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Thresholds for indoor thermal comfort and perceived air quality

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Abstract

This paper examines comfort zone boundaries (thresholds beyond which environmental conditioning is required) using field studies in which acceptability votes were obtained from occupants. Air-conditioned and ventilatively-cooled buildings are examined separately, since the degree of occupant adaptation has been found to differ for these types of buildings. The acceptable zones between the thresholds are found to be 8 – 10 K wide.

The paper also analyzes laboratory studies of air movement to find the positions of warm-side comfort thresholds when different levels of air movement and personal environmental control are added to the environment. These broaden the acceptable temperature range. Perceived air quality (PAQ) is shown to be most closely correlated to thermal comfort, so that as long as comfort is maintained, they will be satisfactory even at high temperatures (28ºC).

Key words

Thermal acceptability, air movement, natural ventilated building, productivity

Introduction

Humans adapt to their environments. As a result, they perceive little difference in the acceptability of the environment across a range of environmental conditions, the center of which is their 'neutral' or 'optimal' temperature. In addition, the individuals in a population differ physiologically, and have environmental and cultural backgrounds, so their optimal temperatures (and ranges) will differ. A change from a given temperature can increase the acceptability for some people while decreasing it for others. This effect lowers the maximum percentage of the population that finds any given temperature acceptable, and broadens the zone that any given percentage of the population finds acceptable. Beyond the zone boundaries, acceptability will drop off, both for a single person and for a given majority of population. Although the comfort literature (and the air conditioning industry) tends to focus on neutral and optimal temperatures, these zone boundaries define the 'thresholds' beyond which energy is actually needed to condition interior space.

Since air-conditioning (HVAC) became widely available, designers have relied on it to engineer buildings to previously unimaginable levels of certainty, guaranteeing comfort for specific fractions of the year (e.g., 99%). This type of engineering had not been done for the naturally ventilated (NV) or free-running designs of the past.

The shift in design was accompanied by more restrictive comfort requirements. If one could do it, why not? From pre-HVAC to now, the 'comfort zone' has shrunk at least 1K at each end. The comfort of a building's entire occupancy is now extrapolated from the predicted thermal sensation of a single representative occupant; the extrapolation is based on laboratory studies in which clothing, activity, and age were homogeneous. This approach is not based on real buildings with real populations of occupants, nor on direct measurement of comfort or acceptability.

However, there have been an increasing number of office and school field studies, in which occupants were surveyed and concurrent physical measurements taken. The American Society for Heating Refrigerating and Air-conditioning Engineers (ASHRAE) has accumulated these into a database (de Dear 1998) allowing analysis of real occupant populations. Such analyses (de Dear and Brager 1998) supported earlier suggestions (Nicol and Humphreys, 1972) that human adaptation varied by type of building (HVAC vs NV), and that zones of equal thermal sensation for the NV buildings were generally broader. 'Adaptive' comfort zones had obvious energy efficiency implications, and adaptive models were first adopted for buildings with operable windows (ASHRAE 55) and then for free-running buildings (CEN/ISO 15251, 7730). Subsequent examination of 'acceptability' votes shows a much broader and flatter acceptable temperature range than when the range is extrapolated from thermal sensation votes (Arens et al. 2009).

Method

Four datasets are used here to analyze the threshold concept for thermal comfort. Thresholds for perceived air quality (PAQ) are examined as well, as PAQ is linked to temperature and thermal comfort.

Dataset 1). The ASHRAE field study database (de Dear and Brager, 1998) is used to identify thermal comfort thresholds using surveys containing thermal-comfort acceptability votes. These locations (studies) are listed in Table 1, separating HVAC from NV plus mixed-mode (MM) buildings. MM buildings contain air-conditioning but operate at times in NV mode.

Table 1. List of locations (studies) of the ASHRAE database used in this study

HVAC (summer +winter, N=4730)	NV and MM (summer, N=2512)	NV and MM (winter, N=2632)
Kalgoolie (summer, winter)	Honolulu, NV	Athens, NV
Townsville (summer, winter)	Berkeley (BCC), NV	Berkeley (BCC), NV
Montreal (summer, winter)	Sydney MM	Sydney MM
Sydney winter	Merseyside NV	Merseyside NV
Honolulu hot season	Merseyside MM	
Honolulu cool season		

Dataset 2). The Berkeley Civic Center (BCC) field study database (Brager and Paliaga, 2004) is combined with the ASHRAE database for NV + MM buildings to analyze thermal comfort thresholds, and to analyze PAQ thresholds (N=1620)

Dataset 3 and 4). Two separate human subject tests carried out in the Environmental Chamber at UC Berkeley are used to analyze the PAQ thresholds and comfort thresholds with and without air movement. In both studies, 18 college students experienced each test condition.

The first one (dataset 3) tested thermal comfort and PAQ under 18, 20, 25, 28, and 30ºC with local cooling/heating devices. Hand- and foot warmers were tested at 18 and 20ºC, and air movement was provided to the breathing zone and hands at 28 and 30ºC (Zhang et al. 2010). At 28ºC, the supply was re-circulated room air. At 30ºC, the breathing zone was supplied with 28ºC air from the air-conditioning system.

The second human subject test (dataset 4) fixed the air temperature at 28ºC. Thermal comfort and PAQ were examined with re-circulated room air from various configurations of nozzles (different airspeeds, nozzle sizes, use of one vs. two nozzles).

Temperature thresholds for thermal comfort

1) Previous work. Arens et al. (2010) analyzed occupants' temperature acceptability votes in the ASHRAE database of 45 central-HVAC office buildings in Kalgoorlie and Townsville (both in Australia), Montreal in Canada, and a NV building in Berkeley. The airspeeds in the buildings were generally very low. The results showed very similar acceptability levels over large temperature ranges. A figure combining all 4 locations and both summer and winter is shown in Figure 1. The data was binned at the middle of each degree, and the brackets indicate +/- 1 standard deviation.

It shows a roughly flat top in acceptability over a 9K temperature range (16.5 – 25.5ºC). Between 25.5 – 28.5ºC, the acceptability reduced significantly and consistently, well below the 80% acceptability as shown by a green line. Because of low vote numbers in cool conditions, it remains unclear whether 17 or 18ºC is acceptable.

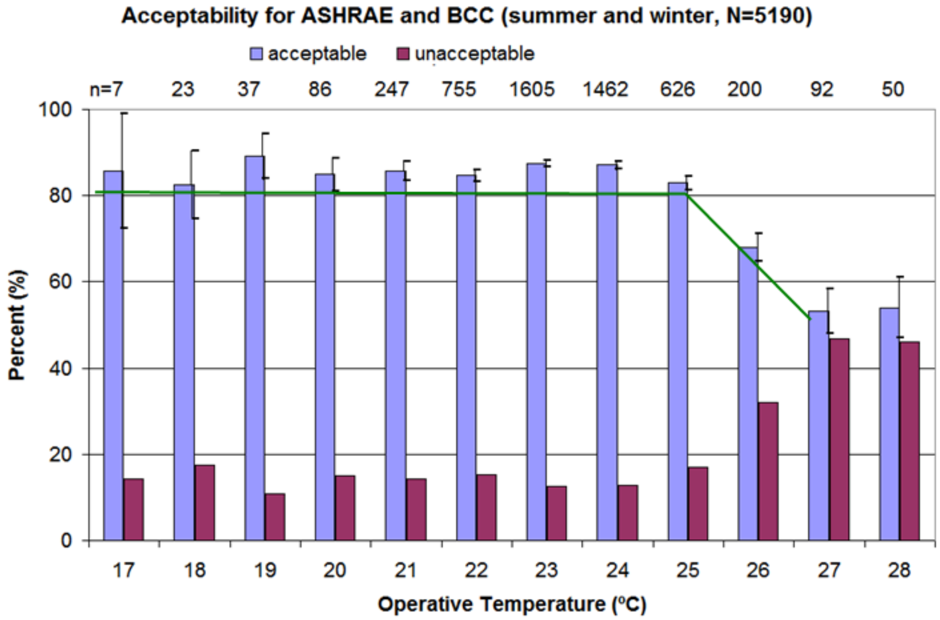


Figure 1. Acceptability against temperature at the workstation, annual, pooled 3 locations of ASHRAE and Berkeley Civic Center (BCC) data.

2). Acceptability thresholds for air-conditioned versus naturally-ventilated buildings .

This paper enlarges the abovementioned dataset by including all ASHRAE database studies in which thermal acceptability was measured. HVAC buildings are treated separately from NV and MM buildings. Because there are not many HVAC building studies that include acceptability votes, and because their indoor temperatures are not very different between summer and winter, we combined both seasons for the HVAC analysis (Figure 2). Figure 3 and 4 show combined NV and MM results, separating winter and summer. The building locations for each figure are listed in Table 1.

In additional to the locations included in the Figure 1 (Kalgoorlie, Townsville, Montreal), there are 3 more HVAC building studies (Honolulu hot- and cool seasons, and Sydney winter) added in Figure 2. Because the BCC in Figure 1 is a NV building, it is not included in Figure 2.

Figure 2 shows a roughly similar acceptability profile as Figure 1. Again it shows a drop below 80% acceptability above 25.5 ºC. Within 16.5 – 25.5ºC, the acceptability does not show a significant and consistent peak value over a specific range, but is mostly above 80% as presented by the flat green line. From both figures, we see that the temperature 16.5 ºC and 25.5ºC are likely to be the thresholds for the HVAC buildings when putting both summer and winter together. Again, there are only 32 votes at temperatures below 19.5 ºC, so the location of the lower threshold remains unclear.

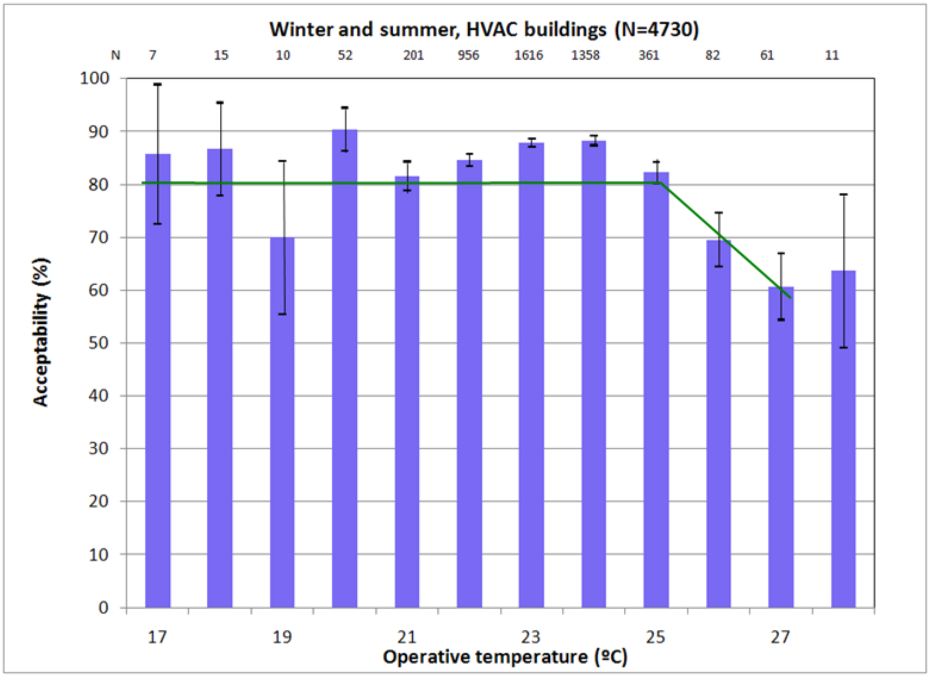


Figure 2. Acceptability against temperature at the workstation; HVAC buildings in the ASHRAE database; 5 locations shown in Table 1.

In NV and MM buildings, the indoor operative temperatures are quite different for winter and summer. The upper threshold at which acceptability drops below 80% occurs at 27.5ºC, 2K higher than the threshold for the HVAC buildings. Between 16.5 – 27.5ºC, there is no specific range that the acceptability is significantly better than the others, although the number of votes at 17 and 18ºC are very small (Figure 3).

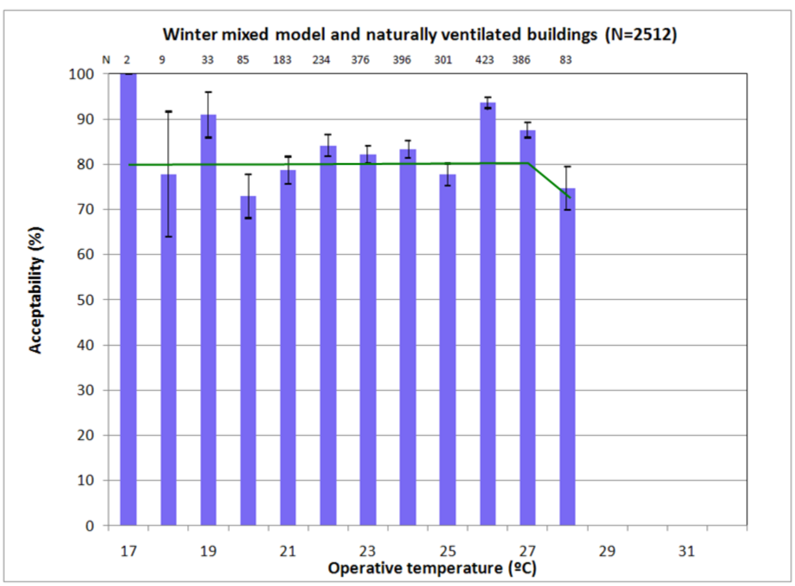


Figure 3. Acceptability against temperature at the workstation; winter; NV and MM buildings in the ASHRAE database; 5 locations shown in Table 1.

In summer, the NV and MM thresholds move towards the warm side (Figure 4). The significant reduction in acceptability below 80% happens at 30ºC, 2K above the threshold in winter. On the cool side, the drop happens at 21.5ºC, clearly at a warmer temperature than in winter. Most acceptability below this temperature is less than 80%.

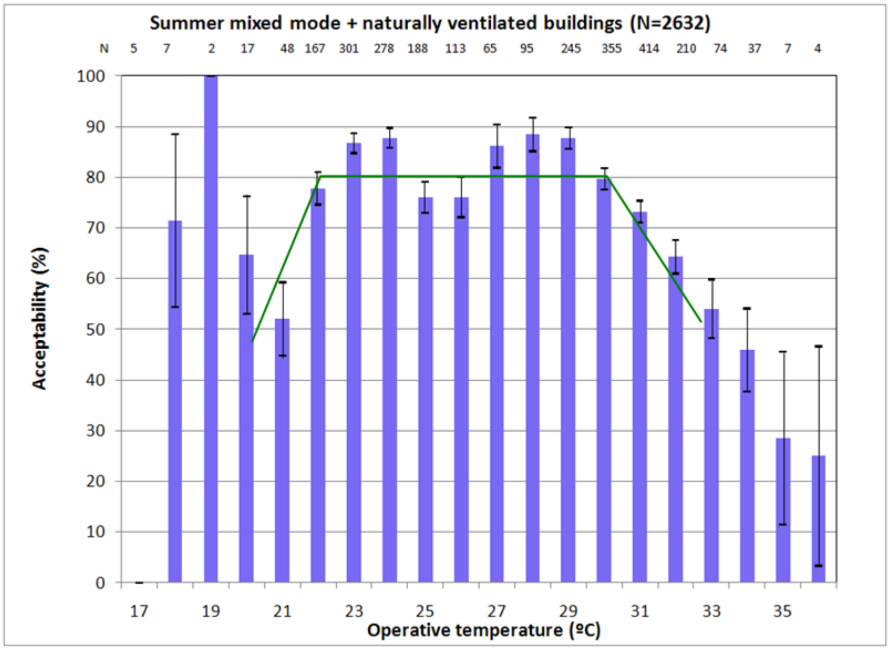


Figure 4. . Acceptability against temperature at the workstation; summer; NV and MM buildings in the ASHRAE database; 4 locations shown in Table 1.

3). Example of difference between AC and NV buildings. If we compare ASHRAE database studies of HVAC and NV in the same climate (Singapore), we see that the acceptability of the two thermal environments (in this case approximated by sensations between -1 and 1 inclusive) was very similar (78 and 76%), although the indoor thermal environmental conditions were very different (Figure 5). The higher thermal thresholds in NV building than in HVAC building are presumably due to expectation, physical and behavior adaptation (de Dear and Brager, 1998), and somewhat stronger air movement in the NV building (average 0.22 and 0.11 m/s for the NV and HVAC buildings respectively).

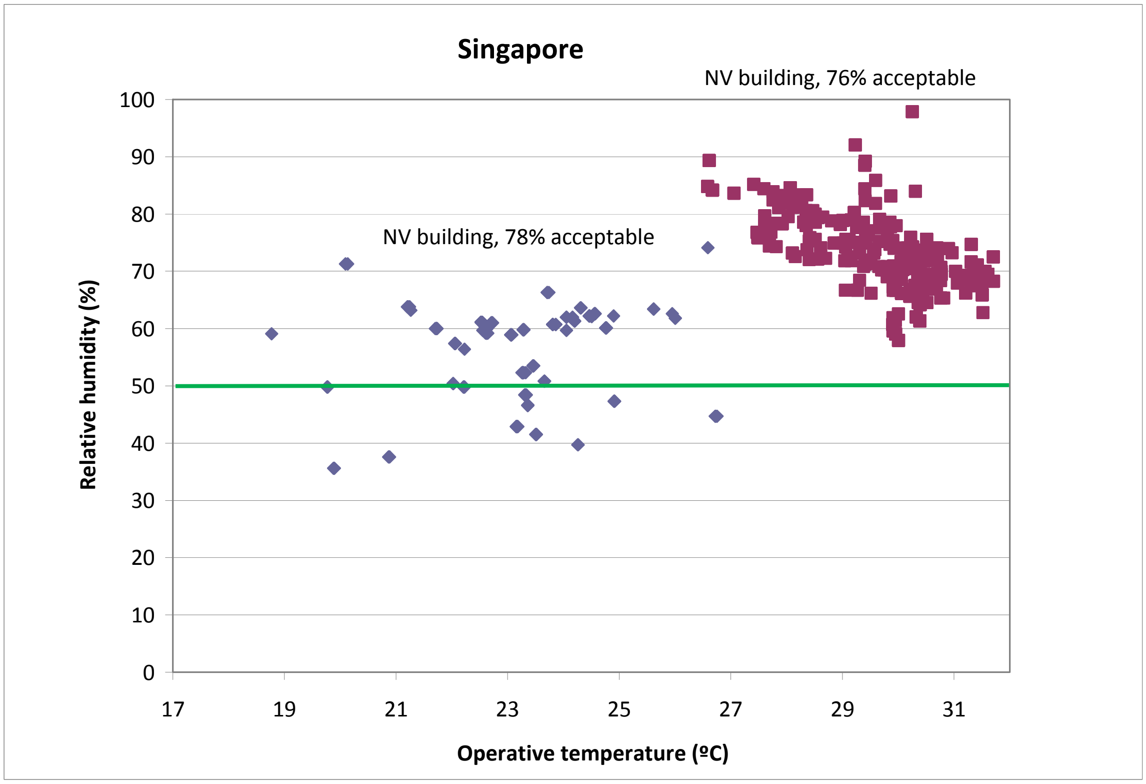


Figure 5. Similar acceptable rate for very different indoor thermal environments in HVAC (blue) and NV (red) buildings in Singapore.

4). Air movement effects on thresholds in HVAC buildings

In Figure 4, the 5K higher upper threshold in NV + MM versus HVAC buildings, may also be due to expectation, adaptation, and possible higher air movement acting to cool the occupants in NV buildings. The higher air movement was found only in Athens (average 0.4 m/s) and in Honolulu (0.3 m/s). For the rest of the studies, velocities were around 0.1 – 0.2 m/s, very similar to velocities found in HVAC buildings.

For 26, 27, and 28ºC, at which acceptability dropped off in the HVAC buildings (Figure 2), the average thermal sensations for the dissatisfied people were 1.4, 2, and 1.8 respectively. These indicate that these people felt warm discomfort. Looking at the air movement preferences for these unacceptable votes, we found that with one exception, all the 53 votes wanted more air movement (Table 2). The occupants perceive that air movement could potentially provide them comfort. The question is to what extent this is true.

Table 2. Dissatisfied people in warm environments for the unacceptable votes in the ASHRAE HVAC buildings (shown in Figure 2)

Ambient temperature	Number of	Average thermal	Air movement preference

(ºC)	votes	sensation	less	no change	more
26	25	1.4	0	0	25
27	24	2.0	0	0	24
28	4	1.8	0	1	3

Since the ASHRAE database contains a limited number of high air movement values, we look at laboratory studies in which air movement is provided by local fans. A recent study in the UC Berkeley environmental chamber (dataset 4) showed that with air movement in the upper body region, air movement at 0.6 and 1 m/s maintained comfort at 28ºC room air temperature (Figure 6). Since higher room air temperatures were not tested, we conclude that with the air movement, the threshold could be 28ºC or higher. In a different test (dataset 3), subjects in a room air temperature of 30ºC were cooled by 28ºC air movement in their breathing zone, and their comfort was equivalent to that of Figure 5.

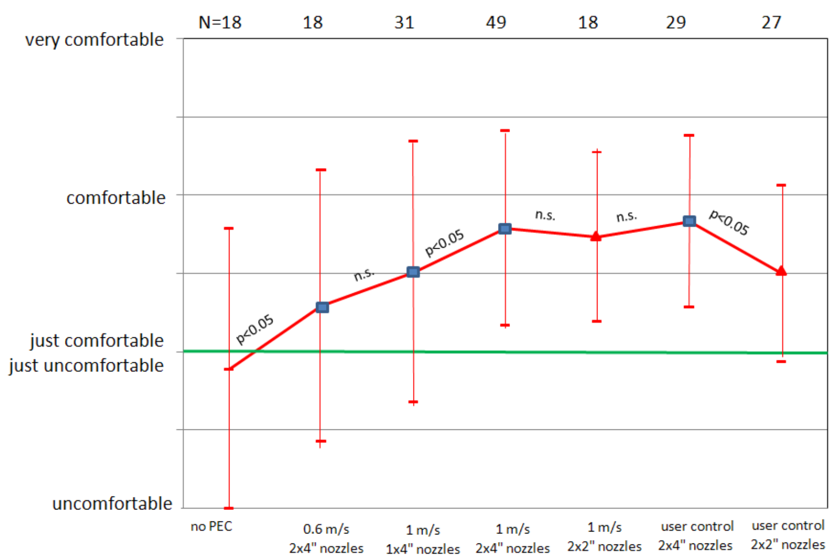


Figure 6. Whole-body thermal comfort with air movement (dataset 4)

5). Radiation effects on thresholds

Heating sources (such as radiant heaters) were not being used by the occupants in the ASHRAE database, and in general the warming effect of radiant sources is represented in the operative temperature as measured in the ASHRAE study (three heights above floor at the body's location). If our threshold temperature is being measured at a remote location (e.g., the thermostat) it is possible that local radiant heating of the occupant could expand the room's acceptable lower threshold, just as air movement can increase the upper threshold. In dataset 3

(Zhang et al. 2010), radiant and conductive heating of feet and hands was found to provide comfort at 18ºC, reducing the lower threshold for air temperature alone by more than 2K.

6). Thresholds for combinations of heating and cooling systems

Figure 7 uses the above results to suggest thresholds for HVAC buildings in which radiation and air movement sources are added to lower the acceptable heating boundary and to raise the cooling boundary. The thresholds are subdivided into two categories—1) sources that affect communal space conditions (radiant floors, ceiling fans) and 2) sources that affect the occupant directly and are under their control (personal environmental conditioning, or PEC).

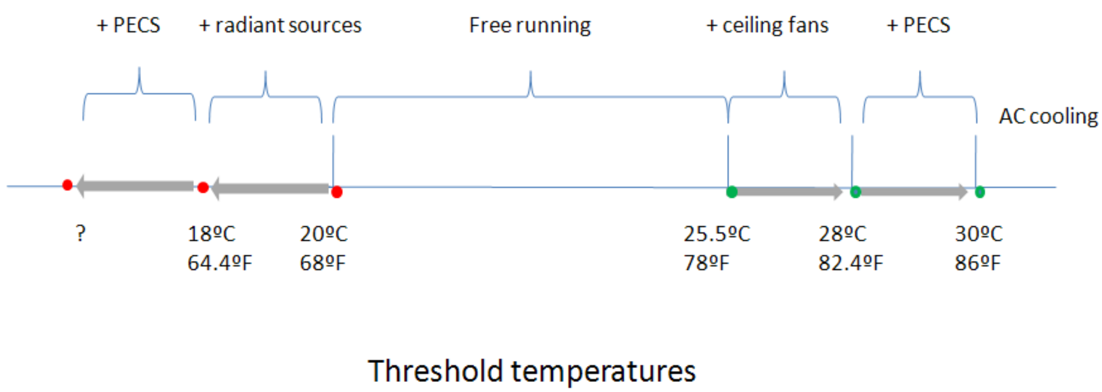


Figure 7. Thermal comfort temperature ranges with fans and radiant sources in buildings

7). Thresholds related to occupants' thermal preferences. Figure 8 shows the thermal sensation and the preferred thermal sensation from one of the laboratory studies (dataset3). Within sensation –1.5 (between slightly cool to cool) to 2 (warm), there is no clear trend for the preferred thermal sensation (within the box shown in the figure). That means within a certain sensation range, people's preferences are quite different. It is interesting to see that within the box, when people felt warm or cool, quite a number of people preferred a thermal sensation on the warm or cool sides (see the two shaded areas in the figure), but with a lower numeric value (lower than the 45 degree line in the figure). The preferred sensation did not go to the opposite side, in which, e.g., people who felt warm might have preferred a cool sensation.

Since one thermal sensation unit corresponds to about 3K temperature difference, thermal sensation preference over about 8K (sensation between –1.5 to 2) does not show strong difference. It is only when the thermal sensation reached to 2 or –1.5 and beyond, that the preferred sensation starts to indicate that people prefer cool/neutral when they felt warmer, and warm/neutral when they felt cooler (outside of the box).

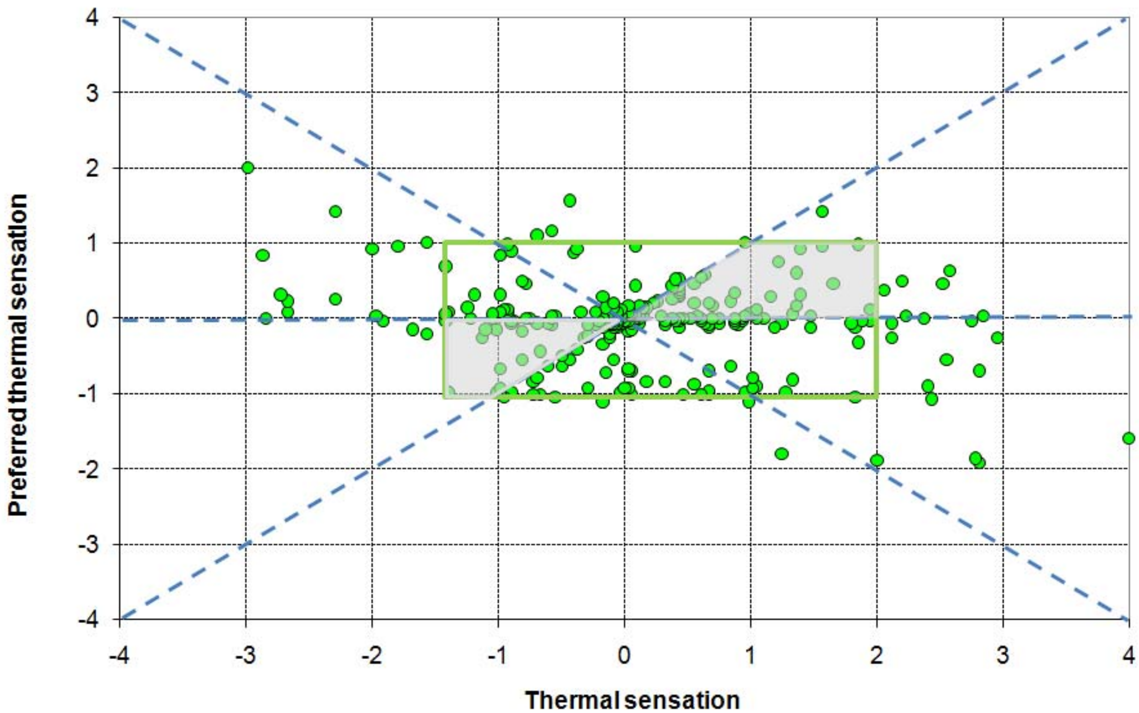


Figure 8. Thermal sensation vs. preferred thermal sensation (dataset3)

Thresholds for perceived air quality (PAQ)

Does perceived air quality also impose limits on comfort zone boundaries? If so, where are the thresholds? The ASHRAE database does not include PAQ questions. We will attempt to obtain answers from studies conducted in the UC Berkeley environmental chamber (dataset 3), and the field study at the Berkeley Civic Center (dataset 2).

1). PAQ related to thermal sensation

Figure 9 are the results from two laboratory studies, showing the PAQ votes compared to the difference between the subjects' thermal sensation and preferred thermal sensation. The PAQ scale is +0 (just acceptable) to 4 (very good), -0 (just unacceptable) to -4 (very bad). The sensation difference scale was introduced by Griffiths (1990) and Humphreys. By accounting for differences in individuals' ideal sensations, the scale measures how closely the environment matches the individuals' preferred environments. A positive value on the X axis (thermal sensation -preferred thermal sensation) means that people felt warm and would have preferred a cooler sensation (represented by red circles and yellow triangles); negative value means that people felt cool and would have preferred to be warmer (represented by blue circles).

This figure shows that when people felt cool and wanted to be warmer, the PAQ does not change (no trend). When people felt warm, the PAQ declined significantly. The decline happened when the difference of thermal sensation and preferred thermal sensation was around 0.5 scale unit (right boundary of the green rectangle). This figure suggests that the PAQ follows a "threshold" on the warm side, with no threshold on cool side for these test conditions.

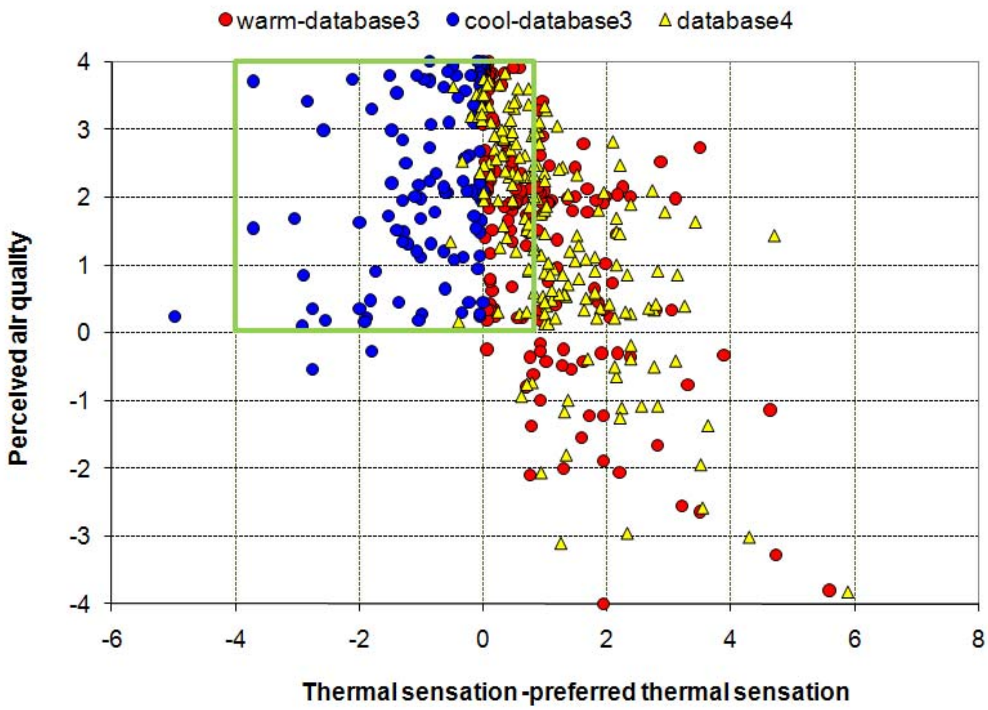


Figure 9. Perceived air quality vs. difference between thermal sensation and preferred thermal sensation.

2). PAQ related to air temperature and air movement

Now we would like to see where this threshold is located in terms of air temperature. Figure 10 shows that at air temperatures from 18 to 25ºC, the PAQ is quite identical. It drops significantly at air temperature 28ºC, and is further reduced at 30ºC. The drop happens between 25 and 28ºC, although the particular test conditions do not allow the exact temperature to be determined. Air movement is seen to bring PAQ at 28 and 30ºC back to the level found under neutral conditions (see the squares and triangles in the figure, Arens et al. 2008). Therefore, with air movement, the threshold is beyond 30ºC.

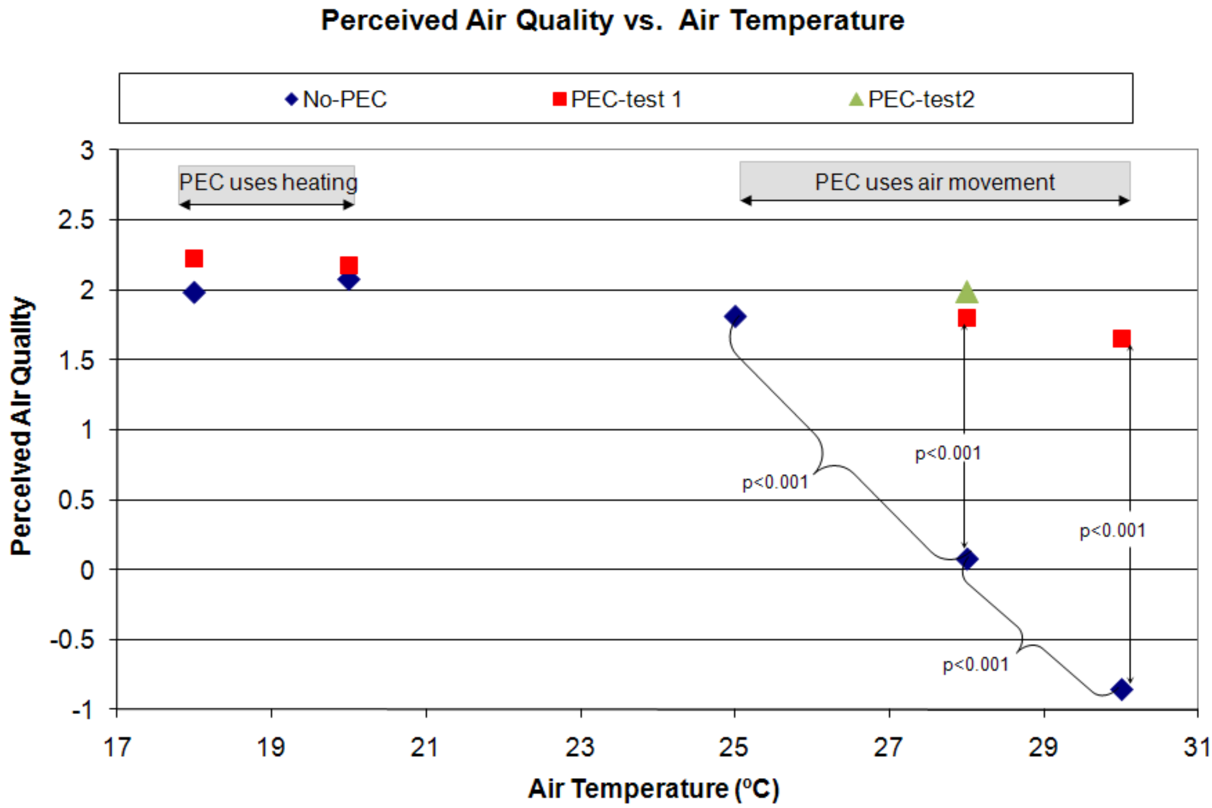
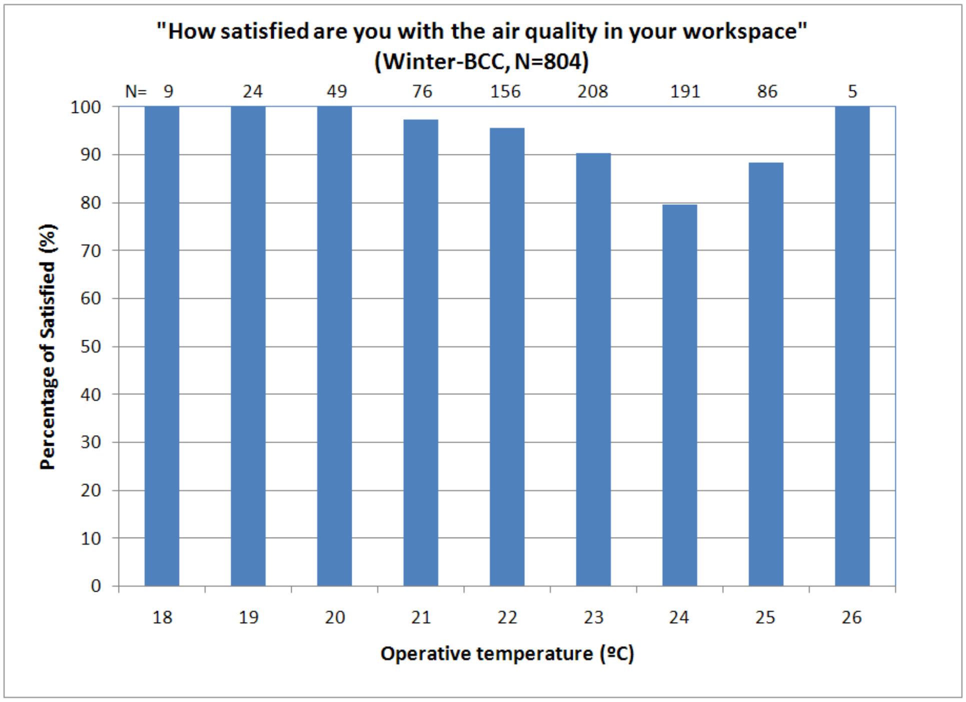


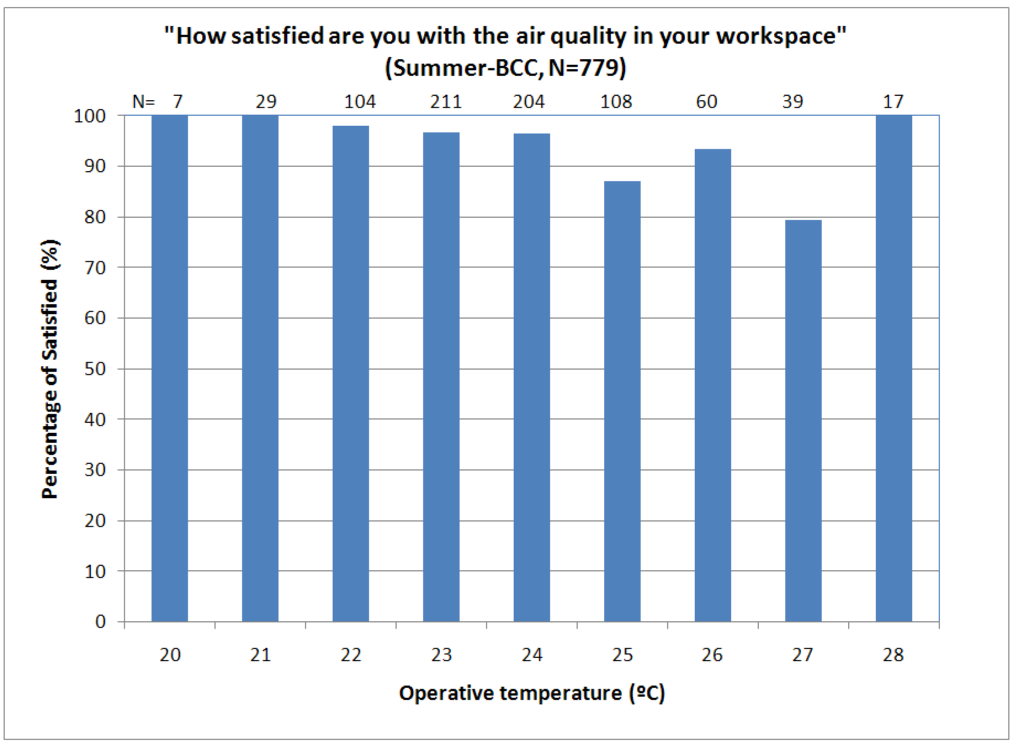
Figure 10. PAQ vs. air temperature and air movement

3). PAQ as measured in the Berkeley Civic Center

The threshold for PAQ without air movement is not clear from Figure 9. We looked for this in the BCC field data (dataset 2), the only study in which perceived air quality and concurrent air temperatures have been measured. The questions and the answers are presented in Figures 11a and b, for winter and summer studies respectively. It shows that for the air temperature ranges measured (up to 26ºC in winter and 28ºC in summer), no clear threshold was reached. Although the BCC is a NV building, measured velocities were low, averaging 0.04 m/s in summer and 0.05 m/s in winter.



a. Winter BCC: clear threshold not reached within 18 – 26ºC.



b. Summer BCC: clear threshold not visible within 20 - 28 ºC.

Figure 11. PAQ vs. temperature for BCC database

4). PAQ related to thermal comfort

In the absence of a clear temperature threshold for PAQ, we looked for other means of controlling it. Figure 12 shows that PAQ is closely correlated with thermal comfort. The figure is from the two laboratory studies (datasets 3 and 4). If this strong correlation holds in real buildings, we might assume that when comfort is maintained, PAQ is maintained as well.

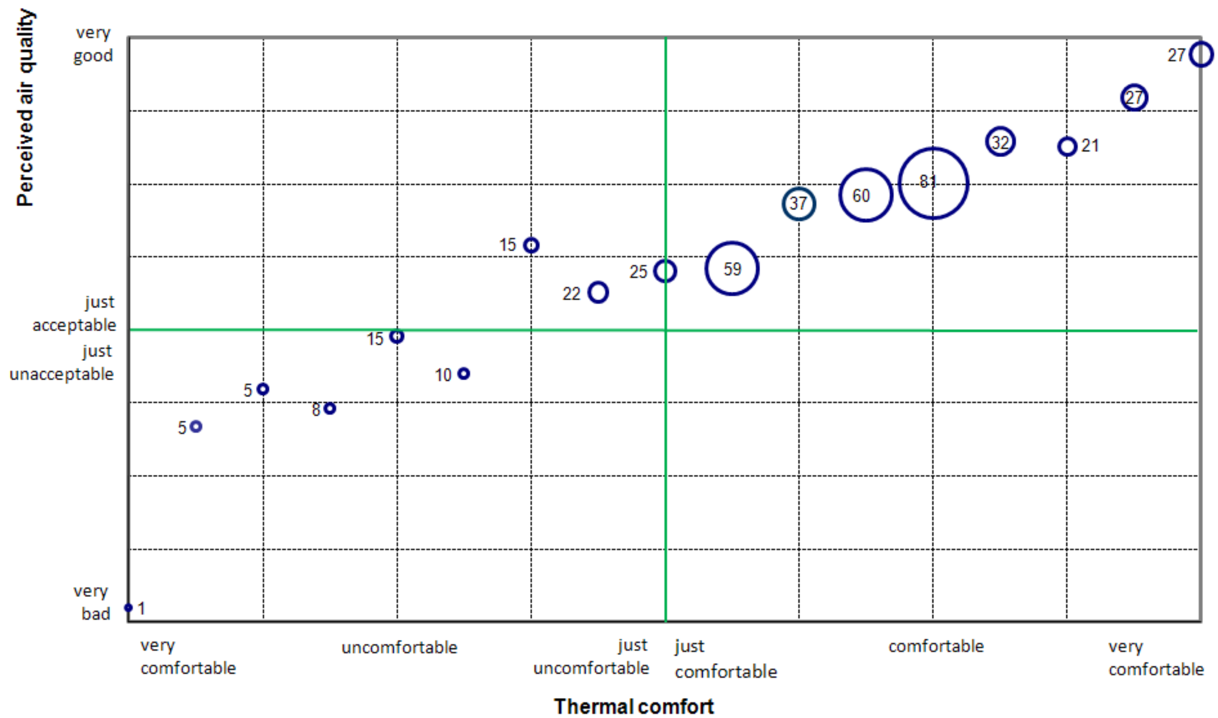


Figure 12. PAQ vs. thermal comfort, binned data. The circle diameters represent the number of votes shown nearby (N=450, datasets 3&4).

Discussion

1). Thresholds for productivity. Productivity might also follow a threshold in temperature or comfort. Figure 13 (adapted from Seppanen et al. 2003 by adding results from Tawada et al. 2010) shows that within air temperatures from 21 – 27ºC, there is no obvious best temperature for productivity. Beyond this range, productivity declines in most of the studies. However, one should note that these tests did not have elevated air movement under warm conditions, so if productivity were linked to comfort, the temperatures shown might not represent productivity in naturally ventilated buildings.

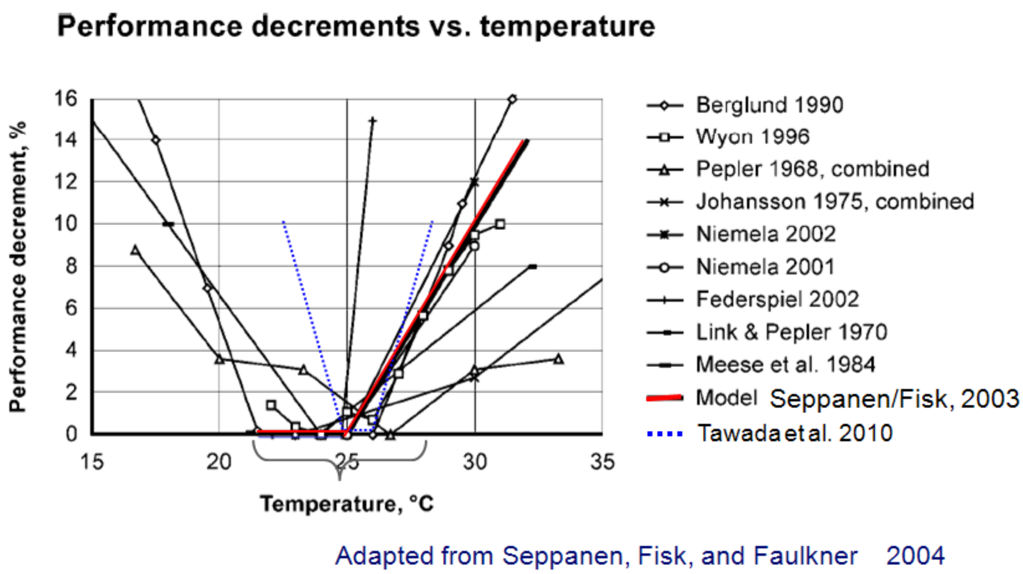


Figure 13. Summary of the studies on the effect of room temperature on decrement of performance and productivity (adapted from Seppanen et al. 2003, adding Tawada et al. 2010).

A study by Uchida et al. (2009) shows that self-estimated performance is strongly related with thermal comfort satisfaction (Figure 14, r=0.97). When correlating the self-estimated performance with air temperature, the correlation is very poor, r=-0.21. This result is strongly similar to that shown for PAQ in Figure 12. This might lead to the hypothesis that making people thermally comfortable is the key factor in maintaining PAQ and productivity.

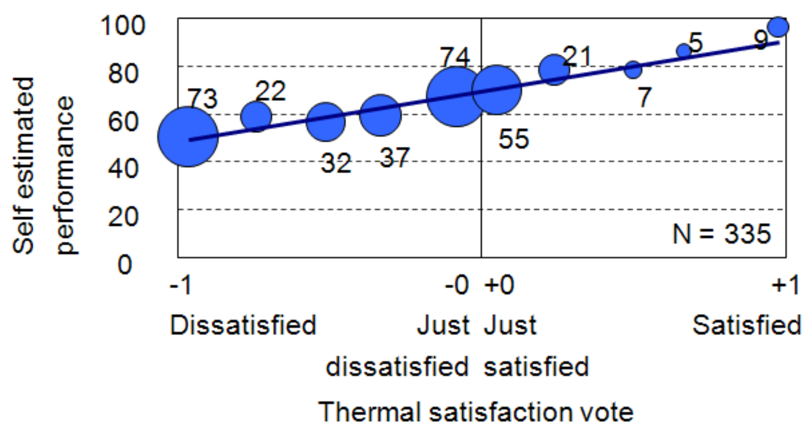


Figure 14. Self estimated performance vs. thermal satisfaction - 335 observations from workers. R=0.97 (Uchida et al. 2009)

2). Overcooling and overheating in HVAC buildings. Recent field studies in a large number of US office buildings (Mendell 2009 for 95 buildings, and Choi 2010 for 20 buildings) show that the average indoor air temperature is being maintained cooler in summer than in winter (22.9ºC summer and 23.4ºC winter in Mendell and 23.3ºC and 23.5ºC in Choi). This summer overcooling works against human adaptation, and the reasons for it are unclear, since the practice increased both discomfort (Mendell and Choi) and sickness symptoms (Mendell) in each season. In addition, health surveys in a large number of buildings (Burge et al. 1987, Zweers et al. 1992, Fisk et al. 1993) found that sick building syndrome is significantly more prevalent in air-conditioned buildings than in naturally ventilated buildings. We need to understand why this obviously non-adaptive operation of HVAC buildings is so widespread, and what role it might be playing in the worldwide conversion of NV buildings to HVAC.

3). Energy impacts of thresholds in HVAC buildings. By focusing on the environmental conditions outside of the thresholds and not tightly-controlling within them, the threshold concept encourages the designs of free-running, mixed-mode, or naturally ventilated buildings. It also encourages the use within HVAC buildings of energy efficient technologies with limited cooling capacity (such as evaporative coolers); and increases the effectiveness of other energy efficient measures that may be inherently slow-acting or unpredictable (such as radiant ceilings/floors) and that inherently cause fluctuation in space air temperature.

Figure 15 shows that, by broadening the interior temperature thresholds in HVAC buildings, each 1K broadening corresponds to about 7 – 15% energy saving (see Figure 13, Hoyt 2009).

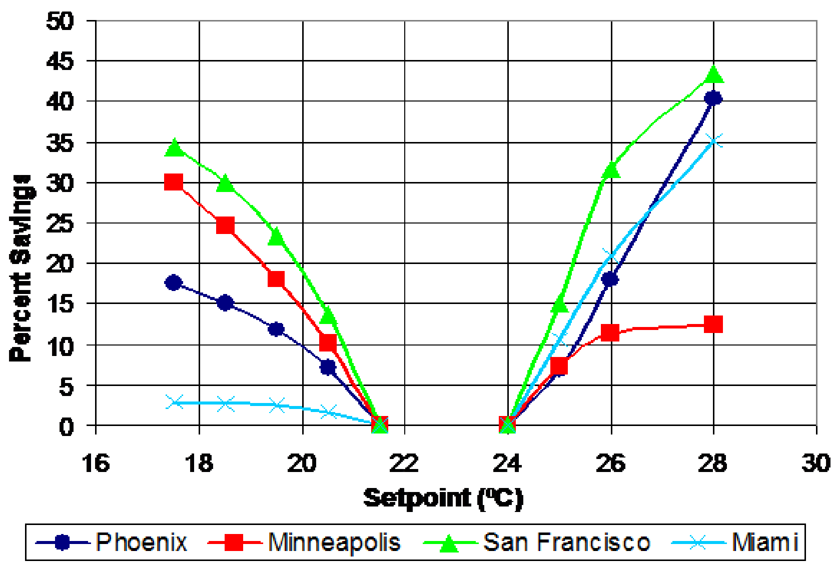


Figure 15. HVAC energy savings for widened air temperature setpoints relative to conventional setpoint range in San Francisco, Miami, Phoenix, and Minneapolis (Hoyt et al. 2009)

In addition to the operational savings seen in Figure 15, savings may be obtained by reducing the required sizes of equipment and ducts.

4). *Threshold applicability*. The thresholds described in this paper are based on occupant surveys taken at random times. The rate of change that may have been occurring in the occupants' environments was not measured. If the temperature is changing rapidly, people may not adapt to the full threshold range observed. The thresholds do not shed light on the extent of adaptation within short time ranges, such as an hour or a day, but they do reflect typical changes occurring in real buildings.

Conclusion

The threshold patterns shown in this paper suggest that when indoor air temperature is within defined thresholds, there is little advantage to fine-tuning the air temperature to an optimum. The air-conditioning system should focus on environmental conditions outside the thresholds to bring them within. In NV buildings the thresholds are quite broad due to occupant adaptive behavior. Thresholds may be successfully broadened in both HVAC and NV buildings by adding air movement and radiation to the occupied space or the occupants directly through PEC systems. The energy impacts are very substantial. The threshold concept makes the design of free-running-mode- and naturally ventilated buildings more feasible, and reduces the need for energy-intensive air-conditioning in buildings.

References

Arens, E, M Humphreys, R de Dear, H Zhang (2010), Are 'Class A' temperature requirements realistic or desirable? *Building and Environment* 45(1), 4 - 10.

Brager G, Paliaga G, deDear R (2004), Operable windows, personal control and occupant comfort. *ASHRAE Transactions* 110 (2): 17-35.

Burge, A, A Hedge, S Wilson, JH Bass, A Robertson (1987), Sick building syndrome: A study of 4373 office workers, *Annals of Occup. Hygiene* 31(4A), 493 – 504

Choi, JH, Azizan Aziz, V. Loftness (2010), Investigation on the impacts of different genders and ages on satisfaction with thermal environments in office buildings, *Building and Environment*, 2010.

de Dear, R (1998), A global database of thermal comfort field experiments. *ASHRAE Transactions* 104(1b): 1141-1152.

de Dear, R, Brager, GS (1998), Developing an adaptive model of thermal comfort and preference, *ASHRAE Transactions* 104(1B) (1): 145–167.

Fisk WJ, Seppänen O, Faulkner D, Huang J (2003), Cost benefit analysis of ventilation control strategies in an office building, *Proceedings of Healthy Buildings 2003 Conference.* Singapore. December 2003. Vol 3:361-366.

Fisk WJ, MJ Mende11, JM Daisey, D Faulkner, AT Hodgson, M Nematollahi, JM Macher, (19930, Phase 1 of the California Healthy Building Study: A Summary, *Indoor Air* 3, 246 – 254.

Griffiths, ID (undated, circa 1990), Thermal comfort in buildings with passive solar features: field studies. Report to the Commission of the European Communities ENS3S-090-UK, Department of Psychology, University of Surrey, GU 2 5XH, UK, pp123.

Hoyt, T, HL Kwang, H Zhang, E Arens, T Webster (2009), Energy savings from extended air temperature setpoints and reductions in room air mixing. *International Conference on Environmental Ergonomics* 2009, August.

Nicol JF, MA Humphreys (1972), Thermal comfort as part of a self regulating system, in: Langdon, Humphrers, Nicol (Eds.), Proc. Of CIB Commission W45 Symposium – Thermal comfort and moderate heat stress, Building Research Establishment Report, Her Majesty's Stationery Office (HMSO), London, 263 – 274.

Humphreys, MA (unpublished manuscript), Do people like to feel 'neutral'? Systematic variation of the desired sensation on the ASHRAE scale of subjective warmth.

Humphreys, MA, JF Nicol, KJ McCartney (2002), An analysis of some subjective assessments of indoor air-quality in five European countries. *Indoor Air 2002*.

Mendell, M, A Mirer (2009), Indoor thermal factors and symptoms in office workers: findings from the US EPA BASE study, *Indoor Air 2009*, 19, 291 – 302.

Tawada, T, T Ikaga, S Murakami, S Uchida, H Ueda (2010), The total effect on performance and energy consumption caused by office's thermal Environment, *J. Archit. Plann. Environ. Eng., AIJ*, No.648, 213-219, Feb., 2010 September.

Uchida, S, S Tanabe, N Nishihara, M Haneda, S Nakamura, G Kawaguchi (2009), The evaluation of productivity in COOL BIZ office by field measurement of thermal environment and questionnaire survey, *Proceedings of Healthy Buildings 2009,* September.

Zhang, H, E Arens, D Kim, E Buchberger, F Bauman, and C Huizenga (2010), Comfort, perceived air quality, and work performance in a low-power task-ambient conditioning system, Building and Environment 45(1), 29 – 39.

Zweers, T, L Preller, B Brunekreef, JSM Boleij (1992), Health and indoor climate complaints of 7043 office workers in 61 buildings in the Netherlands, *Indoor Air* 2, 127 – 136.