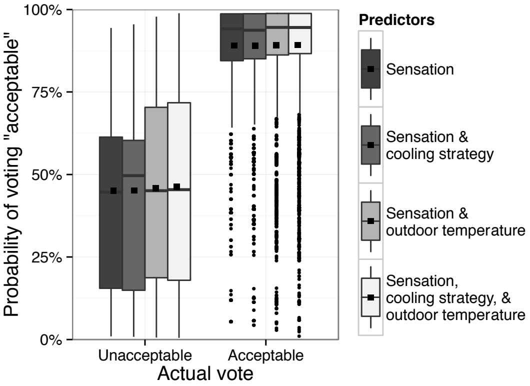


Figure 17 Predicted probabilities vs. actual acceptability votes for probit models
NOTE: square points indicate the mean of the sample

Using this probit model, I calculated the probability of voting “acceptable” based on thermal sensation for every observation. I call this “calculated acceptability”.

Alternate metrics

Several of the studies in the database asked people whether their environment was acceptable or how comfortable they were. Figure 18 shows the representative relationship—acceptability is the least stringent metric of satisfaction and preference is the most.

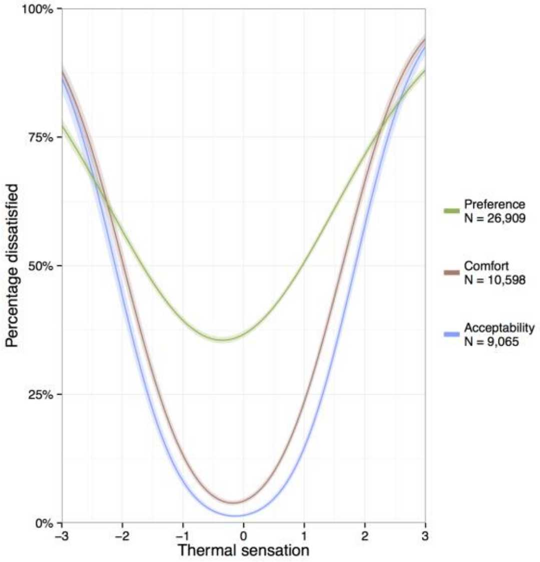


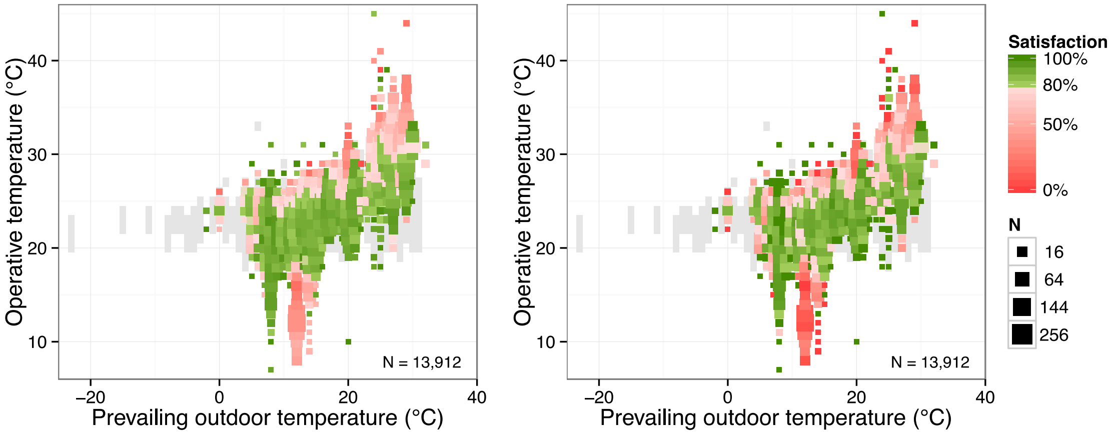
Figure 18 Comparison of satisfaction metrics

4.3.2 Interactive thermal comfort visualization tool, part II: visualization

Effects of cooling strategy

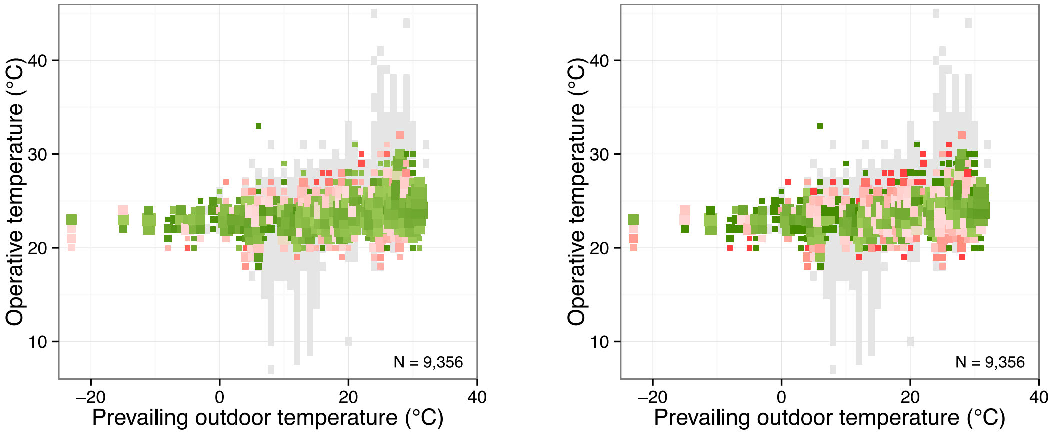
Figure 19 a&c show the 2D bin visualizations for NV and AC buildings using calculated acceptability as the satisfaction metric. The clearest difference between the two is, as you might expect, that there is more variation in indoor operative temperature for NV than AC buildings and that this variation depends strongly on prevailing outdoor temperature. Another big difference is the height of the green band indicating the zone of at least 80% acceptability. For NV buildings, the green area has a height of at least 8K, and since it is mostly unbounded by red on the bottom, the real comfort zone might be even taller. For AC buildings, by contrast, the green area is only about 6K at its tallest, and it is as narrow as 3-4K at low prevailing outdoor temperatures. Unlike for NV buildings, there is a red band on both sides of the green AC zone, although these bins represent many fewer votes than the green ones do (represented by the size of the points). This means that we can be more confident that the green area is comfortable than that the red area is uncomfortable.

Another big difference between the two comfort regions is that for AC buildings the comfortable zone is about 23-27°C regardless of the outdoor conditions, while in NV buildings it varies from 16-24°C during cooler conditions to up to 30°C during warmer conditions. These results are unsurprising given the previous analysis of RP-884 (de Dear and Brager, 1998). Another difference the visualization shows is that the ASHRAE 55 adaptive comfort zone could be continued to outdoor temperatures as low as 7°C. Beyond that we do not have any data.



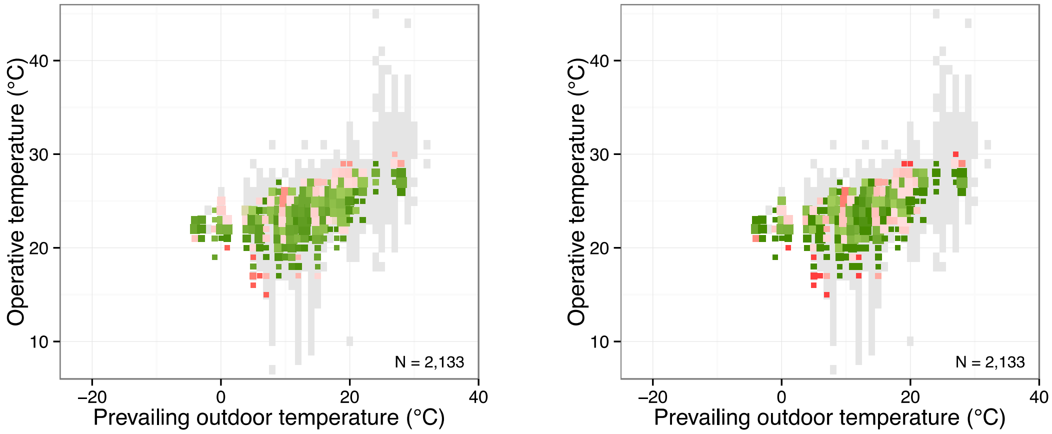
a. NV buildings—calculated acceptability

b. NV buildings—sensation ±1.5



c. AC buildings—calculated acceptability

d. AC buildings—sensation ±1.5



e. MM buildings—calculated acceptability

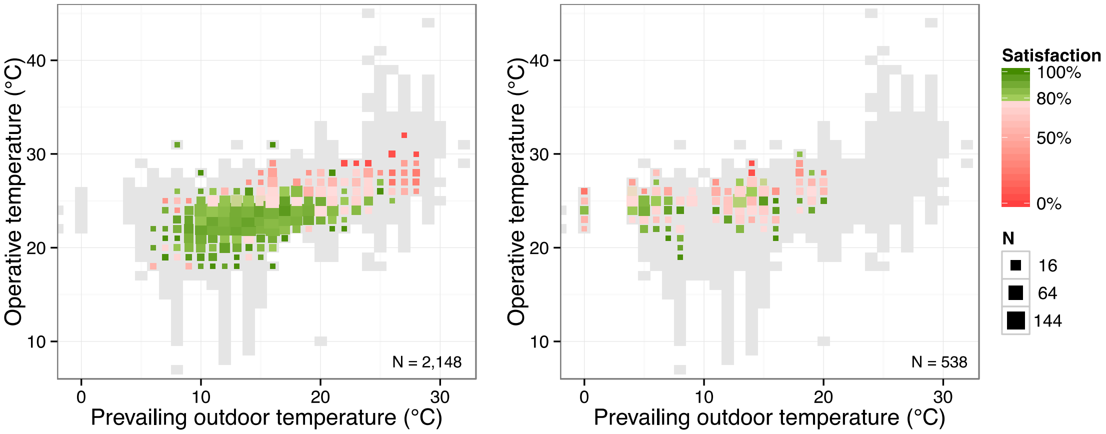
f. MM buildings—sensation ±1.5

Figure 19 Comparison of comfort zones for NV, AC, and MM buildings

Figure 19 b&d show the same visualizations but using a sensation range of ±1.5 to indicate satisfaction. Because the probit calculation tends to overestimate acceptability (Figure 17), it is interesting to compare the metrics. As expected, the sensation-based graphs indicate more dissatisfaction than the ones based on calculated acceptability. However for NV buildings, this has essentially no impact on which regions are green and which are red; the change is almost entirely in the darkening of the red. For AC buildings a surprisingly large area of the comfort zone based on calculated acceptability is uncomfortable when sensation is used as the metric instead; in some areas the color distribution is more like patchwork than distinct regions. The differences are visible at both the upper and lower limits of the comfort zone, but it is surprising that the upper limit for outdoor temperatures around 30°C is among the least well defined areas. Taken together, these four graphs clearly indicate that occupants of NV buildings are more accepting of wider indoor conditions that those of AC buildings.

From the limited data that is available from MM buildings, the comfort zone looks more similar to the NV than the AC zone (Figure 19 e&f). The comfort deadband is about 6-8K instead of 4-5K for AC buildings and extends to 28-29°C in warm conditions. However, not only is the overall sample size much smaller than for the other cooling strategies, the range of operative temperature sampled is narrow enough that neither edge of the comfort zone is well defined.

It is important to remember that the results shown in Figure 19 are overall trends and that they may vary drastically in individual buildings. As an example of this, Figure 20 shows the results for a building in Berkeley and six buildings in London. In both cases, there are conditions that are squarely within the general comfort zone for NV buildings but distinctly outside of it for these subsets. The 80% satisfaction goal was not met in Berkeley for prevailing outdoor temperatures above 22°C or in London for almost any conditions.



a. Berkeley

b. London

Figure 20 Comparison of NV buildings in Berkeley and London to overall trend (calculated acceptability)

Effects of climate zone

The comparison of the buildings in Berkeley and London raises the question of whether those differences can be accounted for by climate zone. I used the classification system developed at Macquarie University, show in Figure 21, and used for RP-884 (de Dear et al., 1997; Macquarie University Department of Geography, 2002). Figure 22 shows the visualizations of calculated acceptability for NV buildings in climate zones that have results for at least four prevailing outdoor temperatures. The results for hot arid and Mediterranean climates (a&b) are very similar for the regions where they both have data. The responses in the west coast marine climates (c) are predominantly dissatisfied and do not show a clear pattern. The dark green streak at 15°C prevailing outdoor temperature is entirely from the three buildings in Oxford, so it seems that the other 10 buildings, 9 of which are also in the UK, were not providing thermal comfort for their occupants.

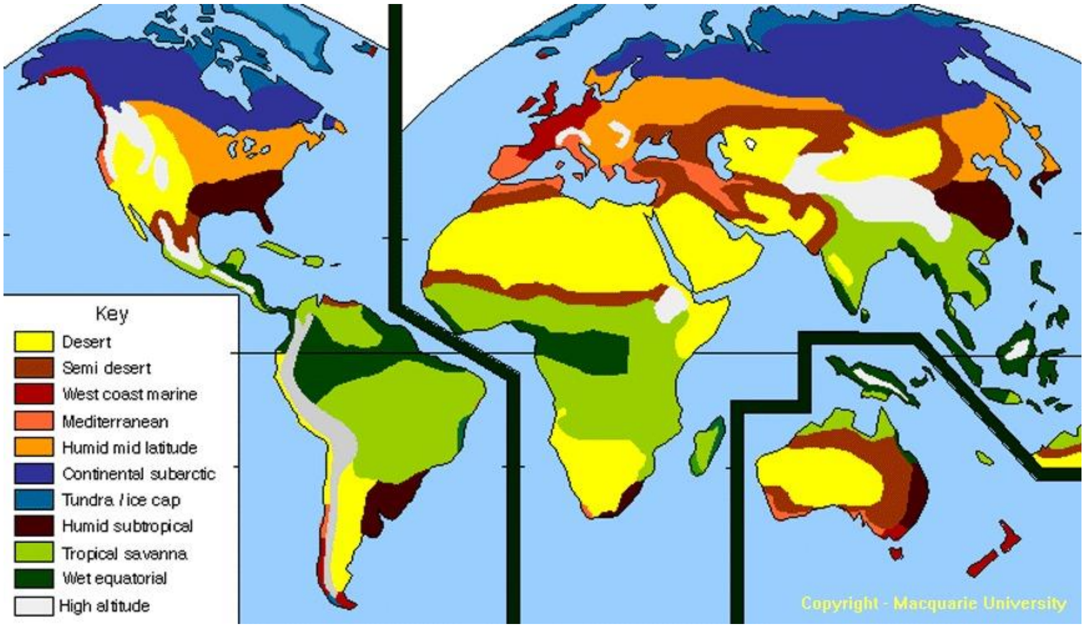
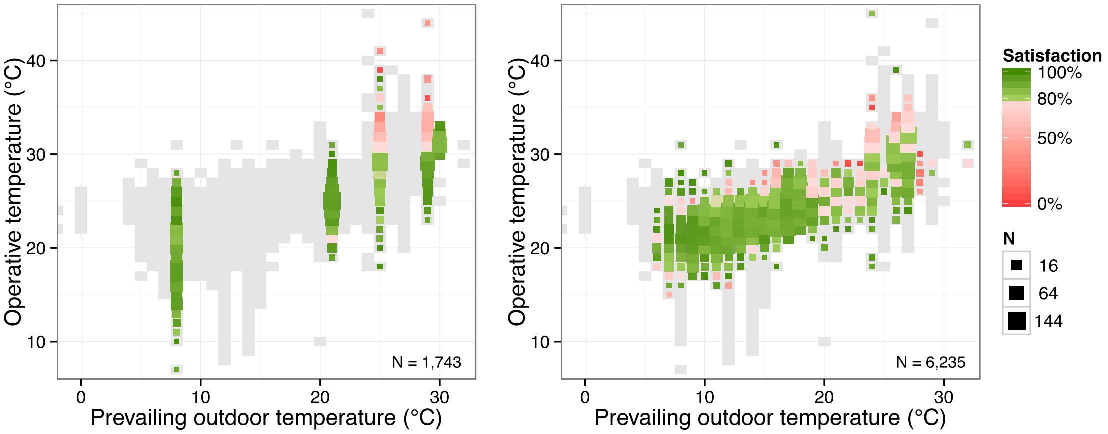
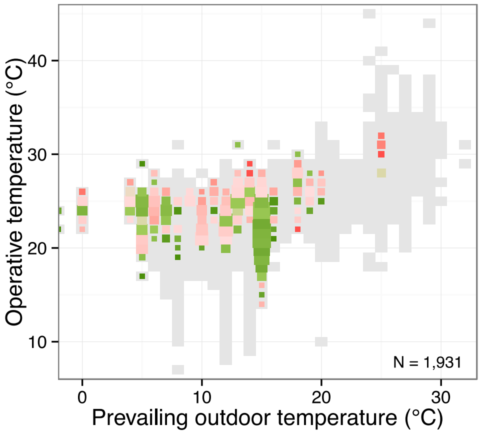


Figure 21 Climate zone classification



a. Hot arid

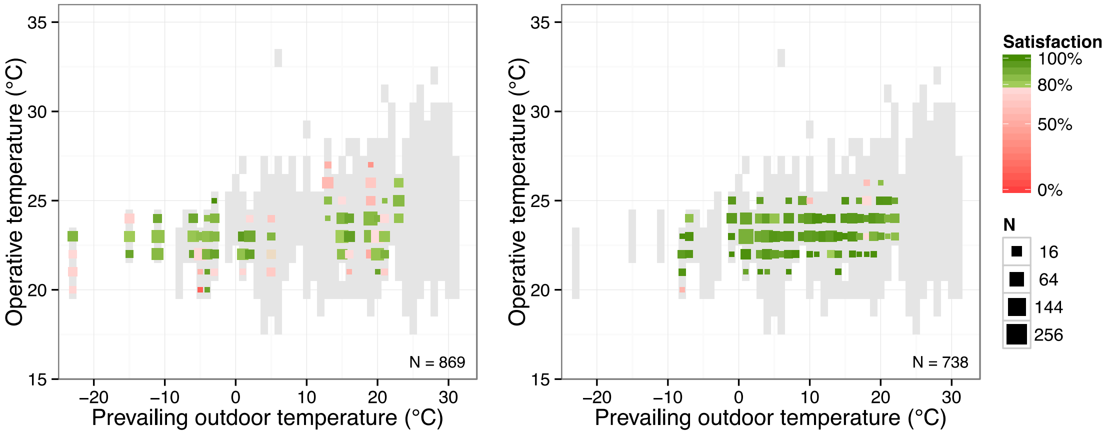
b. Mediterranean



c. West coast marine

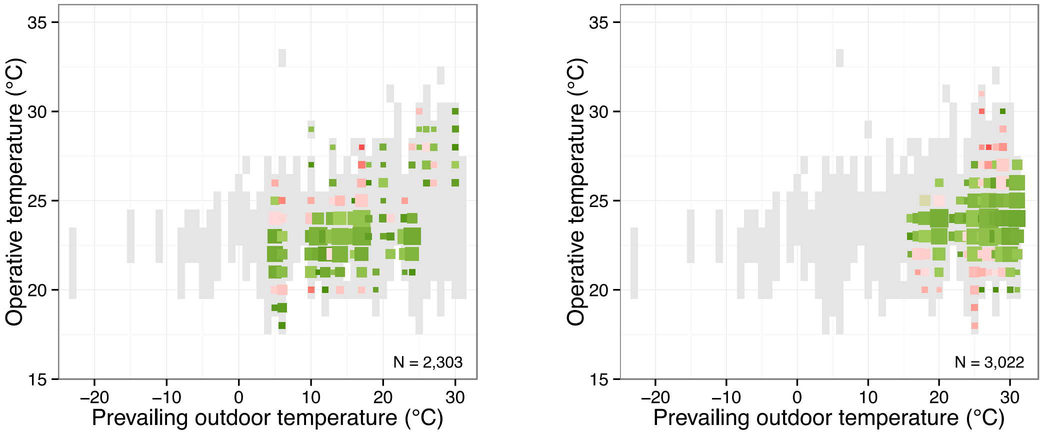
Figure 22 NV buildings by climate zone (calculated acceptability)

For AC buildings, the areas of at least 80% satisfaction are very similar in all of the climate zones except for west coast marine (Figure 23). All of the responses except 18 are from the UK, so it seems that the British are very particular about their thermal environments or they have poorly performing buildings.



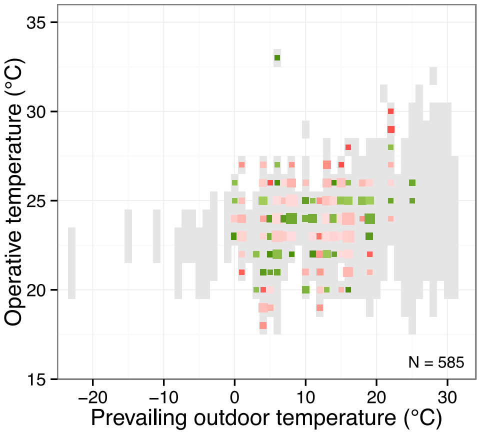
a. Continental subarctic

b. Humid mid latitude



c. Mediterranean

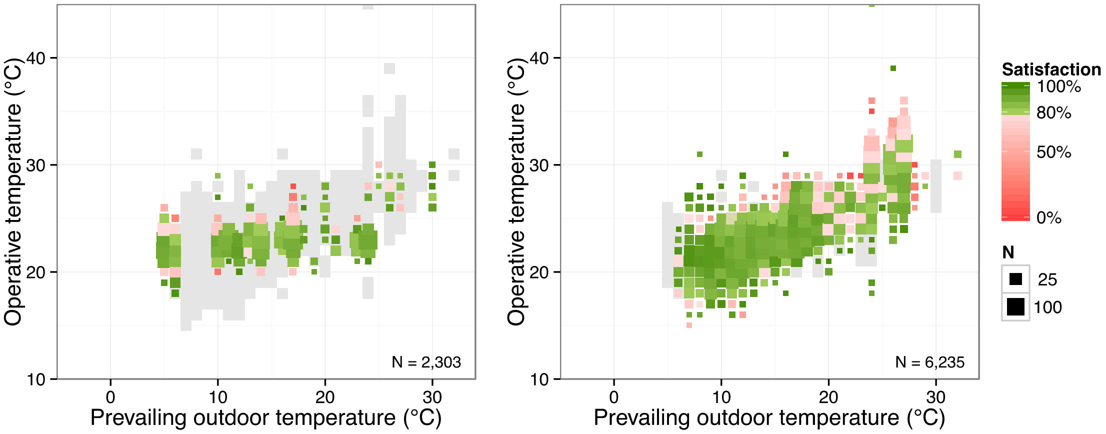
d. Tropical savannah



e. West coast marine

Figure 23 AC buildings by climate zone (calculated acceptability)

Except for west coast marine, which does not seem to have a comfort zone, I only have enough data from Mediterranean climates to compare building type within a single climate. For the most part, the AC buildings did not get to high enough indoor temperatures to cause discomfort, but the uncomfortable combinations were found to be comfortable in the NV buildings (Figure 24).



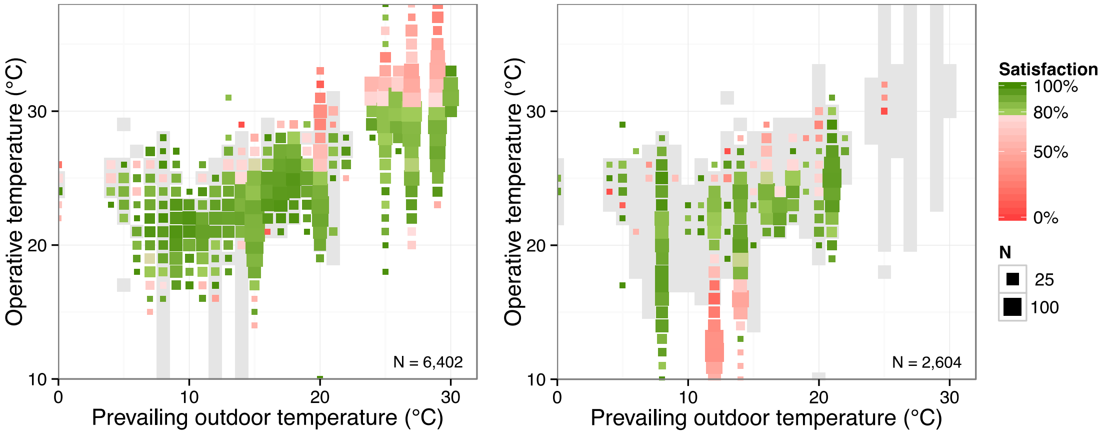
a. Mediterranean—AC

b. Mediterranean—NV

Figure 24 AC vs. NV buildings in Mediterranean climates (calculated acceptability)

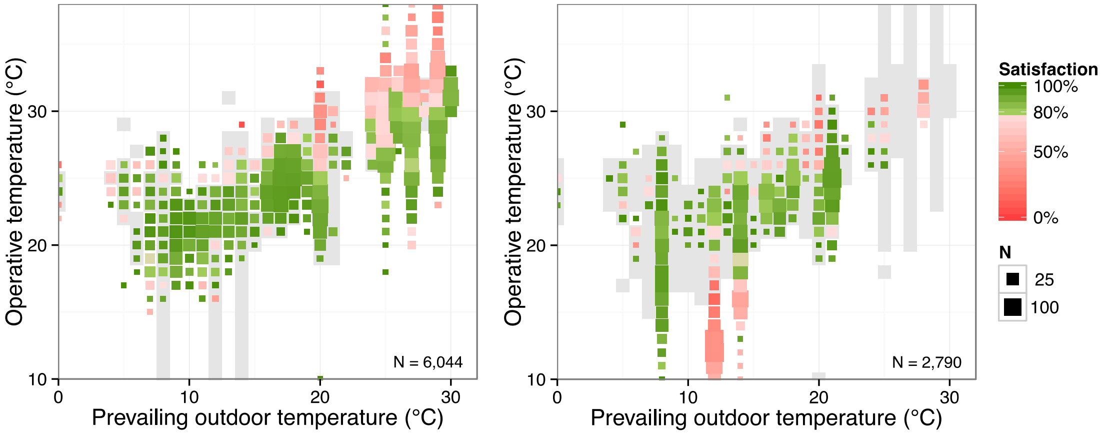
Effects of personal control

In NV buildings, the main concern is about how to keep people comfortable during hot weather when the indoor temperature rises. The adaptive hypothesis suggests that giving people access to controls will help. Figure 25 shows the comfort results in NV buildings for people with and without access to controls that allow them to cool themselves or their workspace. The main differences are related to the conditions under which the surveys were taken. For windows and fans (a-d), there are very few observations from people without control at high outdoor and indoor temperatures. In all the figures (a-h), there are slightly more red and slightly fewer green squares for operative temperatures in the range of 25-28°C. However, these differences are not large enough to provide convincing evidence that the controls and non-controls groups are responding differently.



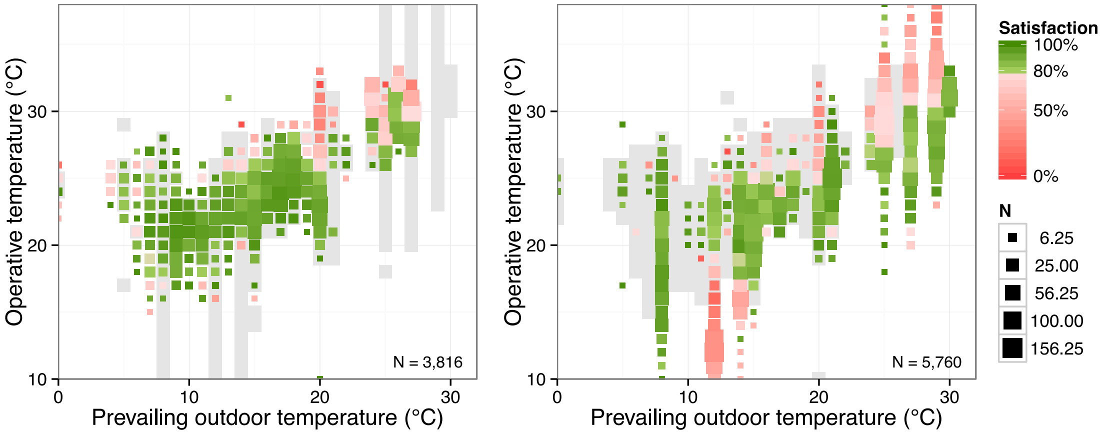
a. Access to window

b. No access to window



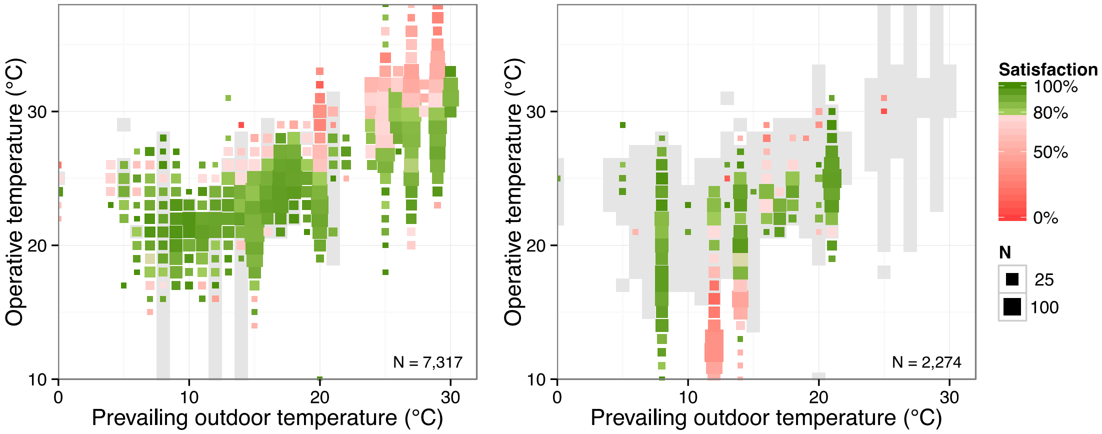
c. Access to local fan

d. No access to local fan



e. Access to curtains/blinds

f. No access to curtains/blinds

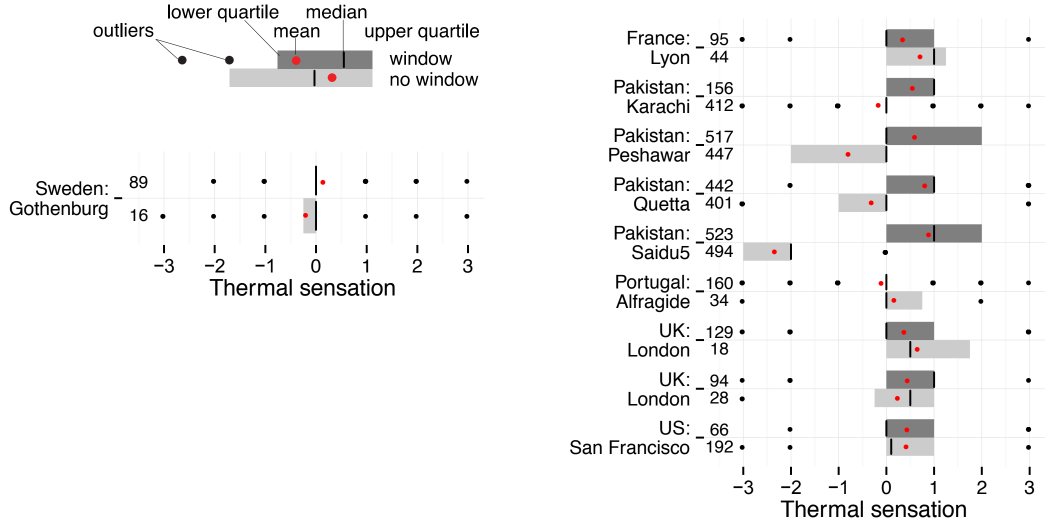


g. Access to window, fan, or curtains/blinds

h. No access to window, fan, or curtains/blinds

Figure 25 Effects of personal controls in NV buildings

Another way of looking at the control question is to compare the thermal sensation of people who do and don't have access to a control in the same building. Figure 26 shows the mean and median thermal sensations of people with and without access to a window. Only those buildings in which there are at least ten people in the window and no window groups are shown. Because of the large sample sizes, virtually all of the differences are statistically significant, but they are negligibly small except for two buildings in Pakistan. In those two Pakistani buildings, the people with access to windows have higher thermal sensations than those who do not. This is exactly the opposite of what I expected, particularly in such hot climates as the ones in Pakistan. But if the building has thermal mass and is generally cooler inside than out, someone who opens the window in the hottest part of the day might feel hotter. Equivalent graphs for curtains/blinds and local fans show similarly small differences in thermal sensations between the control and no control groups (Appendix C).

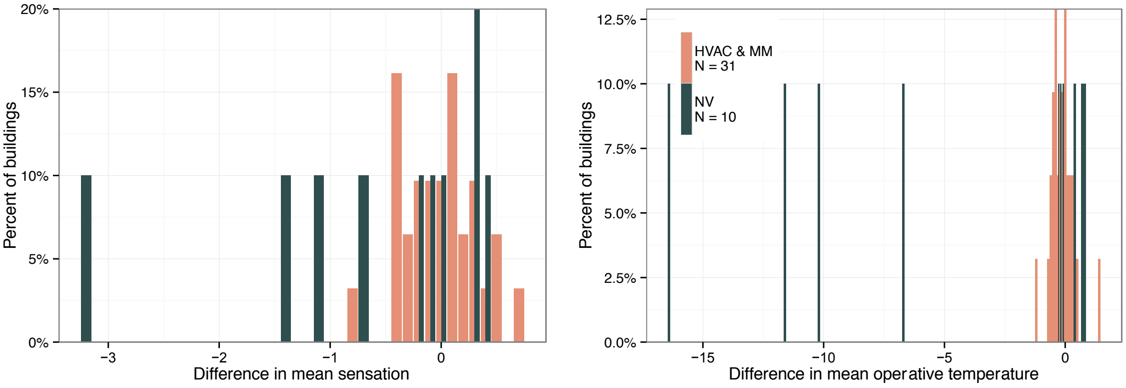


a. MM buildings b. NV buildings

Figure 26 Effect of window controls on thermal sensation by building
NOTE: Only buildings with at least 10 votes from people with and people without windows are shown

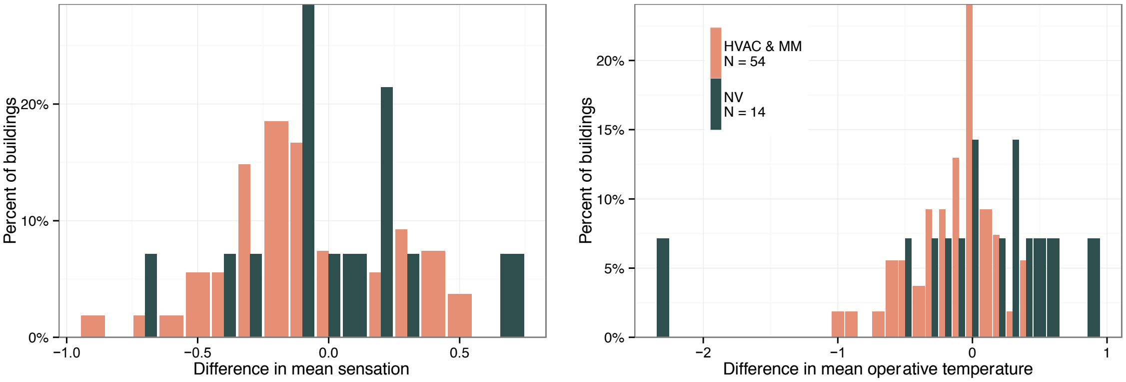
To investigate whether these differences in sensation might be due to differences temperature, I made histograms of the mean sensation and operative temperature differences for the people with and without control in the same building. Positive differences indicate that the group without controls has higher sensation or temperature. Figure 27 shows that mean differences in sensation and temperature are more or less normally distributed around zero except for a couple of outliers in the window and fan cases. In these groups there are four NV buildings in which the people with access to windows and fans experience consistently higher temperatures and therefore report higher thermal sensations. Perhaps in these cases the people with windows and fans are in sunlit perimeter zones that are hotter than thermally massive building interiors. I do not have the data to test this, though.

This analysis shows that having access to a window, fan, or curtain does not have a systematic influence on the conditions that are comfortable or the sensation reported.



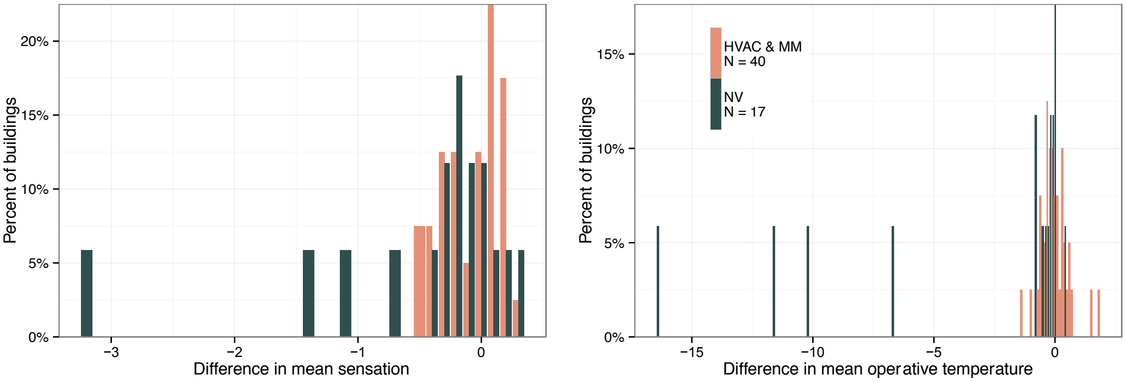
a. Sensation with and without windows

b. Operative temperature with and without windows



c. Sensation with and without curtains/blinds

d. Operative temperature with and without curtains/blinds



e. Sensation with and without local fans

f. Operative temperature with and without local fans

Figure 27 Differences in mean sensation and operative temperature between control and no control groups in the same building

NOTE: Only buildings with at least ten observations for each group are shown. Positive values indicate that the “no control” values are higher.

4.3.3 Predicting thermal sensation

My original goal was to predict the probability of acceptance (“calculated acceptability”) directly from physical parameters such as indoor and outdoor temperature, cooling strategy, air movement, etc. However I was unable to find a linear model that did not seriously violate the model assumptions of randomly and normally distributed residuals. So I developed a model for thermal sensation instead.

I modeled thermal sensation using a linear mixed model with respondent nested within building as the random effects. Table 5 shows the standard deviation of the residuals for models using all of the buildings, only NV buildings, and only AC buildings. In models with multiple predictors I considered interactions between each subsequent predictor and operative temperature. For example, the form of model 2 is

$$sensation = b_0 + b_1 * Top + b_2 * Tprev + b_3 * Top * Tprev \qquad (6)$$

As expected, including the respondent in the random effects substantially reduces the standard deviation of the residuals because there are many more degrees of freedom. Otherwise, there is remarkably little difference in the success of the model as new predictors are added.

Interestingly, thermal sensation can be more accurately predicted in NV than AC buildings simply based on operative temperature (0.76 vs. 0.81). This is likely to be related to the clearer pattern shown in the visualizations for NV than AC buildings (Figure 19 a&b vs. c&d). However, the accuracy of the AC predictions can be improved to a similar level by including prevailing outdoor temperature, metabolic rate, relative humidity, and air velocity in the model. It is not clear which supplementary parameters have the most effect since none of them individually substantially reduce the standard deviation of the residuals (Table 5). This the opposite of what I expected based on the adaptive model.

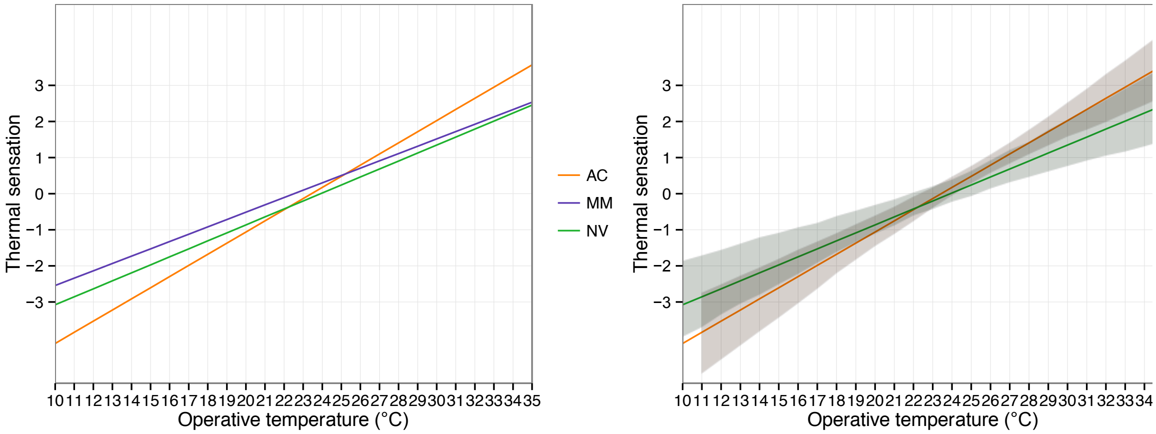
Although PMV is a more comprehensive index that includes more than just temperature, it has similar or less predictive power for thermal sensation than operative temperature does by itself. In particular, for NV buildings PMV has a higher standard deviation of the residuals (0.81) than operative temperature (0.76) (Table 5).

Model	**Fixed effects**	**All buildings**	**NV**	**AC**	**MM**
1	Top*	0.93	0.91	0.97	
2	Top	0.78	0.76	0.81	0.85
3	Top, Tprev	0.77	0.76	0.87*	
4	Top, cs	0.78			
5	Top, RH	0.78	0.75	0.81	
6	Top, vel	0.78	0.75	0.79	
7	Top, met	0.78	0.76	0.80	
8	Top, clo	0.78	0.76	0.81	
9	Top, met, RH, vel, clo, cs	0.76			
10	Top, met, RH, vel, clo	0.78	0.75	0.79	
11	Top, Tprev, met, RH, vel, clo	0.77	0.75	0.76	
12	PMV	0.81	0.81	0.80	

Table 5 Standard deviation of residuals for linear mixed models using respondent nested in buildings for the random effects
NOTE: Top=operative temperature; Tprev=prevailing outdoor temperature; cs=cooling strategy; vel=average air speed; * only the building (and not the respondent) was used for the random effects

Figure 28a shows the results of predicting thermal sensation only with temperature (model 2) for AC, MM, and NV buildings. As expected, the slope is slightly higher for AC buildings, indicating the occupants are more sensitive to changes in temperature than they are in NV and MM buildings. Nevertheless, at 0.27 scale units per K, it is only about half of 0.5 scale units per K, the value that McCartney and Nicol (2002) used for the SCATs project.

Figure 28b gives an indication of the variations from person to person and building to building. I took a random sample of 10,000 respondents and calculated their predicted sensation at each temperature. The shaded region shows the interquartile range of these estimates with the solid line being the mean. From this we can see that there is very little difference in the temperatures that have neutral predicted sensations and that there is substantial overlap even at more extreme temperatures.



a. Comparison of AC, MM, NV

b. Interquartile range of estimates

Figure 28 Sensation predicted by operative temperature using building and respondent as random effects

4.4 Discussion

4.4.1 Methods

My method of visualizing the comfort zone by calculating the percentage of satisfied votes for combinations of indoor and outdoor temperature has both advantages and disadvantages. The best thing about it is that the raw data is translated very directly to the desired information of satisfaction percentage in areas of indoor-outdoor temperature space. This means that we can include data that does not produce a statistically significant regression or we can look at all data without making assumptions about the relationship between thermal sensation and indoor temperature (de Dear and Brager, 1998; McCartney and Nicol, 2002). Although there is still some uncertainty about how best to define satisfaction, I improve on previous methods by using acceptability or calculated acceptability as the metric instead of an assumed range of sensation.

Another advantage of this method is that the visualization technique can be used for small datasets. When no statistical analysis is performed, whatever data is available can be displayed without making assumptions about areas around it where there are no observations. This means that researchers and practitioners can quickly look at and compare subsets of the overall data. While the adaptive model accounts for climatic differences by including outdoor temperature (daily, monthly, running mean), it does not differentiate between cultures, building types, the kinds of adaptive opportunities are available, etc. Using this tool, it is possible to consider only those studies that are most relevant to the project of interest. This is a particular advantage for mixed mode (MM) buildings because there are not very many studies that have been conducted in them.

A significant disadvantage of this method is that it does not give a well defined comfort zone, which makes it less useful for standards and quantitative analysis. The interactive tool allows users to filter the dataset and get immediate results and display only the information that is relevant to a particular project. Because this information might be limited and depend on a small sample size that does not allow valid statistical analysis, the fact that this tool is primarily for visualization is an advantage.

Unlike the visualization method, the linear mixed models account for the repeated measurements within buildings and from the same occupants. They can give a well-defined comfort zone but require that some range of sensation be considered comfortable. The probits that relate sensation to acceptability are only of limited use for this question because they consider individual instead of average sensation votes. If 80% of people find a sensation of -1.5 to be acceptable, what percentage of people will find the conditions to be acceptable when the average sensation is -1.5? At what average sensation will 80% of people find the conditions to be acceptable? This is likely to be closer to neutral than ±1.5 because the slope of the curve relating dissatisfaction and sensation is steeper at more extreme sensations (Figure 15). So for the following analysis, I will assume that 80% of people are satisfied at an average thermal sensation of ±1.

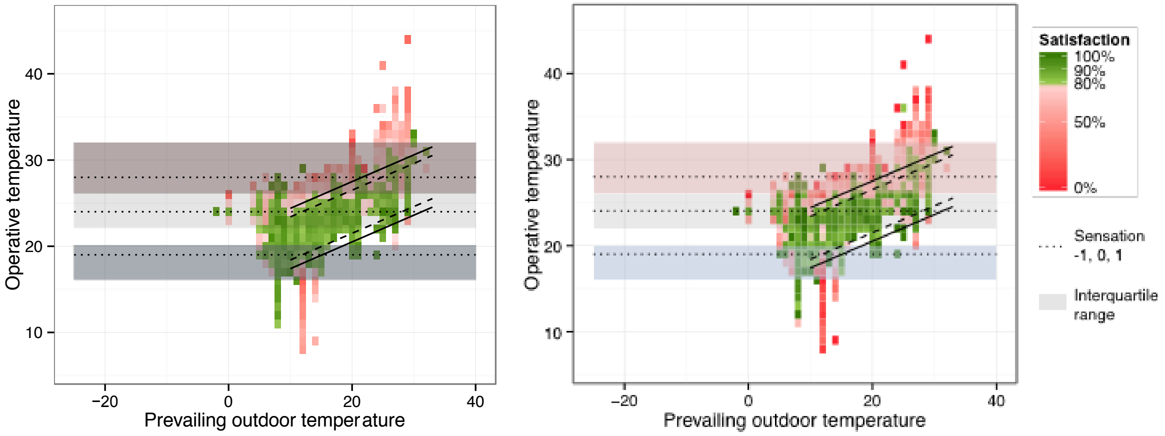
4.4.2 Results

The results from the visualization and the linear mixed model are very different (Figure 29). For NV buildings, the 2D bin visualization shows a strong dependence on outdoor conditions with comfortable operative temperatures ranging from 16-24°C (8K deadband) during cooler conditions to up to 30°C during warmer conditions. The linear mixed model does not indicate any dependence of thermal sensation on prevailing outdoor temperature—the mean neutral temperature is 24°C regardless of the outdoor conditions. Using the mean predicted temperatures, the distance from sensation -1 to +1 is 9K. Considering the variation between individual people and individual buildings, the neutral temperature by itself varies from 22-26°C, and the deadband expands to 16K. Because the neutral temperature from the regression is independent of the outdoor conditions, it is in the middle of the range of operable temperatures spanned by green but on the upper and lower edges depending on the outdoor conditions for NV buildings.

In AC buildings, the visualization shows that operative temperature should be 23-27°C (4K deadband) regardless of the outdoor conditions. The regression model shows a constant but slightly lower neutral temperature of 22-24°C but with a 7K deadband between mean sensations of ±1. With the variation between people and buildings, the deadband widens to 9K.

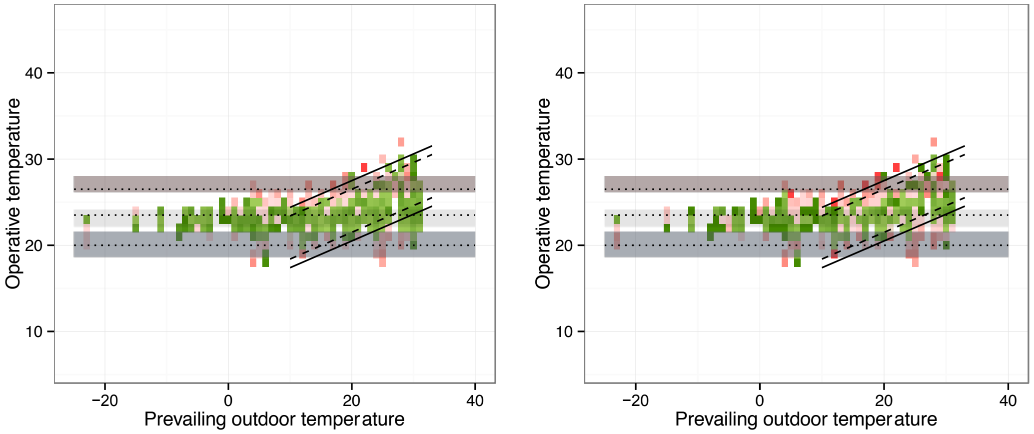
In terms of method, the linear mixed models are more similar to the analysis performed by de Dear and Brager (1998) than the visualization because they are both based on linear regression and the assumption that the neutral temperature equals the comfort temperature. However, the results from the visualization are more similar to their results for NV buildings. Perhaps this is related to the operative temperature not being low enough to induce discomfort and therefore leaving a gap at low operative and high prevailing outdoor temperature. The 2D bin visualization shows this gap in the data very clearly. For NV buildings, the upper bound of the comfort zone is clearly demarcated by a strip of red above the green comfortable area, whereas the lower bound is undefined except for votes from Pakistan at prevailing outdoor temperatures between 14-16°C (Figure 19).

Although the details of the comfort zones are very different based on the visualization and the regression analysis, the conclusion that a wider range of temperatures are comfortable in NV than AC buildings is the same. The zones that are too hot according to the visualization but comfortable according to the regression model might be due to the fact that overall the votes were mostly 84% "acceptable," 44% neutral, and 80% between -1 and +1. In other words, the moderate votes might be overwhelming the extreme ones when considered as a whole instead of bin by bin.



a. NV buildings calculated acceptability

b. NV buildings sensation ±1.5



c. AC buildings calculated acceptability

d. AC buildings sensation ±1.5

Figure 29 Comparison of visualization, linear mixed models, and ASHRAE 55 comfort zones

It is surprising that adding addition predictors to the linear models did not help them better predict sensation. This could be because these parameters, for example relative humidity, are not good predictors of sensation or because the relationship between the two is not linear and instead more complex. Simple one or two predictor plots did not reveal clear relationships, but if they are as complicated as those in the PMV equation, then they would be hard to spot using these methods.

While there are substantial differences between the conditions that lead to thermal comfort in NV and AC buildings, they are not at the level of which sensations are acceptable. The probits do not show a significant difference in the likelihood of a sensation being acceptable to occupants of AC and NV buildings (Table 4). Occupants are not consciously or subconsciously accepting sensations that they would otherwise find acceptable because they like being able to open their window, for example. Instead, the difference is in the sensations that the conditions evoke.

Simple access to personal controls did not have a meaningful impact on the respondents' thermal sensations or the conditions that they found comfortable (Figure 26, Figure 25). Paciuk (1990) and Langevin (2012) found that perceived control had a bigger impact on comfort than available control, so perhaps this result is an indication of this difference.

5 Overall thermal satisfaction

The goal of this part of the analysis is to investigate whether access to personal controls such as windows or fans predict thermal satisfaction over and above differences between individual buildings.

5.1 Database description

5.1.1 Data collection methods

As discussed in section 2.3, the Center for the Built Environment (CBE) administers an online survey that asks about occupants' satisfaction in nine areas of indoor environmental quality (IEQ) including thermal comfort, light, indoor air quality, acoustics, and noise. When occupants are dissatisfied with an element of the environmental quality of their workplace, they see additional questions to probe the reasons for their dissatisfaction. The occupants also answer background questions including their type of workspace and which types of personal controls they have access to. The building manager reports on the general building characteristics such as its floor area, date of last renovation, and cooling strategy.

I consider three mixed-mode buildings as case studies. The surveys in these buildings were extended to gather further information about occupants' interactions with and perceptions of windows and ceiling fans. These additional questions fit into three general categories: satisfaction with IEQ and ability to control IEQ, reasons for and patterns of using windows and fans, and satisfaction with the windows and fans. The questions that are used in this analysis from both the core and expanded survey are listed in Appendix A.

5.1.2 Description of case study buildings

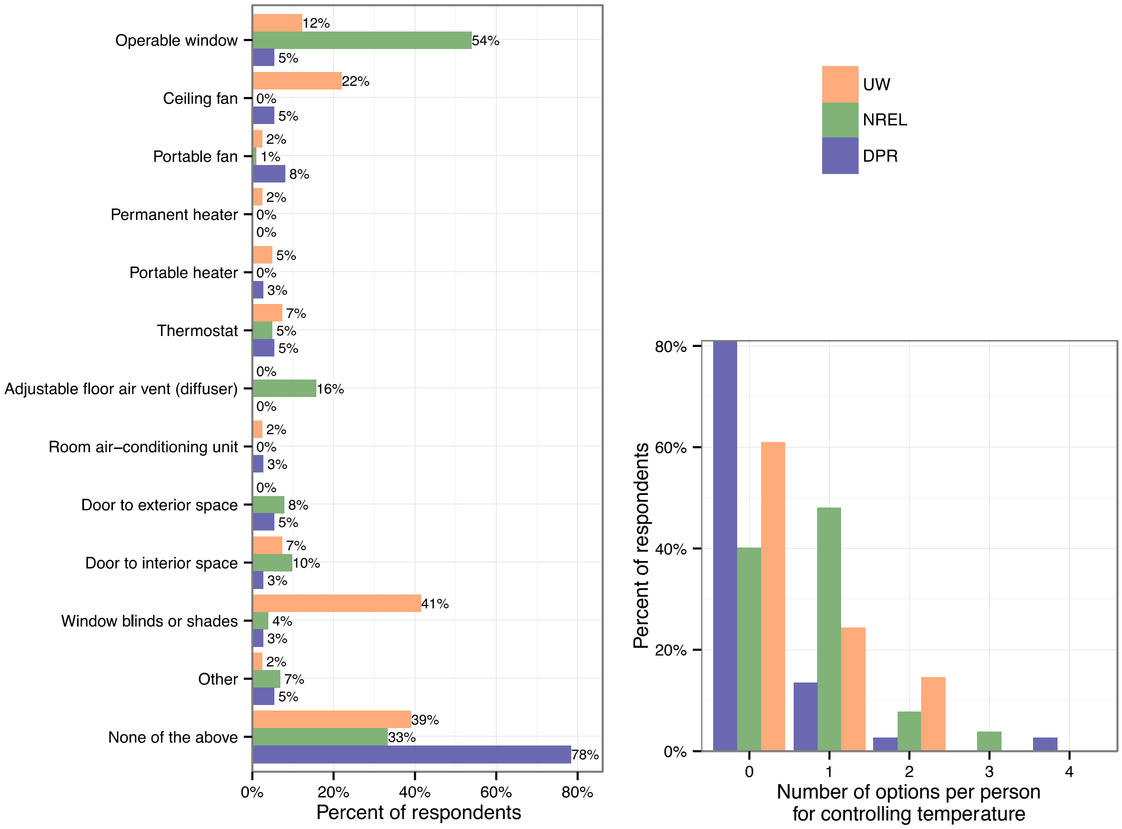
The three case study buildings are all mixed mode and have operable windows. The Phoenix office of DPR Construction is in a net zero energy office building and has ceiling fans in addition to operable windows. The set point for the mechanical cooling is 27°C. 37 out of the 45 employees surveyed in the office (82%) answered the survey.

The Molecular Engineering and Sciences Building at the University of Washington (UW) is a LEED Gold building with both offices and laboratories. It has ceiling fans in addition to operable windows and is operated with temperature set points of 20–22°C in the offices and 20-21°C in the laboratories (Clark, 2014). The upper windows are automatically controlled while the lower ones are manually controlled by the occupants (ZGF Architects LLP,). 41 of the 118 occupants surveyed (34%) answered the survey.

The Research Support Facility (RSF) at the National Renewable Energy Lab (NREL) is LEED Platinum office building. Its relatively narrow floor plate (60' wide) allows all workstations to be located within 30’ of a window. Slightly more than half of the windows are manually operated, and the rest are fully automated. When required, the building is mechanically cooled with radiant and evaporative cooling. The CBE survey was administered twice in this building as part of a project investigating and implementing a change in control logic. 62 out of the 104 (60%) occupants surveyed answered the pre survey. Only 40 occupants (38%) answered the post survey. The results of both surveys are included in this analysis (Tanner, 2014; Tanner et al., 2014).

Access to personal controls

Access to personal control varied widely between the three buildings. Almost 80% of the respondents in the DPR building said that they do not have access to any controls, while only 33% and 39% were in a similar position in NREL and UW. Overall, 54% of the respondents from NREL had access to operable windows, which is unsurprising given the narrow floorplate. In both UW and DPR, less than half of the respondents (20% and 40%) had access to controls that affect temperature (i.e. windows, fans, heaters, air conditioning, thermostats, diffusers). In NREL, about half of the respondents had access to one temperature control, usually a window (Figure 30).



a. Types of controls

b. Controls per person

Figure 30 Personal controls available by building

5.2 Analysis methods

I use this dataset from the CBE general survey to investigate the effects that access to personal controls has on (1) satisfaction with thermal comfort parameters and (2) the reasons for dissatisfaction. For the first one, I use simple linear regression analysis to find which parameters are related as well as boxplots to visualize the results. In particular, it is useful to see whether statistical differences translate into non-negligible differences.

For the second part, I only use graphical analysis because the sample sizes are too small to perform useful statistics. I consider the differences between buildings as well as the differences for distinct groups within the same building.

5.3 Results

5.3.1 Satisfaction responses

In the NREL, UW, and DPR buildings, there were a total of 180 responses; 57% of them came from one of the two NREL surveys. Although all three buildings are at or above the 70th percentile for thermal comfort in the CBE database, only in the NREL post survey was 80% satisfaction achieved. However, all of the participants were satisfied with their building overall (Table 6, Figure 31).

	NREL—pre	NREL—post	UW	DPR
Number of responses (rate)	62	40	41 (35%)	37 (82%)
Temperature satisfaction: mean vote (% satisfied[3])	0.95 (75%)	1.18 (85%)	0.38 (55%)	0.97 (70%)
Overall satisfaction: mean vote (% satisfied)	NA	2.45 (100%)	2.03 (100%)	2.19 (100%)

Table 6 Basic survey results for NREL, UW, and DPR

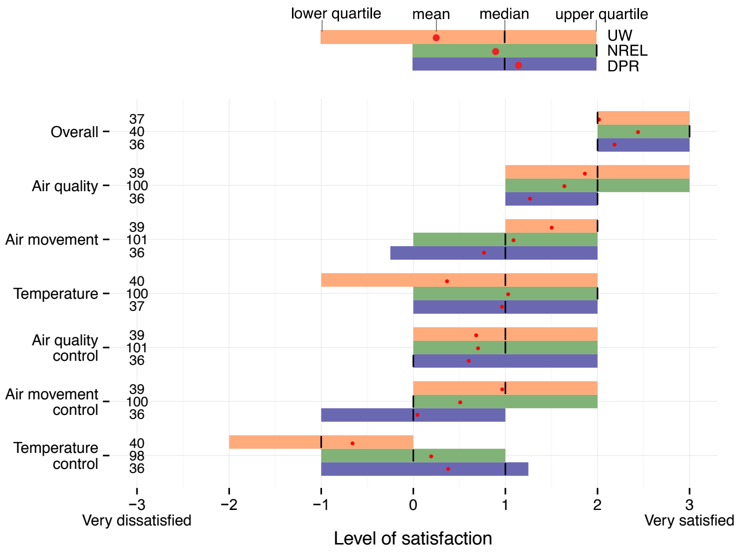


Figure 31 Satisfaction levels by building

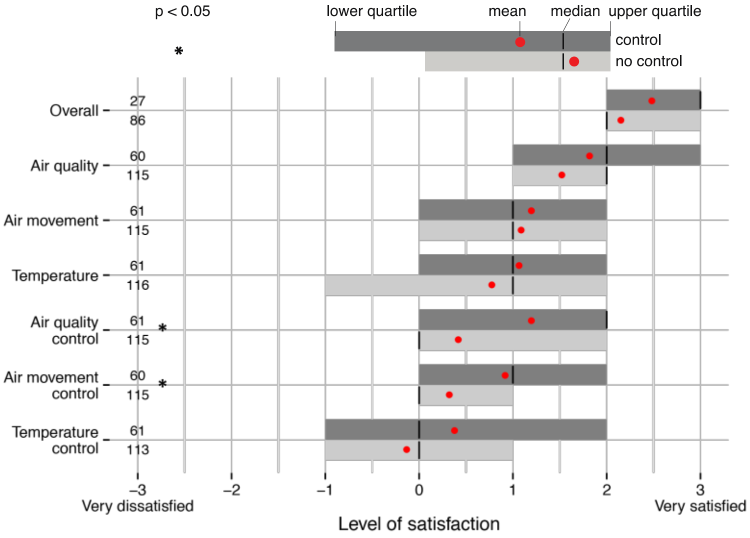
Satisfaction for people with and without access to personal controls is not appreciably different in these buildings (Figure 32). Even people who have no personal controls whatsoever have comparable levels of satisfaction with thermal

---

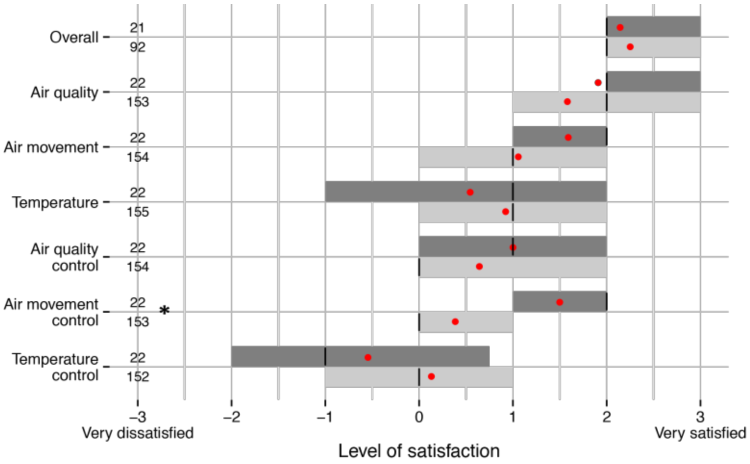
[3] This includes "neutral" votes.

comfort parameters as those who do (c). The biggest difference in mean satisfaction scores based on the availability of controls is for air movement satisfaction and curtains/blinds (b). However, this is more related to the controls that are available in each building than to the effects of the curtains/blinds. Almost all the respondents who have access to curtains/blinds happen to be at UW, which, as described below, is where there were the most complaints about air movement (Figure 30, Figure 29).

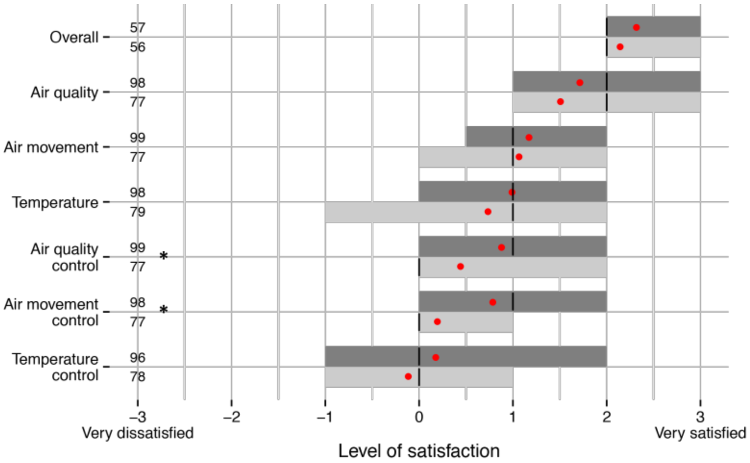
Surprisingly, having a private office vs. a cubicle with low partitions also doesn't appreciably affect satisfaction with the thermal comfort parameters or with the building overall (e).



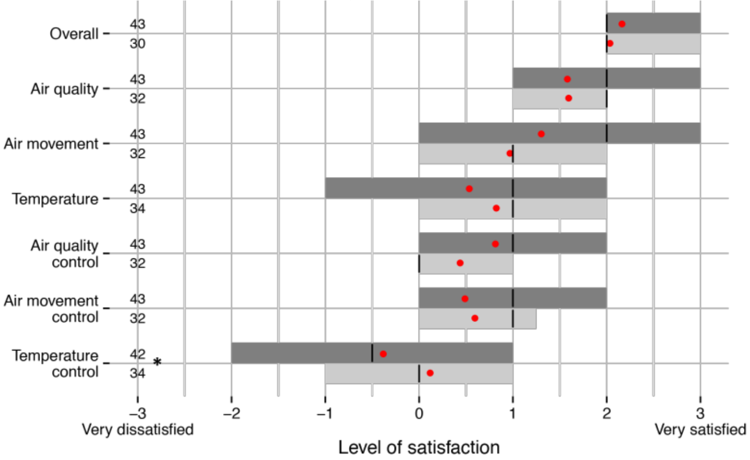
a. Windows



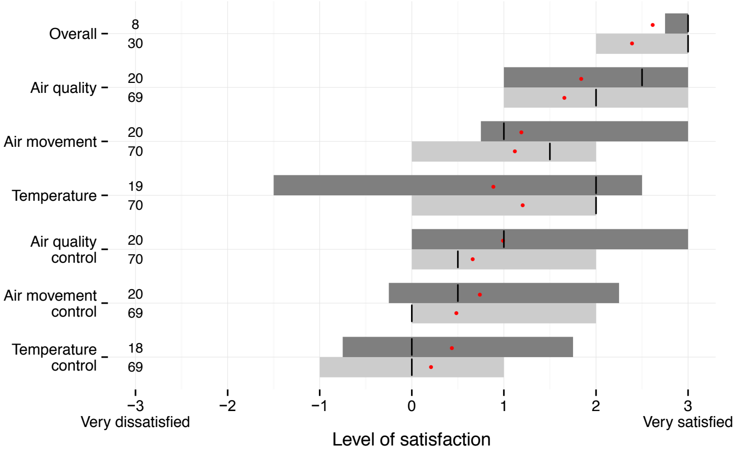
b. Blinds or curtains



c. Any control



d. Consider thermal comfort when dressing (DPR & UW only)

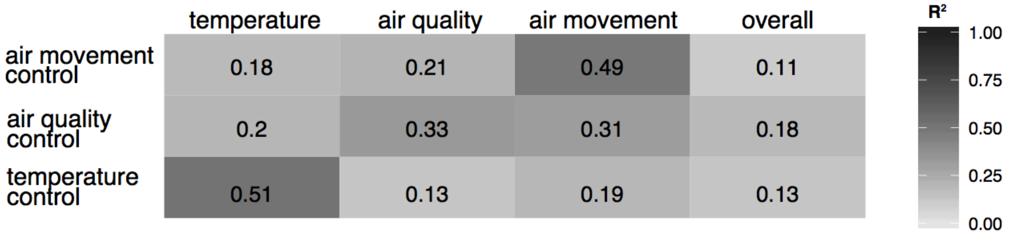


e. Private office vs. cubicle with low partitions (NREL only)

Figure 32 Satisfaction levels based on access to controls

Access to personal controls does not correlate with temperature, air movement, air quality, or overall satisfaction regardless of whether the controls are considered one by one or as a group, or whether the buildings are taken together or individually.

However, satisfaction with the ability to control the three thermal comfort parameters is correlated with satisfaction with those parameters. For example, satisfaction with the ability to control temperature and satisfaction with temperature itself are well correlated (R^2=0.51). The relationship is particularly strong with air movement and temperature (Table 7). Interestingly, satisfaction with the ability to control one parameter is correlated with satisfaction with all of the thermal parameters, not just the one that is being controlled.



	temperature	air quality	air movement	overall
air movement control	0.18	0.21	0.49	0.11
air quality control	0.2	0.33	0.31	0.18
temperature control	0.51	0.13	0.19	0.13

Table 7 Squared correlations between satisfaction with thermal parameters and the ability to control them

Surprisingly, control satisfaction is not correlated with access to personal controls or the restrictiveness of the dress code. The only measured parameter that it is correlated with is the confidence that adjusting a window will have the desired effect. Closing confidence is correlated with satisfaction with all three types of control (R^2=0.21-0.27), but opening confidence is only correlated with temperature control satisfaction (R^2=0.13). While interesting, these results should be treated with caution because only 40% of the respondents answered the questions. It is not clear why that is because the recorded responses come from people with and people without access to a window.

5.3.2 Reasons for dissatisfaction

There are distinct differences in the complaints between the three buildings. DPR is the only building in which a significant percentage of the dissatisfied people complained about being too hot or that the air movement was too high. Since the summer setpoint is 27°C, the occupants rely on the fans to provide a cooling effect, but some people complained that they blow dust and papers around. In UW, people complained overwhelmingly of being too cold, whether it was their hands, their feet, or their workspace, in both warm and cool weather. Year round, the temperature setpoints are 20-22°C, which is at the lower end of the winter temperatures recommended by ASHRAE. Evidently this operation strategy is making people uncomfortable and does not take advantage of the low and no energy features of the design. The most common cause of dissatisfaction in NREL was the air movement being too low, which was not a problem in either of the other buildings. No one in any building complained that the clothing policy was so strict that it caused them thermal discomfort (Figure 33).

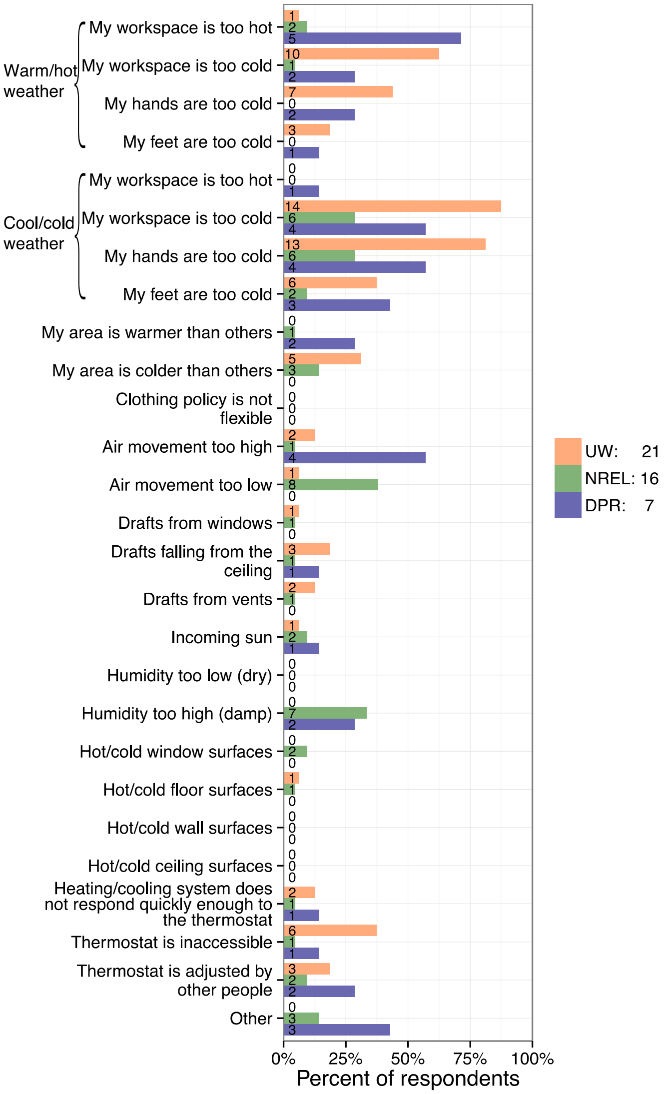
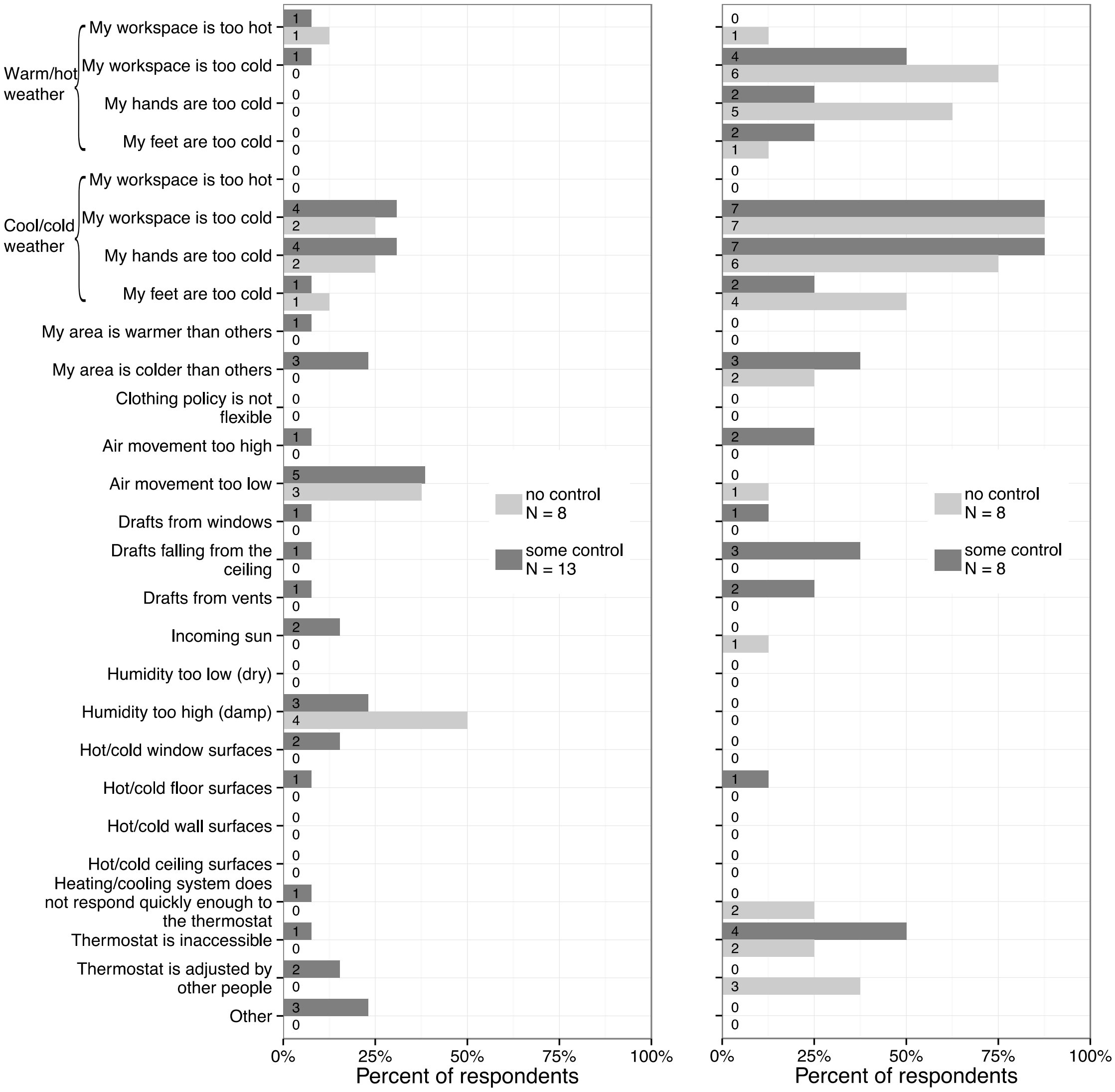


Figure 33 Reasons for temperature dissatisfaction by building

Because the main complaints and available controls are distinct for each building, I compared the controls-no controls groups by building. For both NREL and UW, there aren't any appreciable differences in the reasons for dissatisfaction with temperature depending on whether or not the respondent had access to a personal control (Figure 34). DPR had only 7 respondents who were dissatisfied with the temperature, so I did not consider them here.



a. NREL b. UW

Figure 34 Reasons for temperature dissatisfaction by available controls

5.4 Discussion

In these three buildings, there isn't a correlation between having access to controls and satisfaction with IEQ parameters or even with satisfaction with the ability to control IEQ parameters. This might speak to the difference between available controls and the perception of control. For example, the available controls might be irrelevant for the most common problem. This appears to be the case at UW, where the dominant complaint was being too cold and the most common controls were curtains/blinds and ceiling fans. Since the controls don't address the problem, it is not surprising that there was not a substantive difference in temperature satisfaction between the controls and no controls groups at UW.

Besides the other satisfaction ratings, confidence that opening or closing the window will have the desired result are the most strongly related variables to satisfaction with temperature control. The simple fact of having a window is not a good predictor, but the occupants' feelings about it is. This is in line with the finding of Langevin et al. (2012) that perceived control was a better predictor of comfort than simple access to controls in the RP-884 database.

Satisfaction with your ability to control something is not the same as your perception of your control over it, however. People might be very happy with their ability to control temperature if they are already comfortable most or all of the time even if they have no control and know that they have no control. It is tempting to think that satisfaction with the ability to control something causes satisfaction with that thing, but the causality could easily go the other direction.

6 Conclusions and future work

6.1 Conclusions

I investigated the effects of cooling strategy and access to personal controls on comfortable thermal conditions and satisfaction with IEQ variables. Using a combined database that includes the data from RP-884, SCATs and two other field studies, I calculated probit curves to relate thermal acceptability to thermal sensation. The results, which were remarkably similar across all three building cooling strategies, show that the cutoff for 80% acceptability is around ±1.5.

I developed a method for visualizing data from thermal comfort field studies that shows the results with as few intermediate steps as possible. I bin the survey responses using the indoor and outdoor temperatures under which they were given and then color the corresponding points based on the percentage of satisfied votes in each bin. In order to allow anyone to explore the results and answer their own questions with the data, I created an interactive tool. It is also useful for diagnosing problems and discovering where exactly surprising or unbelievable results are coming from because users can compare subsets of the data based on climate zone, city, cooling strategy, and access to controls.

With this tool, I compared combinations of indoor and prevailing outdoor that are associated with at least 80% satisfaction for NV and AC buildings. I found that the deadband for NV buildings is about 4K wider than for AC buildings (8K vs. 4K) and that the upper bound of comfortable indoor temperatures in NV buildings depends on the prevailing outdoor temperature. There was not enough data at cooler indoor temperatures in NV buildings to define the lower bound of the comfort zone.

I also compared the comfort zones for individuals in NV buildings with and without access to various personal controls. This analysis only relied on a smaller subset of the data because not all of the studies asked participants whether or not they had access to things like operable windows and local fans. From the data that is available, I did not find any substantial differences in comfort zone based on which personal controls, if any, the respondents had access to.

I considered these questions statistically using linear mixed models. I found that thermal sensation can be best predicted by operative temperature and that it is not dependent on the outdoor conditions even in NV buildings. Although the details of the comfort zones from this analysis were very different from the ones given by the visualization tool, the conclusion that a wider range of temperatures are comfortable in NV than AC buildings is the same.

To investigate the effects of personal control on overall satisfaction with temperature, I considered three MM buildings where the CBE occupant satisfaction survey had been administered. I found that the differences in satisfaction ratings and reasons for dissatisfaction were more substantial between the three buildings than between occupants with different levels of personal control. Surprisingly, access to controls, individually or in aggregate, was not a significant predictor of satisfaction with the ability to control components of IEQ. This may be related to the difference between access to control and perceived control.

From this study I conclude that

- the interactive tool that I developed allows users to explore the thermal comfort field data and ask their own questions of it
- the relationship between thermal sensation and thermal acceptability does not depend on the cooling strategy of the building
- the range of indoor temperatures that can satisfy 80% of the occupants is wider in NV buildings than AC buildings
- access to personal controls does not have a substantial impact on either the physical conditions that provide comfort or general satisfaction with temperature or the building as a whole

6.2 Future work

While we have a lot of field data from NV and AC buildings, we have much less from MM buildings. In my analysis I have shown preliminary results that comfort in MM buildings is more similar to that of NV than AC buildings, but the conclusion is not very strong because of the small sample size and in particular the small range of conditions under which the surveys were administered. Further field studies in MM buildings are needed to fill in this gap, especially because the operating strategies for MM buildings vary so widely. Do concurrent, switchover, and zoned MM buildings behave differently and how do they compare to NV and AC buildings?

While thermal sensation is a useful metric for understanding what is going on in the building, I think that future studies should also ask about acceptability. The standards are written in terms of acceptability, so asking the question directly would remove a step in the interpretation of the results. This is particularly important since the model I developed to relate sensation and acceptability significantly underestimates likelihood of unacceptability.

Access to personal controls did not predict general satisfaction with IEQ parameters or influence the conditions under which respondents were comfortable, which may speak to the difference between access to controls and perceived control. Other researchers have found that perceived control is more important for occupants' experience (Langevin et al., 2012; Paciuk, 1990). It would be useful to confirm this result on the time scales of both background and right-now surveys. However, assessing the factors that influence perceived control is even more important because of its potential to give guidance to designers. The adaptive hypothesis rests in part on the idea that personal control influences thermal comfort, but from this analysis, simple access to controls is not enough. For designers to be able to take full advantage of adaptive principles, they need to know what is required for occupants to perceive that they have control over their thermal environments.

7 References

Abbaszadeh, S., Zagreus, L., Huizenga, C., Lehrer, D., 2006. Occupant satisfaction with indoor environmental quality in green buildings, in: Proceedings of Healthy Buildings 2006. Presented at Healthy Buildings, Lisbon, pp. 365–370.

Altomonte, S., Schiavon, S., 2013. Occupant satisfaction in LEED and non-LEED certified buildings. Building and Environment 68, 66–76. doi:10.1016/j.buildenv.2013.06.008

ANSI/ASHRAE, 2013. Standard 55: Thermal environmental conditions for human occupancy.

Arens, E., Humphreys, M.A., de Dear, R., Zhang, H., 2010. Are "class A" temperature requirements realistic or desirable? Building and Environment 45, 4–10. doi:10.1016/j.buildenv.2009.03.014

Arens, E., Turner, S., Zhang, H., Paliaga, G., 2009. Moving air for comfort. ASHRAE Journal 8–18.

Arens, E., Zhang, H., Honnekeri, A., Pigman, M., 2014. Thermal comfort in offices with elevated air movement. In Natural ventilation for energy savings in California commercial buildings, P.F. Linden et al., (Draft final report for California Energy Commission contract 500-10-025).

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R.H.B., Singmann, H., 2014. lme4: Linear mixed-effects models using Eigen and S4.

Bates, D.M., 2010. lme4: Mixed-effects modeling with R. Springer.

Bauman, F., Carter, T., Baughman, A., Arens, E., 1998. Field study of the impact of a desktop task/ambient conditioning system in office buildings. ASHRAE Transactions 104, 1–19.

Bischof, W., Brasche, S., Kruppa, B., Bullinger, M., 2002. Do building-related complaints reflect expectations? in: Proceedings: Indoor Air 2002. Presented at Indoor Air, International society of indoor air quality and climate, Monterey, CA.

Brager, G.S., Baker, L., 2008. Occupant satisfaction in mixed-mode buildings, in: Air Conditioning and the Low Carbon Cooling Challenge. Presented at Windsor, Network for comfort and energy use in buildings, Windsor, UK.

Brager, G.S., de Dear, R.J., 1998. Thermal adaptation in the built environment: a literature review. Energy and Buildings 27, 83–96. doi:10.1016/S0378-7788(97)00053-4

Brager, G.S., Paliaga, G., de Dear, R., 2004. Operable windows, personal control, and occupant comfort. ASHRAE Transactions 110, 17–35.

Burnham, K.P., Anderson, D.R., 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer.

CEN, 2007. Standard EN15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

Christensen, R.H.B., 2013. ordinal: regression models for ordinal data.

Clark, E., 2014. University of Washington Molecular Engineering and Sciences building.

de Dear, R., Brager, G., 1998. Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions 104, 145–167.

de Dear, R., Brager, G., Cooper, D., 1997. Developing an adaptive model of thermal comfort and preference (Final report ASHRAE RP-884).

de Dear, R.J., 1998. A global database of thermal comfort field experiments. ASHRAE Transactions 104, 1141–1152.

Fanger, P.O., 1970. Thermal comfort: analysis and applications in environmental engineering. McGraw-Hill, New York.

Fanger, P.O., Toftum, J., 2002. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy and Buildings 34, 533–536. doi:10.1016/S0378-7788(02)00003-8

Fobelets, A.P.R., Gagge, A.P., 1988. Rationalization of the effective temperature, ET*, as a measure of the enthalpy of the human indoor environment. ASHRAE Transactions 94, 12–31.

Haghighat, F., Donnini, G., 1999. Impact of psycho-social factors on perception of the indoor air environment studies in 12 office buildings. Building and Environment 34, 479–503.

Huizenga, C., Abbaszadeh, S., Zagreus, L., Arens, E., 2006. Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey, in: Proceedings of Healthy Buildings 2006. Presented at Healthy Buildings, Lisbon, pp. 393–397.

Huizenga, C., Zagreus, L., Abbaszadeh, S., Lehrer, D., Goins, J., Hoe, L., Arens, E., 2005. LEED post-occupancy evaluation: taking responsibility for the occupants.

Huizenga, C., Zagreus, L., Arens, E., Lehrer, D., 2003. Measuring indoor environmental quality: A web-based occupant satisfaction survey.

Humphreys, M.A., Nicol, J.F., 2002. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy and Buildings 34, 667–684. doi:http://dx.doi.org/10.1016/S0378-7788(02)00018-X

Humphreys, M.A., Nicol, J.F., 2004. Do people like to feel “neutral”? Response to the ASHRAE scale of subjective warmth in relation to thermal preference, indoor and outdoor Temperature. ASHRAE Transactions 110, 569–577.

Humphreys, M.A., Rijal, H.B., Nicol, J.F., 2013. Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. Building and Environment 63, 40–55.

ISO, 2005. Standard 7730: Ergonomics of the thermal environment.

Kim, J., de Dear, R., 2012. Impact of different building ventilation modes on occupant expectations of the main IEQ factors. Building and Environment 57, 184–193. doi:10.1016/j.buildenv.2012.05.003

Kovalchik, S., 2014. Personal communication.

Kwok, A.G., 1997. Thermal comfort in naturally-ventilated and air-conditioned classrooms in the tropics. UC Berkeley.

Langevin, J., Wen, J., Gurian, P.L., 2012. Relating occupant perceived control and thermal comfort: statistical analysis on the ASHRAE RP-884 database. HVAC&R Research 18, 179–194. doi:10.1080/10789669.2011.607882

Leaman, A., Bordass, B., 2013. Are users more tolerant of “green” buildings? Building Research & Information 35, 662–673.

Liu, J., Yao, R., McCloy, R., 2012a. A method to weight three categories of adaptive thermal comfort. Energy and Buildings 47, 312–320. doi:10.1016/j.enbuild.2011.12.007

Liu, J., Yao, R., Wang, J., Li, B., 2012b. Occupants’ behavioural adaptation in workplaces with non-central heating and cooling systems. Applied Thermal Engineering 35, 40–54. doi:10.1016/j.applthermaleng.2011.09.037

Macquarie University Department of Geography, 2002. Climate Classification. URL http://aws.mq.edu.au/rp-884/ashrae_rp884_climates.html (accessed 5.4.14).

McCartney, K.J., Nicol, J.F., 2002. Developing an adaptive control algorithm for Europe. Energy and Buildings 34, 623–635. doi:10.1016/S0378-7788(02)00013-0

National standard of the People’s Republic of China, 2012. Evaluation standard for indoor thermal environment in civil buildings.

Nicol, F., McCartney, K.J., 2000. Final report for task 2: conducting comfort surveys throughout Europe, Smart Controls and Thermal Comfort Project. Oxford Brookes University School of Architecture.

Nicol, J.F., Humphreys, M.A., 1973. Thermal comfort as part of a self-regulating system. Building Research and Practice 1, 174–179. doi:10.1080/09613217308550237

Nicol, J.F., Humphreys, M.A., 2010. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. Building and Environment 45, 11–17. doi:10.1016/j.buildenv.2008.12.013

Paciuk, M., 1990. The role of personal control of the environment in thermal comfort and satisfaction at the workplace. Environmental Design Research Association 21, 303–312.

Pinheiro, J.C., Bates, D., DebRoy, S., Sarkar, D., EISPACK authors (src/rs.f), 2014. nlme: linear and nonlinear mixed effects models.

Pinheiro, J.C., Bates, D.M., 2000. Mixed-effects models in S and S-PLUS, Statistics and Computing. Springer-Verlag, New York.

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

RStudio, Inc, 2013. shiny: web application framework for R.

Schweiker, M., Brasche, S., Bischof, W., Hawighorst, M., Voss, K., Wagner, A., 2012. Development and validation of a methodology to challenge the adaptive comfort model. Building and Environment 49, 336–347. doi:10.1016/j.buildenv.2011.08.002

Steyerberg, E., Vickers, A., Cook, N., Gerds, T., Gonen, M., Obuchowski, N., Pencina, M., Kattan, M., 2010. Assessing the performance of prediction models: a framework for some traditional and novel measures. Epidemiology 21, 128–138. doi:10.1097/EDE.0b013e3181c30fb210.1097/EDE.0b013e3181c30fb2

Tanner, R., 2014. Stochastic optimization of building control systems for mixed-mode buildings. University of Colorado, Boulder, CO.

Tanner, R., Henze, G., Pigman, M., Ackerly, K., Brager, G., 2014. Stochastic control optimization of mixed-mode buildings (Final report ASHRAE RP-1597).

UCLA statistical consulting group. R data analysis examples: mixed effects logistic regression. URL http://www.ats.ucla.edu/stat/r/dae/melogit.htm

US Department of Energy, 2011. Buildings energy data book.

Wickham, H., Chang, W., 2013. ggplot2: an implementation of the grammar of graphics.

Winter, B., 2013. Linear models and linear mixed effects models in R with linguistic applications.

Yao, R., Li, B., Liu, J., 2009. A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV). Building and Environment 44, 2089–2096. doi:10.1016/j.buildenv.2009.02.014

ZGF Architects LLP. University of Washington Molecular Engineering Building: a naturally ventilated office. URL http://www.engr.washington.edu/sites/default/files/about/bldgs/mole/MolE_ventilation.pdf

Zhang, H., Arens, E., Fard, S.A., Huizenga, C., Paliaga, G., Brager, G., Zagreus, L., 2007. Air movement preferences observed in office buildings. International Journal of Biometeorology 51, 349–360. doi:10.1007/s00484-006-0079-y

Zhang, H., Arens, E., Pasut, W., 2011. Air temperature thresholds for indoor comfort and perceived air quality. Building Research & Information 39, 134–144. doi:10.1080/09613218.2011.552703

Appendix A Survey questions

Samples from “right now” surveys

Thermal sensation: How do you feel right now?

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

Thermal preference: Would you prefer to be

-1	0	1
Cooler	No change	Warmer

Thermal Comfort: Please rate how comfortable you are feeling right now.

-3	-2	-1	1	2	3
Very uncomfortable	Moderately uncomfortable	Slightly uncomfortable	Slightly comfortable	Moderately comfortable	Very comfortable

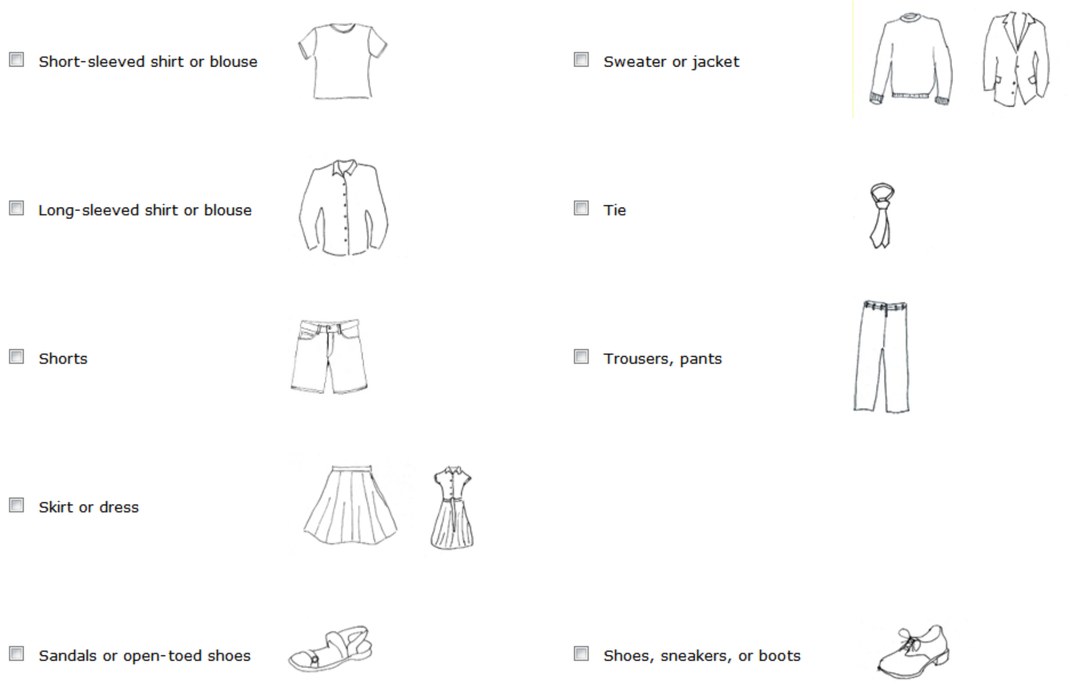
Thermal acceptability: Right now, is the temperature at your workplace acceptable?

0	1
Unacceptable	Acceptable

Metabolic rate: What have you been doing in the past hour? (Nicol and McCartney, 2000)

Sitting - Passive (SP)
Sitting - Active (SA)
Standing - Relaxed (SR)
Standing - Working (SW)
Walking - Indoors (WI)
Walking - Outdoors (WO)

Clothing insulation: Please mark in the list below all the garments you are wearing now. (Arens et al., 2014)



☐ Short-sleeved shirt or blouse

☐ Long-sleeved shirt or blouse

☐ Shorts

☐ Skirt or dress

☐ Sandals or open-toed shoes

☐ Sweater or jacket

☐ Tie

☐ Trousers, pants

☐ Shoes, sneakers, or boots

CBE background survey

General notes:
Answers of the form “very satisfied: very dissatisfied” are on a 7-point scale.
* indicates that an analogous question was asked about ceiling fans.

- Which of the following best describes your personal workspace?
    - Enclosed office, private
    - Enclosed office, shared with other people
    - Cubicles with high partitions (about five or more feet high)
    - Cubicles with low partitions (lower than five feet high)
    - Workspace in open office with no partitions (just desks)
    - Other:
- Which of the following do you personally adjust or control in your workspace? (check all that apply)
    - Window blinds or shades
    - Operable window
    - Thermostat
    - Portable heater
    - Permanent heater
    - Room air-conditioning unit
    - Portable fan
    - Ceiling fan
    - Adjustable air vent in wall or ceiling

    - Adjustable floor air vent (diffuser)
    - Door to interior space
    - Door to exterior space
    - None of the above
    - Other:
- How satisfied are you with the temperature in your workspace?
    - Very satisfied: very dissatisfied
- You have said that you are dissatisfied with the temperature in your workspace. Which of the following contribute to your dissatisfaction?
    - In warm/hot weather, the temperature in my workspace is: (check all that apply)
        - Often too hot
        - Often too cold
    - In warm/hot weather... (check all that apply)
        - My hands are too cold
        - My feet are too cold
        - Other:
    - In cool/cold weather, the temperature in my workspace is: (check all that apply)
        - Often too hot
        - Often too cold
    - In cool/cold weather... (check all that apply)
        - My hands are too cold
        - My feet are too cold
        - Other:
    - How would you best describe the source of this discomfort? (check all that apply)
        - Humidity too high (damp)
        - Humidity too low (dry)
        - Air movement too high
        - Air movement too low
        - Incoming sun
        - Hot/cold floor surfaces
        - Hot/cold ceiling surfaces
        - Hot/cold wall surfaces
        - Hot/cold window surfaces
        - Heat from office equipment
        - Drafts from windows
        - Drafts from vents
        - Drafts falling from the ceiling
        - My area is hotter than other areas
        - My area is colder than other areas
        - Thermostat is inaccessible
        - Thermostat is adjusted by other people

        - Heating/cooling system does not respond quickly enough to the thermostat
        - Clothing policy is not flexible
        - Other:
- How satisfied are you with your ability to control the temperature in your workspace?
    - Very satisfied: very dissatisfied
- How satisfied are you with the amount of air movement in your workspace?
    - Very satisfied: very dissatisfied
- How satisfied are you with your ability to control the amount of air movement in your workspace?
    - Very satisfied: very dissatisfied
- You have said that you are dissatisfied with the air movement in your workspace. On average, which would you prefer to have:
    - Much more air movement
    - Somewhat more air movement
    - No change
    - Somewhat less air movement
    - Much less air movement
- When you open the window, what confidence do you have that your action will have the desired effect? *
    - Very sure: very unsure
    - Not Applicable
- When you close the window, what confidence do you have that your action will have the desired effect? *
    - Very sure: very unsure
    - Not Applicable
- When you go to adjust the window, rate your impression of its:
    - Accessibility *
        - Very convenient: very inconvenient
    - Usability *
        - Very clear to operate: very confusing to operate
    - Responsiveness *
        - Very fast or reliable: very slow or unreliable
- To what extent do you feel that what you wear to work is influenced by an implied or explicit dress code (as in, social norms or policy)? [NREL only]
    - Not influenced: very influenced

Appendix B Field study database summary statistics

	Blgs	Subs	N	Cooling	Sensation	Acceptability	Preference	Comfort
Australia: Brisbane	5	260	1,170	NV, AC	0.4 (-0.7 - 1.6)		1.6 (0.9 - 2.3)	
Australia: Darwin	14	197	1,044	AC	-0.3 (-1.5 - 0.9)		2 (1.3 - 2.7)	
Australia: Kalgoolrie	22	95	1,222	AC	0.3 (-0.8 - 1.3)	0.9 (0.5 - 1.2)	1.9 (1.3 - 2.5)	4.7 (3.6 - 5.8)
Australia: Melbourne	4	194	1,061	NV, AC	0.5 (-0.6 - 1.6)		1.7 (1.1 - 2.4)	
Australia: Sydney	2	84	384	AC, MM	0.3 (-0.9 - 1.5)	0.8 (0.4 - 1.2)	1.9 (1.3 - 2.6)	4 (2.4 - 5.7)
Australia: Townsville	12	158	1,220	AC	-0.4 (-1.5 - 0.8)	0.8 (0.4 - 1.2)	2 (1.3 - 2.6)	4.6 (3.5 - 5.7)
Canada: Cap-de-la-Madeleine	1	56	79	AC	-0.4 (-1.4 - 0.5)	0.9 (0.7 - 1.2)	2 (1.4 - 2.5)	4.6 (3.6 - 5.7)
Canada: Gramby	1	47	79	AC	-0.2 (-1.5 - 1)	0.8 (0.5 - 1.2)	2.1 (1.4 - 2.7)	4.3 (2.9 - 5.6)
Canada: Hull	1	48	82	AC	-0.1 (-1.2 - 1)	0.9 (0.5 - 1.2)	1.8 (1.2 - 2.4)	4.7 (3.6 - 5.8)
Canada: Longueuil	2	47	161	AC	-0.5 (-1.7 - 0.6)	0.9 (0.5 - 1.2)	2 (1.4 - 2.7)	4.4 (3.1 - 5.7)
Canada: Maniwaki	1	41	61	AC	0.5 (-1 - 2)	0.7 (0.2 - 1.1)	1.5 (0.8 - 2.2)	3.7 (2.2 - 5.2)
Canada: Montreal	4	59	238	AC	-0.3 (-1.5 - 0.9)	0.9 (0.5 - 1.2)	2 (1.3 - 2.6)	4.3 (2.9 - 5.7)
Canada: Ottawa	4	1371	1,834	AC	0 (-1 - 1)		2.1 (1.5 - 2.6)	
Canada: Shawinigan	1	48	81	AC	-0.4 (-1.7 - 0.8)	0.8 (0.4 - 1.2)	1.9 (1.2 - 2.6)	4 (2.6 - 5.3)
Canada: Trois Rivieres	1	54	88	AC	-0.2 (-1.3 - 0.9)	0.9 (0.5 - 1.2)	1.8 (1.2 - 2.5)	4.2 (3 - 5.5)
France: Lyon	5	112	516	NV, AC, MM	0.4 (-0.7 - 1.5)		1.5 (1 - 2)	4.1 (3 - 5.1)
Greece: Athens	6	19	1,586	NV	0.7 (-0.2 - 1.6)	0.8 (0.3 - 1.2)	1.5 (0.9 - 2)	
Greece: Athens	5	87	325	NV, AC, MM	0.1 (-1 - 1.1)		1.5 (1 - 2)	4.1 (3.2 - 5.1)
Indonesia: Jakarta	7	116	596	NV, AC, MM	0.2 (-0.9 - 1.3)			
Pakistan: Karachi	1	8	568	NV	0 (-0.7 - 0.8)		1.9 (1.2 - 2.6)	
Pakistan: Multan	1	5	332	NV	0.7 (-0.4 - 1.8)		1.4 (0.9 - 1.9)	
Pakistan: Peshawar	1	7	964	NV	0 (-1.6 - 1.5)		2 (1.3 - 2.7)	
Pakistan: Quetta	1	8	843	NV	0.3 (-0.8 - 1.4)		1.8 (1.1 - 2.5)	
Pakistan: Saidu	1	6	1,017	NV	-0.7 (-2.5 - 1.2)		2.1 (1.2 - 3)	

	Blgs	Subs	N	Cooling	Sensation	Acceptability	Preference	Comfort
Portugal: Alfragide	1	28	248	NV	0.1 (-0.9 - 1)		1.7 (1.3 - 2.2)	3.9 (3.4 - 4.5)
Portugal: Lisbon	1	16	136	NV	0.2 (-0.7 - 1)		1.6 (1.1 - 2.1)	3.8 (3.1 - 4.5)
Portugal: Porto	3	146	1,175	NV, MM	0.2 (-0.7 - 1.1)		1.7 (1.3 - 2.2)	4 (3.3 - 4.7)
Singapore: Singapore	2	447	604	NV, AC	0.3 (-1 - 1.6)			
Sweden: Gothenburg	3	104	575	AC, MM	0 (-0.7 - 0.8)		1.7 (1.3 - 2.2)	4.3 (3.5 - 5.1)
Sweden: Halmstad	1	31	137	AC	-0.1 (-0.7 - 0.5)		1.8 (1.3 - 2.2)	4.3 (3.4 - 5.1)
Sweden: Malmo	1	41	258	AC	0.1 (-0.6 - 0.9)		1.7 (1.2 - 2.1)	4.4 (3.6 - 5.2)
Thailand: Bangkok	5	250	1,148	NV, AC	0.4 (-0.8 - 1.5)		1.5 (0.9 - 2.2)	
UK: Chester	3	66	138	NV	0.2 (-1.3 - 1.7)	0.6 (0.1 - 1.1)		
UK: Cwmbran	1	16	16	AC	0.5 (-1.3 - 2.3)		2.4 (1.8 - 3)	
UK: Cwmfelinfach	1	16	16	AC	1.9 (1.3 - 2.6)			
UK: Ebbw Vale	1	15	15	AC	0.9 (-0.6 - 2.4)		1.9 (1.5 - 2.4)	
UK: Liverpool	1	34	34	NV	1.9 (1 - 2.7)	0.4 (-0.1 - 0.8)		
UK: Llanelli	1	6	6	AC	-1.2 (-2.5 - 0.2)			
UK: Llantrisant	2	11	16	AC	0.9 (-0.1 - 2)			
UK: London	6	220	1,285	NV, AC, MM	0.4 (-0.9 - 1.7)		1.4 (0.9 - 1.9)	3.8 (2.7 - 5)
UK: Maesteg	1	32	32	AC	1.6 (0.4 - 2.8)		1.8 (1.2 - 2.3)	
UK: Newport	1	17	17	AC	1.2 (-0.8 - 3.3)		1.5 (0.8 - 2.1)	
UK: Oxford	3	837	837	NV	-0.1 (-1.1 - 0.9)		2.1 (1.4 - 2.7)	
UK: St Helens	3	171	290	NV, MM	0.9 (-0.5 - 2.3)	0.5 (0 - 1)		
US: Alameda	1	13	1,408	NV	-0.1 (-0.8 - 0.6)	1 (0.8 - 1.1)	2 (1.5 - 2.6)	
US: Antioch	1	30	111	AC	0.4 (-0.3 - 1.1)		2.3 (1.7 - 2.9)	4.6 (3.5 - 5.8)
US: Auburn	1	27	126	AC	-0.1 (-0.8 - 0.7)		2 (1.4 - 2.6)	4.7 (3.6 - 5.7)
US: Berkeley	1	54	2,074	NV	0.3 (-0.8 - 1.4)	0.8 (0.5 - 1.2)	2.2 (1.6 - 2.8)	
US: Berkeley	1	25	241	NV	0.2 (-1 - 1.4)		1.9 (1.2 - 2.5)	4.5 (3.1 - 5.8)
US: Grand Rapids	1	16	85	AC	0.3 (-0.6 - 1.1)		2.1 (1.5 - 2.8)	4.7 (3.5 - 5.9)

	Blgs	Subs	N	Cooling	Sensation	Acceptability	Preference	Comfort
US: Honolulu	7	1	3,016	NV, AC	-0.2 (-1.6 - 1.1)	0.9 (0.6 - 1.2)	1.7 (1 - 2.4)	4.3 (3.2 - 5.4)
US: Palo Alto	1	32	192	AC	0.1 (-1 - 1.2)		2 (1.3 - 2.6)	4.5 (3.2 - 5.7)
US: San Francisco	5	158	1,234	NV, AC	0.3 (-0.7 - 1.4)		1.8 (1.1 - 2.4)	4.3 (3.1 - 5.6)
US: San Ramon	3	80	618	AC	0 (-1 - 1)		1.9 (1.3 - 2.6)	4.6 (3.3 - 5.8)
US: Walnut Creek	2	60	416	AC	0.1 (-1.1 - 1.2)		1.9 (1.2 - 2.6)	4.2 (3 - 5.5)

Table 1 Summary of survey responses by city
NOTES: values are: mean (one standard deviation below the mean – one standard deviation above the mean)
sensation ranges from -3 to 3
acceptability: 0=unacceptable, 1=acceptable
preference: 1=want cooler, 2=no change, 3=want warmer
comfort: 1=very uncomfortable, 6=very comfortable

	met	clo	PMV	PPD	Operative (°C)	RH	Prevailing outdoor (°C)
Australia: Brisbane	1.2 (1.1 - 1.3)	0.7 (0.6 - 0.8)	0.5 (-0.2 - 1.2)	0.2 (0 - 0.4)	26 (24 - 28)	55 (48 - 63)	24 (23 - 25)
Australia: Darwin	1.2 (1 - 1.3)	0.7 (0.5 - 0.8)	-0.1 (-0.6 - 0.4)	0.1 (0 - 0.2)	24 (22 - 25)	52 (45 - 60)	27 (25 - 29)
Australia: Kalgoolrie	1.3 (1.1 - 1.5)	0.7 (0.5 - 1)	-0.1 (-0.7 - 0.5)	0.1 (0 - 0.2)	23 (21 - 24)	44 (36 - 52)	
Australia: Melbourne	1.2 (1 - 1.3)	0.8 (0.6 - 1)	0.1 (-0.5 - 0.8)	0.1 (0 - 0.3)	24 (22 - 27)	41 (34 - 48)	20 (19 - 20)
Australia: Sydney	1.2 (1 - 1.5)	0.9 (0.6 - 1.1)	0 (-0.6 - 0.6)	0.1 (0 - 0.2)	23 (22 - 25)	44 (33 - 54)	16 (14 - 19)
Australia: Townsville	1.3 (1.1 - 1.5)	0.6 (0.5 - 0.8)	0 (-0.5 - 0.5)	0.1 (0 - 0.2)	24 (23 - 25)	54 (45 - 62)	23 (19 - 27)
Canada: Cap-de-la-Madeleine	1.2 (1 - 1.4)	1 (0.6 - 1.4)	0 (-0.5 - 0.6)	0.1 (0.1 - 0.2)	23 (22 - 23)	40 (24 - 57)	11 (2 - 20)

	met	clo	PMV	PPD	Operative (°C)	RH	Prevailing outdoor (°C)
Canada: Gramby	1.2 (1 - 1.3)	0.9 (0.5 - 1.2)	-0.1 (-0.7 - 0.5)	0.1 (0 - 0.2)	23 (23 - 24)	27 (12 - 42)	0 (-15 - 16)
Canada: Hull	1.2 (1 - 1.4)	0.9 (0.6 - 1.2)	0 (-0.5 - 0.6)	0.1 (0 - 0.2)	23 (22 - 24)	36 (30 - 43)	4 (-6 - 15)
Canada: Longueuil	1.2 (1 - 1.4)	0.9 (0.5 - 1.2)	-0.1 (-0.7 - 0.4)	0.1 (0 - 0.2)	23 (22 - 23)	37 (23 - 51)	9 (-1 - 20)
Canada: Maniwaki	1.2 (1.1 - 1.4)	0.8 (0.6 - 1.1)	0.3 (-0.3 - 0.8)	0.1 (0 - 0.2)	24 (22 - 26)	37 (31 - 42)	9 (5 - 13)
Canada: Montreal	1.2 (1 - 1.4)	0.9 (0.6 - 1.3)	0 (-0.5 - 0.6)	0.1 (0 - 0.2)	23 (22 - 24)	29 (18 - 41)	3 (-13 - 20)
Canada: Ottawa		0.9 (0.7 - 1.1)	-0.1 (-0.5 - 0.2)	0.1 (0 - 0.1)	23 (22 - 24)	28 (19 - 36)	5 (4 - 5)
Canada: Shawinigan	1.2 (1 - 1.4)	0.8 (0.5 - 1.2)	-0.1 (-0.6 - 0.3)	0.1 (0 - 0.2)	23 (22 - 24)	34 (19 - 49)	7 (-5 - 20)
Canada: Trois Rivieres	1.2 (1 - 1.4)	0.8 (0.5 - 1.2)	0 (-0.4 - 0.5)	0.1 (0 - 0.2)	24 (23 - 25)	31 (13 - 49)	6 (-11 - 23)
France: Lyon	1.4 (1.1 - 1.6)	0.8 (0.5 - 1)	0.5 (0 - 1)	0.2 (0 - 0.3)	25 (22 - 27)	38 (27 - 48)	11 (3 - 19)
Greece: Athens	1.2 (0.9 - 1.4)	0.5 (0.4 - 0.5)	1.2 (0.3 - 2.1)	0.4 (0.2 - 0.7)	30 (28 - 32)	34 (26 - 41)	26 (24 - 27)
Greece: Athens	1.3 (1 - 1.5)	0.7 (0.6 - 0.9)	0.7 (0.1 - 1.2)	0.2 (0.1 - 0.4)	26 (24 - 28)	41 (32 - 51)	22 (16 - 27)
Indonesia: Jakarta	1 (1 - 1)	0.7 (0.7 - 0.8)	0.5 (-0.5 - 1.4)	0.3 (0 - 0.5)	27 (25 - 30)	65 (60 - 71)	28 (28 - 28)**
Pakistan: Karachi	1.2 (0.8 - 1.6)	1 (0.6 - 1.3)	1 (0.1 - 2)	0.4 (0.1 - 0.7)	26 (23 - 30)	49 (30 - 68)	23 (19 - 27)*
Pakistan: Multan	1.2 (0.8 - 1.6)	0.7 (0.5 - 1)	1.9 (1 - 2.8)	0.7 (0.4 - 1)	30 (28 - 33)	68 (58 - 78)	29 (29 - 29)*
Pakistan: Peshawar	1.2 (0.8 - 1.6)	1 (0.6 - 1.4)	0.7 (-0.8 - 2.2)	0.4 (0.1 - 0.8)	25 (18 - 31)	54 (43 - 65)	22 (15 - 30)*
Pakistan: Quetta	1.1 (0.8 - 1.5)	1.1 (0.7 - 1.5)	0.4 (-1 - 1.7)	0.4 (0.1 - 0.7)	25 (19 - 31)	25 (10 - 41)	17 (8 - 26)*
Pakistan: Saidu	1.2 (0.8 - 1.6)	1.2 (0.7 - 1.6)	0 (-1.9 - 1.9)	0.6 (0.2 - 0.9)	21 (12 - 30)	51 (38 - 64)	19 (12 - 27)*
Portugal: Alfragide	1.6 (1.2 - 2.1)	0.8 (0.6 - 1)	0.6 (0.1 - 1.1)	0.2 (0 - 0.3)	23 (21 - 26)	53 (46 - 60)	16 (12 - 19)
Portugal: Lisbon	1.4 (1.1 - 1.7)	0.9 (0.6 - 1.1)	0.7 (0.3 - 1.2)	0.2 (0.1 - 0.3)	24 (21 - 26)	58 (52 - 63)	14 (9 - 18)
Portugal: Porto	1.4 (1.1 - 1.8)	0.8 (0.6 - 1)	0.6 (0.1 - 1)	0.2 (0 - 0.3)	24 (22 - 26)	50 (42 - 58)	14 (10 - 18)
Singapore: Singapore	1.2 (1 - 1.4)	0.5 (0.4 - 0.6)	0.7 (-0.4 - 1.9)	0.4 (0.1 - 0.6)	27 (24 - 30)	67 (55 - 78)	28 (27 - 28)**
Sweden: Gothenburg	1.4 (1.1 - 1.7)	0.8 (0.6 - 1)	0.2 (-0.1 - 0.6)	0.1 (0 - 0.1)	23 (22 - 24)	35 (24 - 46)	8 (1 - 16)
Sweden: Halmstad	1.4 (1.1 - 1.7)	0.8 (0.6 - 1)	0.1 (-0.3 - 0.5)	0.1 (0 - 0.2)	23 (22 - 23)	37 (25 - 49)	6 (0 - 13)
Sweden: Malmo	1.3 (1.1 - 1.6)	0.7 (0.6 - 0.9)	0.2 (-0.1 - 0.6)	0.1 (0 - 0.1)	24 (23 - 25)	38 (24 - 52)	11 (2 - 19)

	met	clo	PMV	PPD	Operative (°C)	RH	Prevailing outdoor (°C)
Thailand: Bangkok	1.1 (1.1 - 1.1)	0.7 (0.6 - 0.8)	0.7 (-0.5 - 1.8)	0.3 (0 - 0.7)	26 (23 - 30)	64 (53 - 74)	30 (29 - 31)
UK: Chester	1.2 (1.2 - 1.2)	0.7 (0.5 - 0.8)	-0.8 (-1.1 - -0.4)	0.2 (0.1 - 0.3)	21 (20 - 22)	48 (45 - 50)	8 (6 - 10)**
UK: Cwmbran	2.7 (2 - 3.4)	0.9 (0.6 - 1.2)	1.1 (0.6 - 1.6)	0.3 (0.1 - 0.6)	19 (18 - 20)	48 (47 - 48)	4 (4 - 4)**
UK: Cwmfelinfach	2.5 (2.2 - 2.8)	0.6 (0.4 - 0.9)	1 (0.6 - 1.5)	0.3 (0.1 - 0.5)	21 (20 - 23)	48 (45 - 51)	12 (12 - 12)**
UK: Ebbw Vale	2.6 (2.6 - 2.6)	0.7 (0.5 - 0.9)	1.2 (1 - 1.4)	0.3 (0.2 - 0.4)	21 (21 - 22)	45 (44 - 45)	16 (16 - 16)**
UK: Liverpool	1.2 (1.2 - 1.2)	0.6 (0.5 - 0.7)	-0.3 (-0.6 - 0.1)	0.1 (0 - 0.2)	24 (23 - 25)	34 (32 - 37)	6 (6 - 6)**
UK: Llanelli	1.4 (1.3 - 1.4)	0.9 (0.8 - 1)	-0.4 (-0.6 - -0.2)	0.1 (0.1 - 0.1)	19 (19 - 20)	44 (43 - 45)	5 (5 - 5)**
UK: Llantrisant	2.3 (1.7 - 2.8)	0.8 (0.5 - 1)	0.9 (0.2 - 1.6)	0.3 (0.1 - 0.5)	22 (21 - 23)	40 (30 - 50)	8 (7 - 9)**
UK: London	1.4 (1.1 - 1.7)	0.7 (0.5 - 0.9)	0.4 (-0.2 - 0.9)	0.1 (0 - 0.2)	25 (23 - 26)	44 (36 - 52)	11 (5 - 16)
UK: Maesteg	2.5 (2.2 - 2.7)	0.6 (0.4 - 0.9)	1.3 (1.1 - 1.6)	0.4 (0.3 - 0.6)	23 (23 - 24)	50 (48 - 53)	16 (16 - 16)
UK: Newport	2.6 (2.5 - 2.7)	0.7 (0.6 - 0.9)	1.7 (1.4 - 2)	0.6 (0.5 - 0.8)	24 (23 - 26)	53 (49 - 56)	13 (13 - 13)**
UK: Oxford	1.2 (0.9 - 1.4)	0.8 (0.6 - 1)	-0.6 (-1.2 - 0.1)	0.2 (0 - 0.4)	22 (20 - 24)	45 (32 - 57)	15 (15 - 15)
UK: St Helens	1.2 (1.2 - 1.2)	0.7 (0.5 - 0.8)	-0.3 (-0.7 - 0.1)	0.1 (0 - 0.2)	23 (21 - 24)	47 (41 - 52)	11 (10 - 13)**
US: Alameda	1.1 (1.1 - 1.1)	0.8 (0.6 - 0.9)			23 (20 - 26)	41 (36 - 45)	14 (10 - 18)
US: Antioch	1.2 (1 - 1.3)	0.8 (0.7 - 1)	0 (-0.4 - 0.3)	0.1 (0 - 0.1)	23 (23 - 23)	45 (43 - 47)	11 (11 - 11)
US: Auburn	1.1 (1 - 1.2)	0.8 (0.7 - 0.9)	-0.5 (-1 - -0.1)	0.1 (0 - 0.3)	22 (21 - 23)	48 (46 - 51)	12 (12 - 12)
US: Berkeley	1.3 (1.2 - 1.3)	0.9 (0.7 - 1.1)	0.1 (-0.4 - 0.5)	9.5 (1.8 - 17.2)	24 (22 - 25)		15 (11 - 19)
US: Berkeley	1.1 (1 - 1.2)	0.7 (0.6 - 0.9)	-0.2 (-0.7 - 0.3)	0.1 (0 - 0.2)	24 (22 - 25)	42 (32 - 52)	16 (16 - 16)*
US: Grand Rapids	1.1 (1 - 1.2)	0.9 (0.7 - 1)	-0.2 (-0.5 - 0.1)	0.1 (0 - 0.1)	23 (23 - 24)	37 (36 - 39)	1 (1 - 1)
US: Honolulu	1.2 (1.2 - 1.2)	0.5 (0.4 - 0.7)	0.2 (-0.6 - 0.9)	0.2 (0 - 0.3)	26 (23 - 28)	61 (54 - 69)	
US: Palo Alto	1.2 (1 - 1.3)	0.8 (0.6 - 1.1)	-0.2 (-0.7 - 0.2)	0.1 (0 - 0.2)	22 (21 - 24)	46 (31 - 62)	11 (5 - 17)*

	met	clo	PMV	PPD	Operative (°C)	RH	Prevailing outdoor (°C)
US: San Francisco	1.1 (1 - 1.3)	0.8 (0.6 - 1)	-0.1 (-0.6 - 0.4)	0.1 (0 - 0.2)	23 (22 - 24)	51 (39 - 64)	15 (12 - 17)*
US: San Ramon	1.1 (1 - 1.2)	0.8 (0.6 - 1)	-0.4 (-0.9 - 0)	0.1 (0 - 0.2)	23 (22 - 23)	39 (26 - 51)	14 (5 - 22)*
US: Walnut Creek	1.1 (1 - 1.3)	0.8 (0.6 - 1.1)	-0.2 (-0.7 - 0.3)	0.1 (0 - 0.2)	23 (22 - 24)	43 (29 - 57)	16 (11 - 21)*

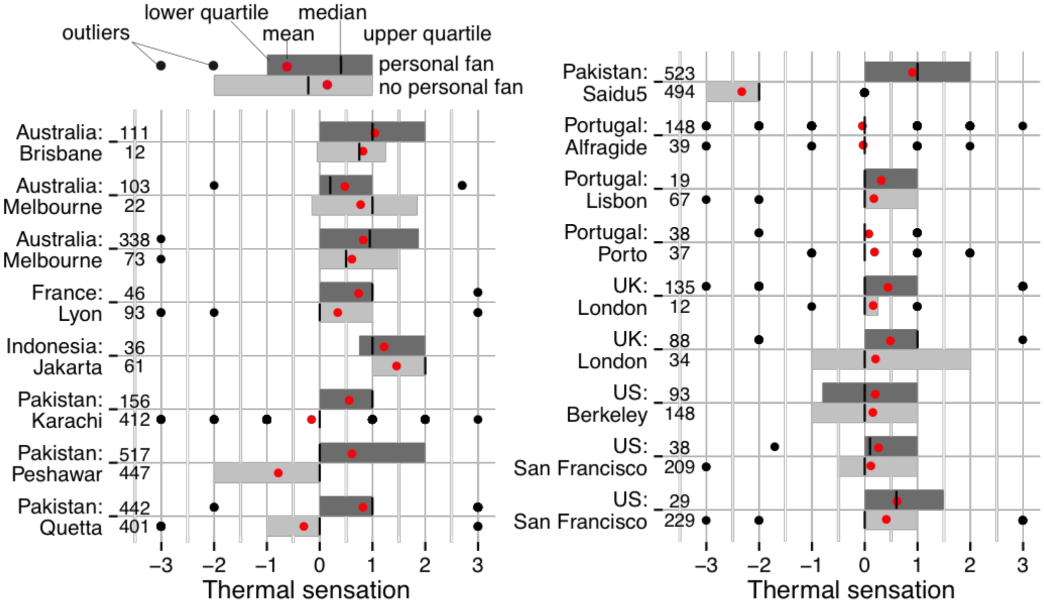
Table 2 Summary of physical measurements by city

NOTES: values are mean (one standard deviation below the mean – one standard deviation above the mean)

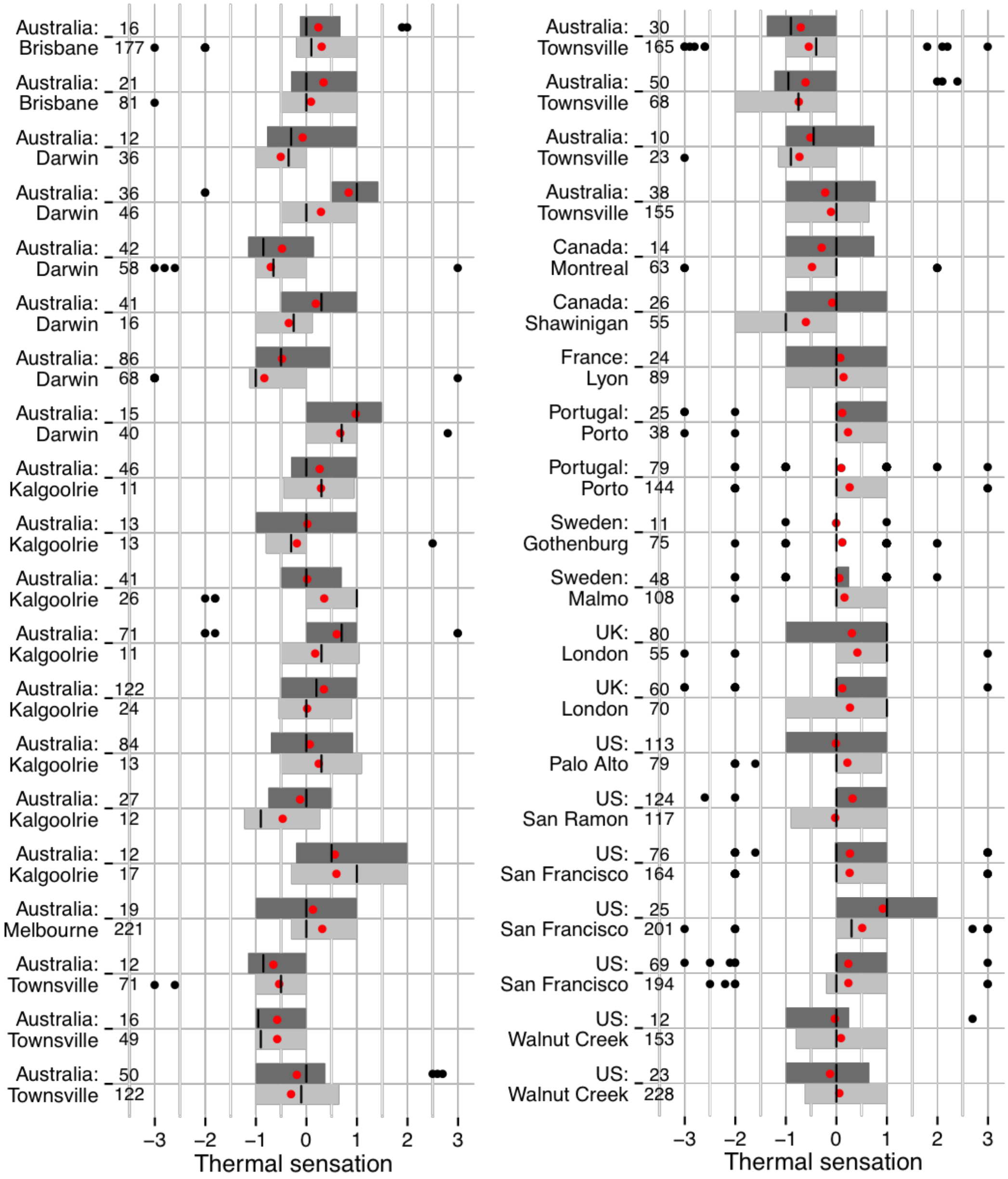
* indicates that the outdoor temperatures were taken from a combination of weather measurements and climatological data

** indicates that the outdoor temperatures were taken from climatological data

Appendix C Personal control and thermal sensation by building

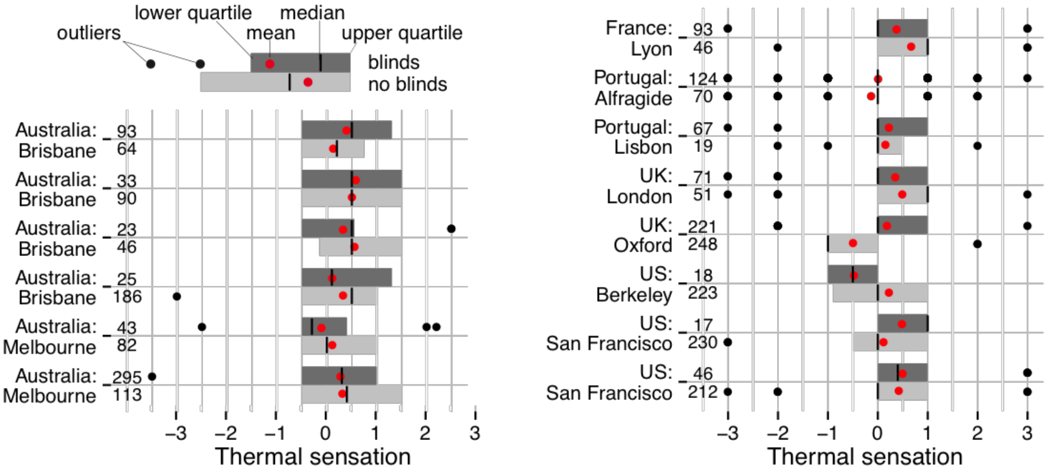


a. NV buildings

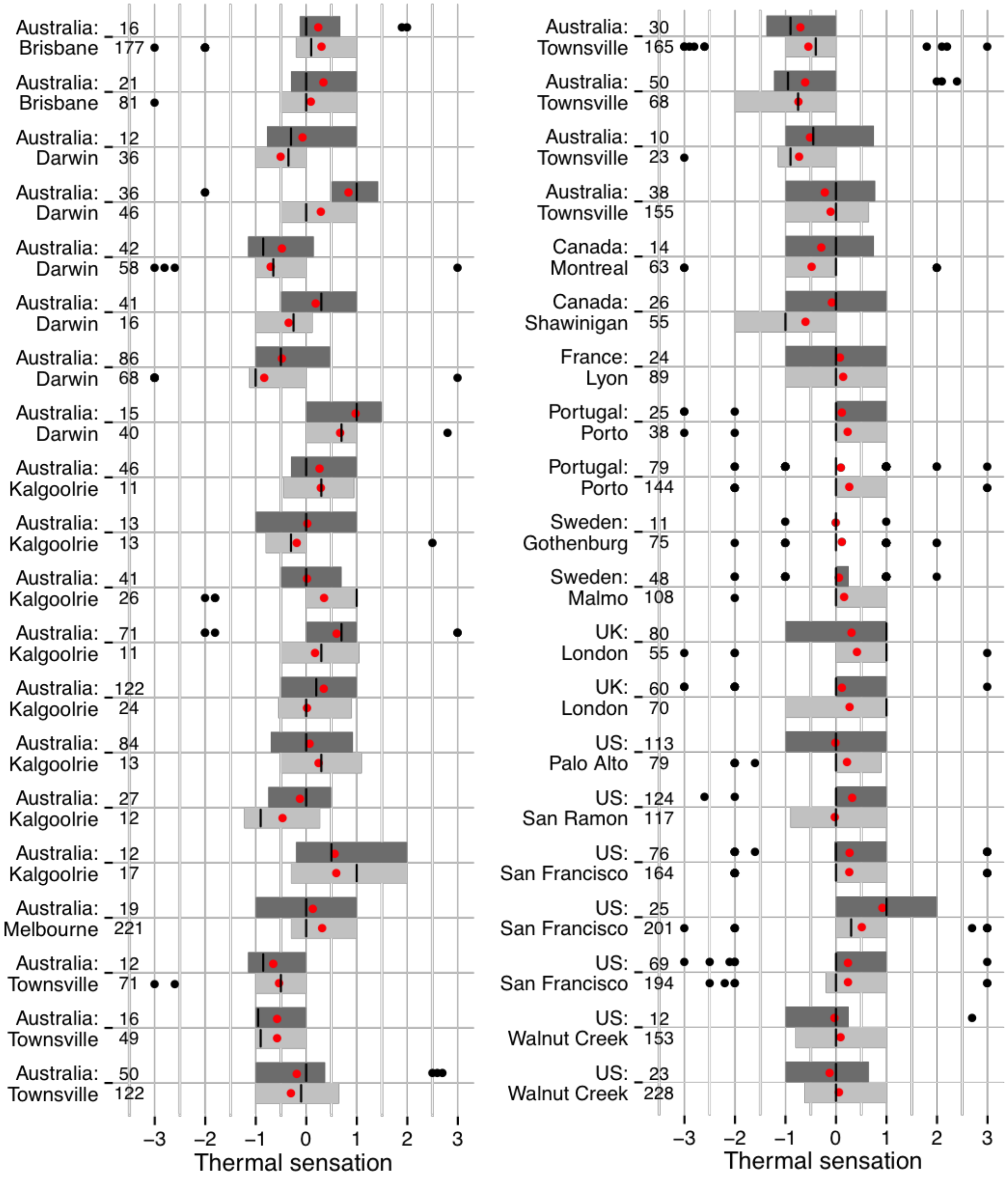


b. AC and MM buildings

Figure 35 Effects of personal fans on thermal sensation by building
NOTE: Only buildings with at least 10 votes from both the fan and no-fan groups are shown



a. NV buildings



b. AC and MM buildings

Figure 36 Effects of curtains/blinds on thermal sensation by building
NOTE: Only buildings with at least 10 votes from both the blinds and no-blinds groups are shown