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Air temperature thresholds for indoor comfort and perceived air quality

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Abstract

Air temperature thresholds are investigated and proposed for acceptable comfort in air-conditioned buildings. Using the ASHRAE database of field studies in which acceptability votes were obtained from occupants, it is shown that within the thresholds, the acceptability is indistinguishable. Therefore, there is little gain from conditioning spaces to an “optimum” air temperature and a significant energy savings. However beyond the thresholds, there is a significant drop-off in acceptability. Ideally, air-conditioning would be used only when the environmental conditions are beyond the thresholds. The use of ceiling fans or personal environmental control systems broadens the threshold range. Thresholds are determined for both air-conditioned and ventilation-cooled buildings in the database. The equally-acceptable range between the thresholds is 8 – 10 K wide in both types of buildings. It is possible that a perception of reduced air quality in warm environments could impose an upper temperature threshold. Perceived air quality (PAQ) is examined in two laboratory studies done at air temperatures from 18 - 30 deg C. PAQ is seen to be closely correlated to thermal comfort rather than temperature; as long as thermal comfort is maintained by the air movement, PAQ will be acceptable. Relationships between temperature thresholds and productivity, operating setpoints, and energy use are also discussed.

Keywords:

Thermal acceptability, air movement, free running, personal environmental control (PEC), air-conditioned buildings, adaptive comfort, thermal comfort

Introduction

A suite of physiological and behavioural adjustments allows one to adapt unconsciously to one's environments. As a result, one is able to experience a range of environmental conditions as equally comfortable, or acceptable. For thermal environments in buildings, this acceptable range roughly centers on the ‘neutral’ or ‘optimal’ temperature for the particular activity or occupancy in the building. Since individual occupants will differ physiologically, and may have somewhat different requirements for their behaviour, their optimal temperatures (and acceptable comfort ranges) will be diverse. 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, it is perhaps more important to examine these zone boundaries and ways to expand them because they are the ‘thresholds’ beyond which energy is needed to condition interior space.

Historically, mechanical air-conditioning (heating, ventilation and air conditioning systems, HVAC) has enabled designers to engineer buildings to previously unimaginable levels of certainty, guaranteeing standards' comfort criteria 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 toward air-conditioning over NV in design practice 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 (using PMV calculated for one clothing and activity level); the extrapolation to the borders where unacceptability or dissatisfaction begins (using PPD) is entirely based on laboratory studies (Standard 55 of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), 2010). This approach is not based on real buildings with real populations of occupants, nor on direct measurement of comfort or acceptability. It is based on an ideal of what HVAC could make possible.

The need to address energy efficiency has forced the authors to look at space conditioning requirements more directly to understand how they affect the occupants of actual functioning buildings. For this one must use the results of field studies in which occupants were surveyed and concurrent physical measurements taken. A number of such studies have been made. A database of their results has been accumulated under the auspices of ASHRAE (de Dear 1998) allowing analysis of real occupant populations in a number of countries worldwide. Another database of European results (SCATs) has been assembled for European countries (McCartney and Nicol, 2002).

Initial examination of these databases found that space conditioning requirements in naturally ventilated (NV) buildings differ from those in HVAC buildings. Analyses (de Dear and Brager 1998) supported earlier suggestions (Nicol and Humphreys, 1972) that human adaptation was more active in NV buildings, and that zones of equal thermal sensation for occupants of NV buildings were generally broader than for those in HVAC buildings. The resulting 'adaptive' comfort zones have obvious energy efficiency implications, and adaptive models of comfort have now been adopted into building codes for buildings with operable windows (ASHRAE Std 55, 2010) and for free-running buildings (CEN/ISO 15251, 2007).

The adaptive comfort zones, like earlier comfort zones, were developed from thermal sensation votes in occupant surveys, employing an assumed relationship between a person's warm/cool sensations and his/her thermal satisfaction. Satisfaction in field studies is assumed when sensation votes are between -1 (slightly cool) and +1 (slightly warm) on a seven-point scale ranging from cold to hot. A more direct approach to determining comfort zones is to obtain the occupants' assessment of whether they find their thermal environment acceptable. (The question is usually a binary 'yes' or 'no' on the survey, but it can also be measured in a continuous scale from 'very unacceptable' to 'very acceptable'). With this question the occupants are judging their thermal condition in the context of their expectations for the type of environment or work setting that they are in. It should be the 'bottom-line' question for determining a building's comfort zone.

Not all field studies have asked an acceptability question, but a substantial number in the ASHRAE database have done so. A previous examination of the 'acceptability' votes in a subset of ASHRAE field studies showed a broader and flatter acceptable temperature range than when the range was extrapolated from thermal sensation votes (Arens *et al.* 2010). The zone boundaries, or thresholds beyond which space conditioning is needed, tended to suggest 'thresholds', since the drop-off beyond them is rapid. In this paper, the threshold concept is examined further, using field survey data from the entire ASHRAE database of acceptability votes. Of particular interest are additional expanded threshold values that might be possible with energy-efficient cooling systems, such as ceiling fans and personal fans that offset warm

temperatures, and personal heating systems that offset cool ambient temperatures.

The paper also examines whether temperature thresholds might be imposed by occupants' perception of air quality. Perceived air quality (PAQ) is a temperature-related issue. If perceptions of bad air quality inevitably occurred at warm temperatures (Fang *et al.*, 1998), the upper threshold of the comfort zone might be ultimately dictated by perceived air quality acceptability, rather than by thermal acceptability. Recent laboratory test results are used to analyse this issue (Zhang *et al.*, 2010).

The paper briefly discusses relationships between temperature thresholds and occupant productivity, HVAC operating setpoints, and building energy use.

Method

Acceptability votes are used for determining for the temperature thresholds. Within the ASHRAE field study database, sixteen studies of 71 buildings in 7 locations include acceptability votes. These are assembled for analysis into Dataset 1. Dataset 2 supplements the ASHRAE database with acceptability votes from an additional building and location, studied in two seasons. It is a naturally ventilated building, the Berkeley Civic Center (BCC, Brager and Paliaga, 2004).

Table 1 shows the study locations for the 72 buildings in Datasets 1 and 2. HVAC buildings are distinguished from NV plus mixed-mode (MM) buildings. MM buildings contain air-conditioning but operate at times in NV mode.

Table 1. ASHRAE database locations analyzed in this paper, by building type.

Location	Season	Number of buildings	T _{max} (°C)	T _{min} (°C)	T _{avg} (°C)
HVAC buildings (N=4730)					
Kalgoolie	summer	21	31.7	19.8	23.7
	winter	22	24.5	16.6	22.1
Townsville	summer	12	27.7	21.2	23.8
	winter	12	25.7	19.8	23.4
Montreal	summer	12	26.9	21.0	23.6
	winter	11	25.0	19.9	22.6
Sydney	winter	2	23.8	20.9	22.3
Honolulu	hot season	2	26.9	19.6	23.3
	cool season	2	23.5	21.0	22.5
NV and MM buildings (summer, N=2512)					
Berkeley	NV	1	30.3	19.7	21.4
Sydney	MM	1	27.3	20.8	24.0
Merseyside	NV	3	25.9	16.6	21.9
Athens	NV	6	36.4	17.7	30.1
NV and MM buildings (winter, N=2632)					
Berkeley	NV	1	27.9	17.6	22.9
Sydney	MM	1	27.3	16.8	23.2
Merseyside	MM	1	25.9	18.7	23.4
Merseyside	NV	8	25.9	18.6	21.9
Honolulu	NV	4	27.6	23.1	26.1

Notes: "N" represents the number of votes in each category. Also shown are number of buildings in each field study, and

their mean measured indoor temperature maxima, minima, and averages.
 HVAC = heating, mechanical ventilation and air-conditioning
 MM = mixed mode
 NV = naturally ventilated

In these field studies, the acceptability scale is a binary scale. The occupants chose either ‘yes’ or ‘no’ to decide whether their thermal environments were acceptable. From these data, the percentage of occupants voting acceptable or unacceptable can be calculated for a range of temperature bins. The criterion for a successful design in comfort standards (ASHRAE, 2010) is 80% of the occupants satisfied. If one can equate ‘satisfaction’ with ‘acceptability’ (which seems reasonable), it can be said the warm and cold thresholds occur when acceptable votes drop below 80%.

The analysis of perceived air quality is done using the BCC results (Dataset 2), since Database 1 surveys did not include a PAQ question. In the BCC study perceived air quality was measured with a 7-point scale ranging from ‘very dissatisfied’ to ‘very satisfied’. The velocities measured in BCC were in general quite low. In order to find thresholds for warm conditions with higher levels of air movement, the results from two human subject studies of local cooling/heating devices (Datasets 3 and 4) were used. These studies were performed in an environmental chamber at the University of California at Berkeley at 18, 20, 25, 28, and 30°C, and the PAQ effect of temperature and air movement was tested, so Dataset 3 and 4 results are used together with Dataset 2 to define the PAQ thresholds. The PAQ scale used in the human subject tests is a continuous scale (Figure 1). It has a break in the middle to force a clear decision in the neutral region. In both environmental chamber studies, 18 college students experienced each test condition.

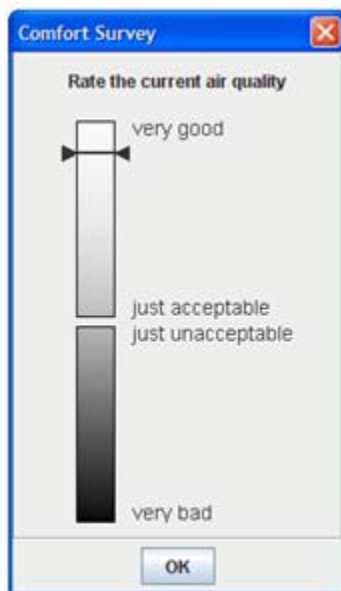


Figure 1. Perceived air quality scale used in the laboratory studies in Datasets 3 and 4.

The results are presented below in two parts, I for thermal acceptability and II for perceived air quality.

Results I: temperature thresholds for thermal acceptability

Previous work

Arens *et al.* (2010) analyzed occupants' operative temperature acceptability votes in the ASHRAE database of 45 central-HVAC office buildings in Kalgoorlie and Townsville (both in Australia), Montreal in Canada, and the NV BCC 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 2. The data was binned at the middle of each degree, and the brackets indicate ± 1 standard deviation.

The figure shows a roughly flat top in acceptability over a 9K temperature range (16.5 – 25.5°C). Between 25.5 – 28.5°C, the acceptability reduced significantly and consistently, well below the 80% acceptability. Because of low vote numbers in cool conditions, it is unclear whether 17 or 18°C is acceptable.

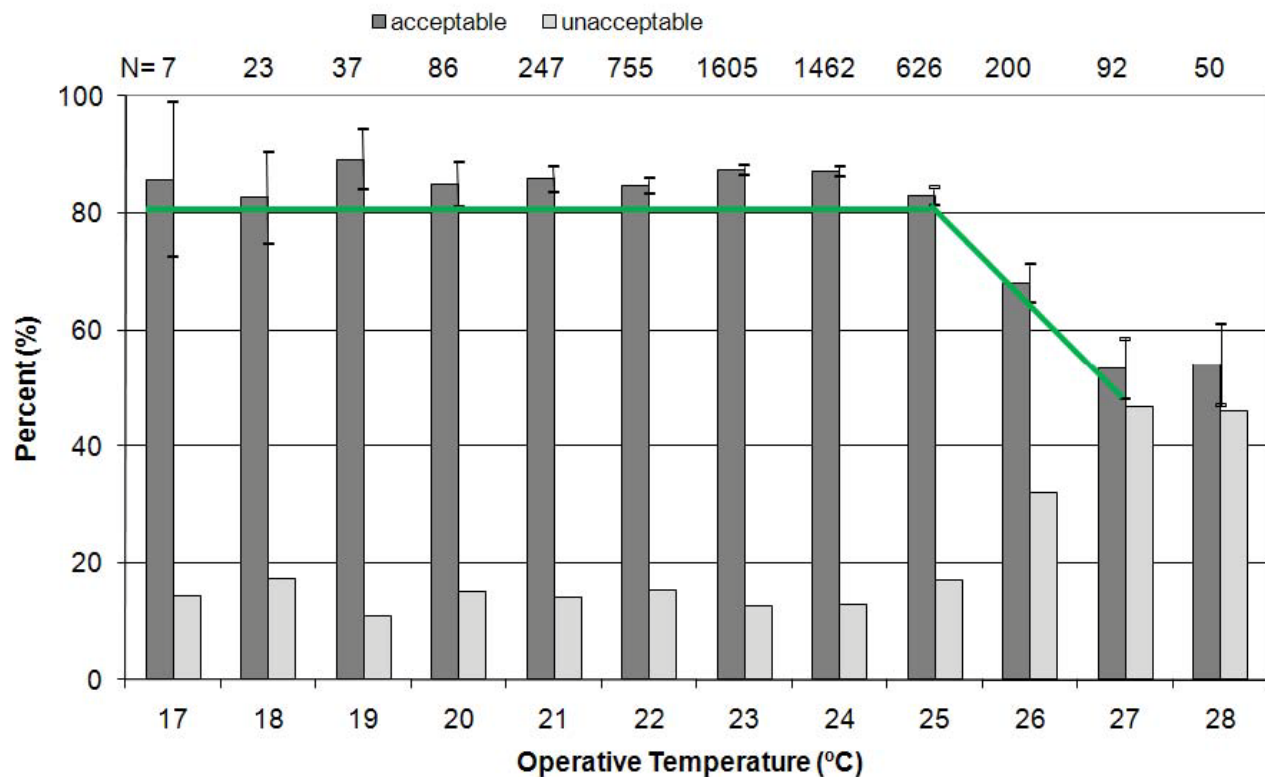


Figure 2. Acceptability against temperature at the workstation, annual; pooled three locations of ASHRAE and Berkeley Civic Center (BCC) data. (summer and winter, N = 5190).

Acceptability thresholds for air-conditioned versus naturally ventilated buildings

The authors have here enlarged the above-mentioned dataset by including all ASHRAE database studies in which thermal acceptability was measured. Three HVAC building studies (Honolulu hot- and cool seasons, and Sydney winter) are added to the locations included in Figure 2 (Kalgoorlie, Townsville, Montreal). Now HVAC buildings are treated separately from NV and MM buildings. Because in the HVAC buildings the indoor temperatures are not very different between summer and winter, we combined winter and summer in Figure 3. Figure 4 and 5 show results for NV and MM buildings, separating winter

and summer. The building locations for each figure are listed above in Table 1.

Figure 3 shows a roughly similar acceptability profile as Figure 2. Again it shows a drop below 80% acceptability above 25.5 °C. Within 16.5 – 25.5°C, 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 line. From both figures, it can be observed that the temperatures 16.5 °C and 25.5°C 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 °C, so the location of the lower threshold remains unclear.

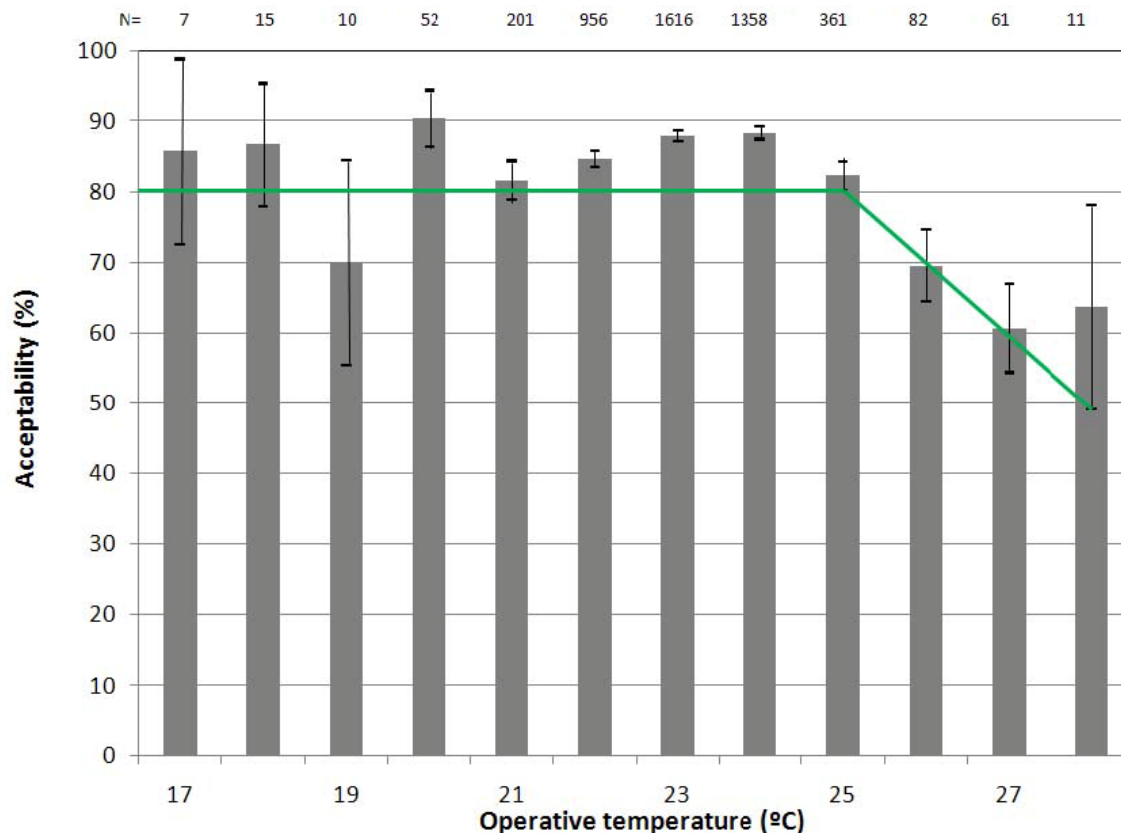


Figure 3. Acceptability against temperature at the workstation, winter and summer; HVAC buildings in the ASHRAE database (N = 4730); five locations shown in Table 1.

In NV and MM buildings, the indoor operative temperatures are quite different for winter and summer. In winter, the upper threshold at which acceptability drops below 80% occurs at 27.5°C, 2K higher than the threshold for the HVAC buildings. Between 16.5 – 27.5°C, there is no specific range that the acceptability is significantly better than the others, although the number of votes at 17 and 18°C are very small (Figure 4).

In summer, the NV and MM thresholds move towards the warm side (Figure 5). The significant drop-off below 80% acceptability occurs at 30°C, 2K above the threshold in winter. On the cool side, the drop happens at 21.5°C, clearly at a warmer temperature than in winter. Most acceptability below this temperature is less than 80%.

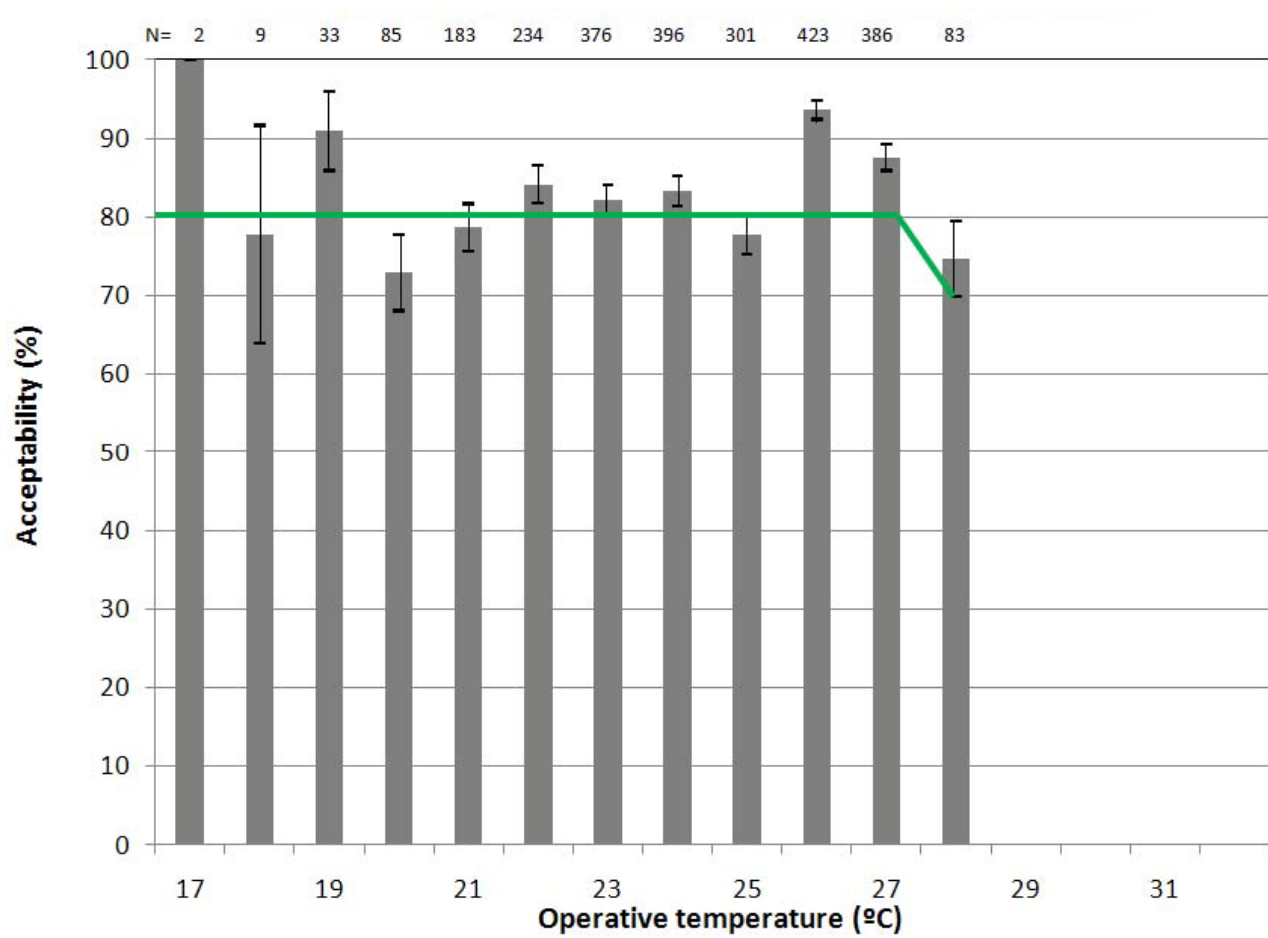


Figure 4. Acceptability against temperature at the workstation; winter; naturally ventilated and mixed-mode buildings (N = 2512) in the ASHRAE and BCC databases; five locations shown in Table 1.

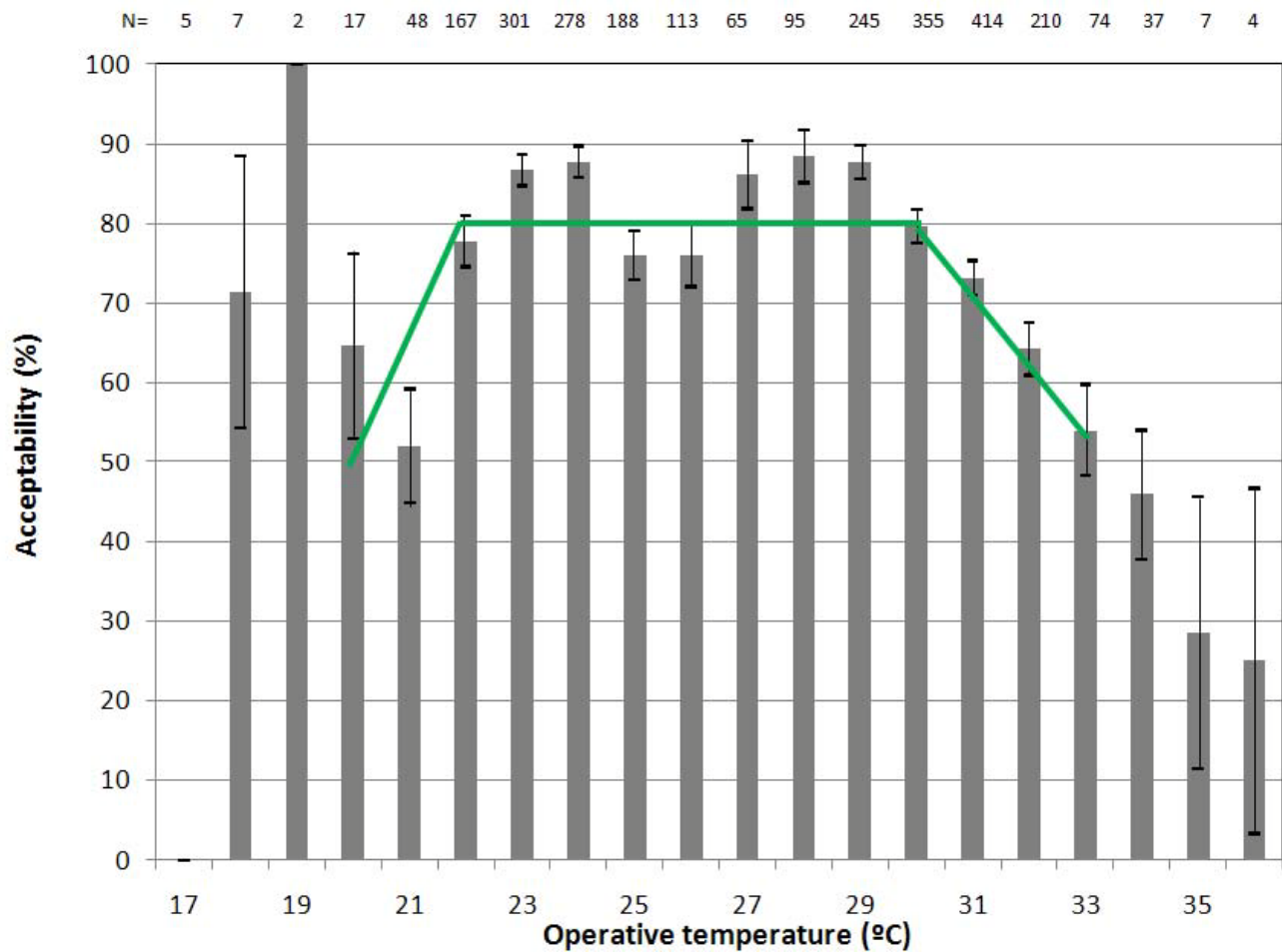


Figure 5. . Acceptability against temperature at the workstation; summer; naturally ventilated and mixed-mode buildings (N = 2632) in the ASHRAE and Berkeley Civic Center databases; four locations shown in Table 1.

There are other field studies in the ASHRAE database which do not have the acceptability question but have been examined for comfort limits based on sensation and comfort questions (*e.g.* Busch 1992, Nicol *et al.* 1999). These studies have found comfortable ranges that are somewhat greater than those shown here.

Example of difference between AC and NV buildings

If the ASHRAE database studies of HVAC and NV in the same climate (Singapore) are compared, it is evident the acceptability of the two thermal environments (in this case approximated by sensations between -1 and 1 inclusive because the acceptability votes are not available) was very similar (78 and 76%), although the indoor thermal environmental conditions were very different (Figure 6). 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 the somewhat stronger air movement in the NV building (average 0.22 m/s versus 0.11 m/s for the HVAC building).

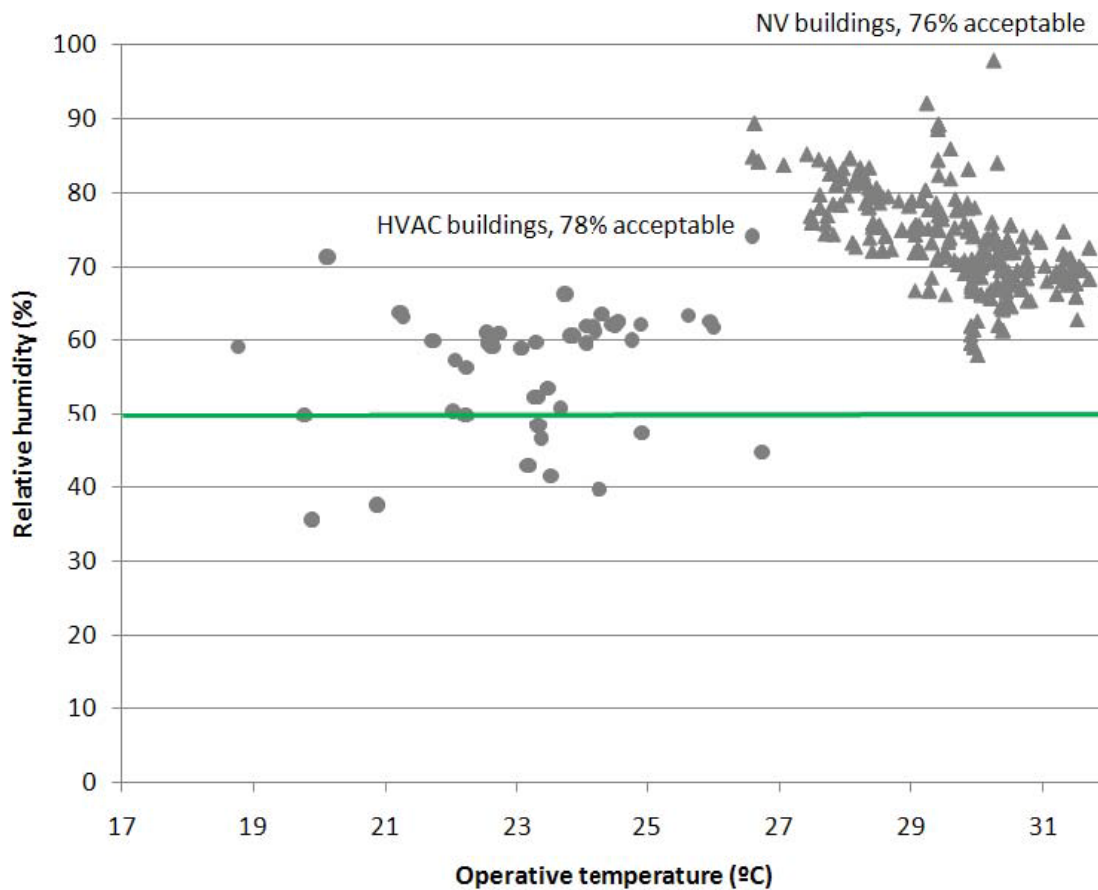


Figure 6. Similar acceptable rate for very different indoor thermal environments in HVAC (dots) and naturally ventilated (triangles) buildings in Singapore.

Threshold concept and values for HVAC buildings

Figure 7 uses the above field results to suggest thresholds for air-conditioned buildings. The thresholds provide guidance for operating HVAC buildings in “free running” mode as much as possible, with HVAC heating and cooling applied only after more energy-efficient alternatives such as fans and local heat sources and sinks have reached their outer temperature limits. The data for the alternative limits is gathered from laboratory studies.

The energy-efficient alternatives in Figure 7 are divided into two categories—1) sources that affect communal space conditions such as ceiling fans and 2) sources that affect the occupant directly and are under their personal environmental control (PEC) such as desk fans and heaters.

Figure 3 reveals that acceptability in HVAC buildings in the ASHRAE database dropped below 80% between 25 and 26°C in warm conditions, and between 19 and 20°C in cool conditions. Therefore, the Figure 7 temperature range for free-running mode is defined between 19.5 and 25.5°C.

On the warm side, area sources like ceiling fans provide comfort, with or without group control, from 25.5 to 28°C (McIntyre 1978, Fountain and Arens 1993, Rohles 1983, Schatzle 1989, Arens et al 2009). PEC fans provide individual-level comfort from 25.5 to 30 °C. Recent PEC studies at 28 and 30°C show that comfort is well maintained with breathing-zone air movements of 0.6 and 1.0 m/s (Zhang and Zhao 2009, Zhang *et al.*, 2010).

On the cool side, the authors' laboratory study (Zhang *et al.* 2010) showed that local radiation sources provide comfort for people at ambient condition 18°C. Below that, a study for automobile industry by Zhang *et al.* (2007) showed that a warmed contact seat can make people comfortable at ambient air temperature 15°C. Recent tests at UC Berkeley found comfort with a heated seat to 12°C ambient. Because it may be too much to extrapolate these tests to building environments, the authors have left the lower limit unknown. Below the unknown mark, space heating is needed.

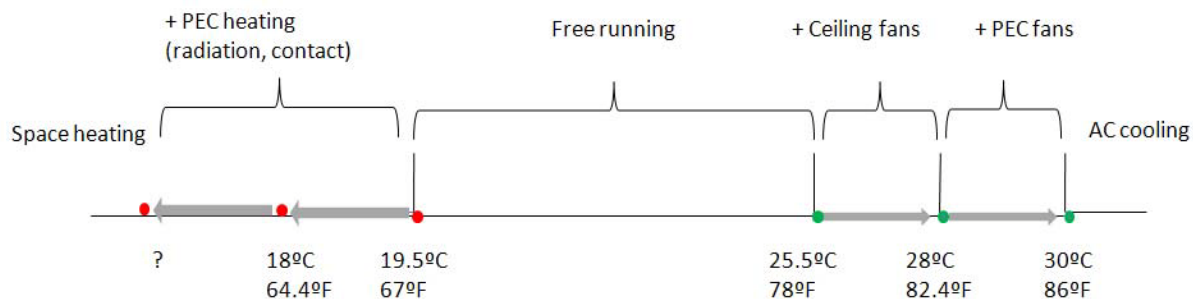


Figure 7. Thermal comfort air temperature thresholds for HVAC buildings with fans and radiant sources in buildings

Results II: thresholds for perceived air quality (PAQ)

If perceived air quality were reduced in warm temperatures, it might impose a practical limit on the warmer comfort zone boundaries. The ASHRAE database does not include PAQ questions. This is investigated using the PEC studies conducted in the University of California at Berkeley environmental chamber (Datasets 3 and 4), and the field study at the Berkeley Civic Center (Dataset 2).

PAQ related to air temperature and air movement

Figure 8 shows that at air temperatures ranging from 18 to 25°C, PAQ is does not vary much (Dataset 3). It drops significantly at air temperature 28°C, and is further reduced at 30°C. The drop happens between 25 and 28°C, although the particular test conditions do not allow the exact temperature to be determined. Air movement is seen to bring PAQ at 28 and 30°C back to the level found under neutral conditions (see the circles and triangles in the figure, Arens *et al.* 2008). Therefore, with air movement, the PAQ threshold is beyond 30°C.

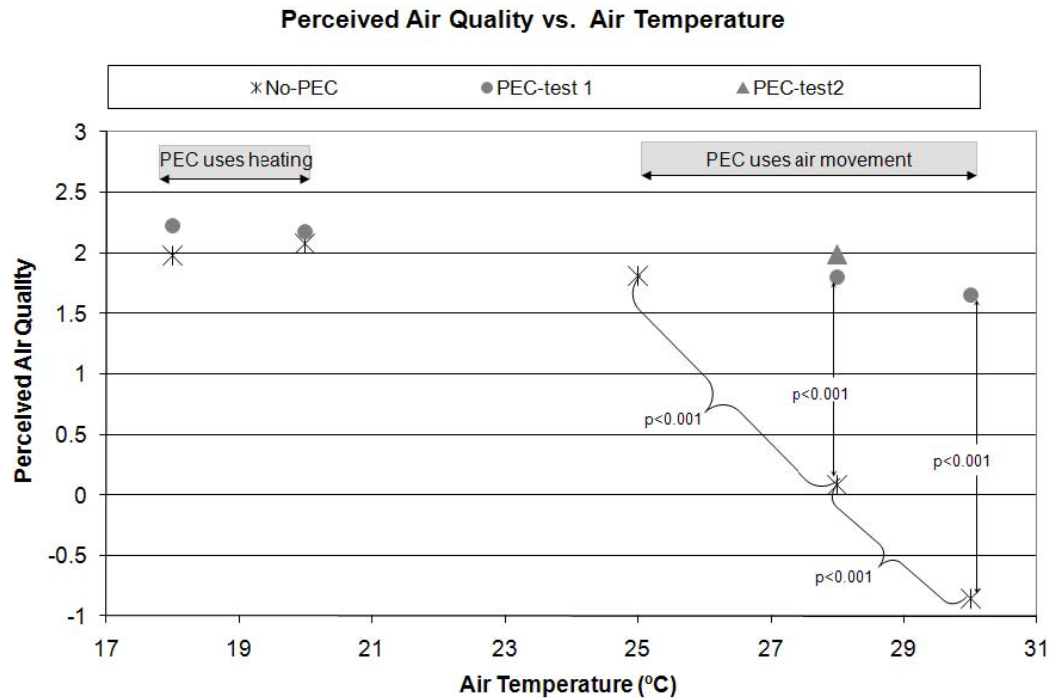


Figure 8. PAQ versus air temperature and air movement

PAQ as measured in the Berkeley Civic Center

The threshold for PAQ without air movement is not clear from Figure 8—it is somewhere between 25 and 27.5 °C. The authors looked for the threshold 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 9a and b, for winter and summer studies respectively. It shows that for the air temperature ranges measured (up to 26°C in winter and 28°C in summer), no clear threshold was reached. It should be noted that 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.

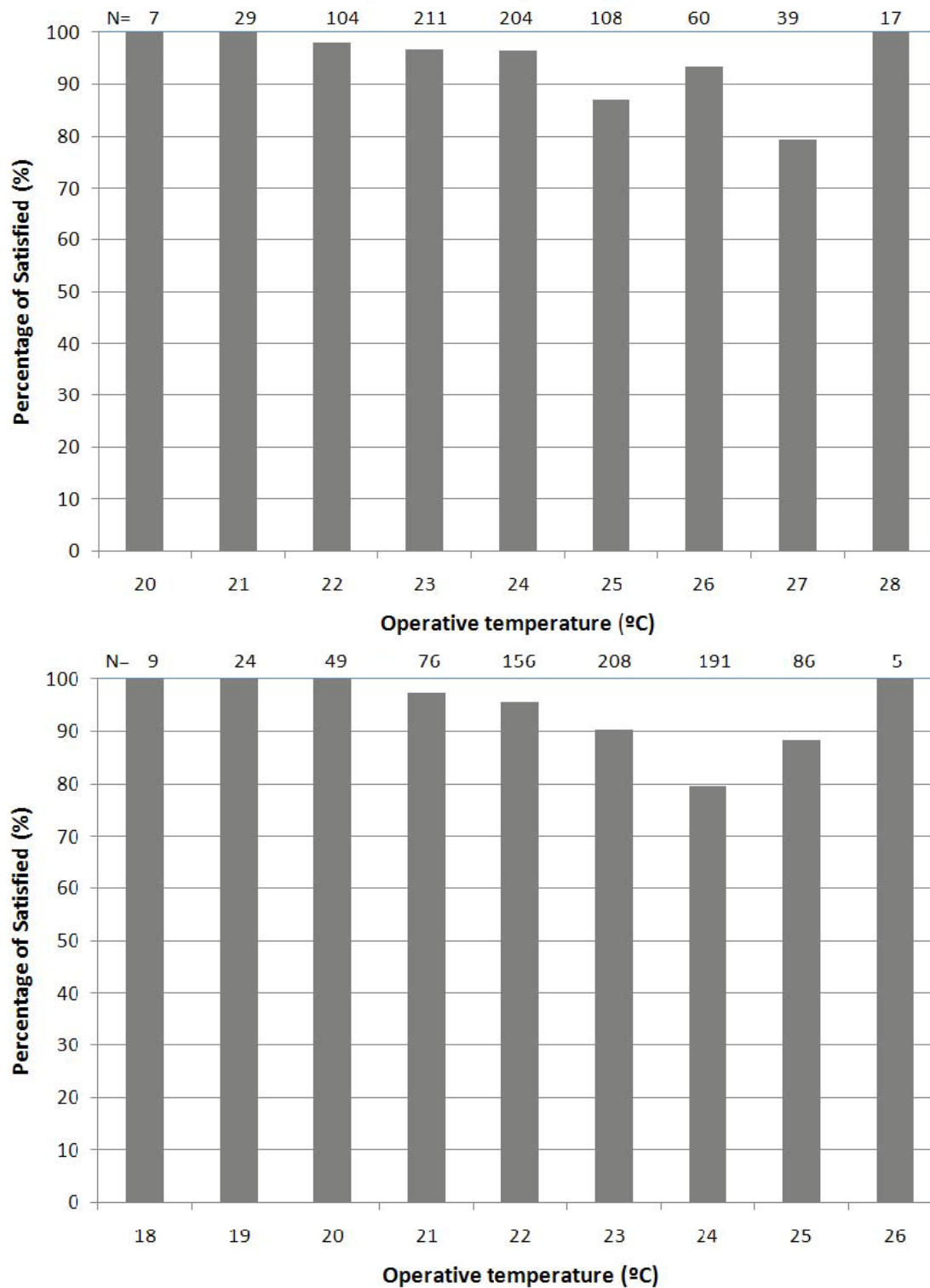


Figure 9. Perceived air quality versus temperature for BCC database: ‘How satisfied are you with the air quality in your workspace?’ (a): winter BCC; N = 804, clear threshold not reached within 18-26°C, and (b): summer BCC; N = 779; clear threshold not visible within 20-28°C.

PAQ related to thermal comfort

In the absence of a clear temperature threshold for PAQ, the authors looked for other means of assuring good PAQ in practice. Humphreys *et al.* (2002) had found that PAQ is mostly related to thermal comfort, as opposed to air temperature. Figure 10 confirms this, showing PAQ to be closely correlated with thermal comfort at a mixture of temperatures and air movements. Figure 10 is from the two laboratory studies (Datasets 3 and 4) where ambient air temperatures were at 28 and 30°C, and PEC fans were used to provide thermal comfort (the comfort scale is presented in the X axis in the figure). If this strong correlation holds in real buildings, it might be assumed that when comfort is maintained, PAQ is maintained as well, and that air movement can be used to provide the necessary thermal comfort at high operative temperatures.

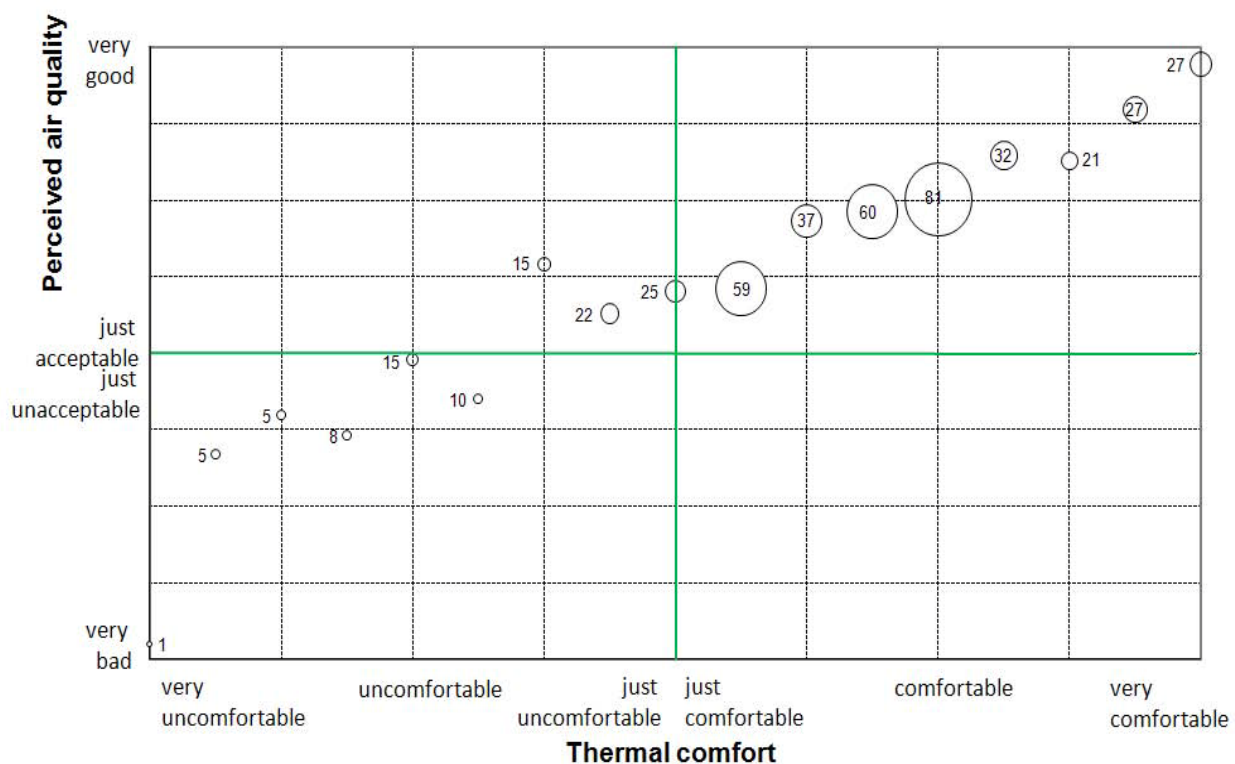


Figure 10. Perceived air quality versus thermal comfort, binned data. Circle diameters represent the number of votes shown nearby (N=450, Datasets 3 and 4)

Discussion

Thresholds for productivity

Productivity might also follow thresholds in temperature or comfort. Figure 11 (adapted from Seppanen *et al.* 2003 by adding results from Tawada *et al.* 2010) shows that within air temperatures from 21 – 27°C, 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. If productivity were actually a function of occupant comfort instead of temperature, the temperatures shown might not represent productivity in buildings where air movement is present.

Performance decrements vs. temperature

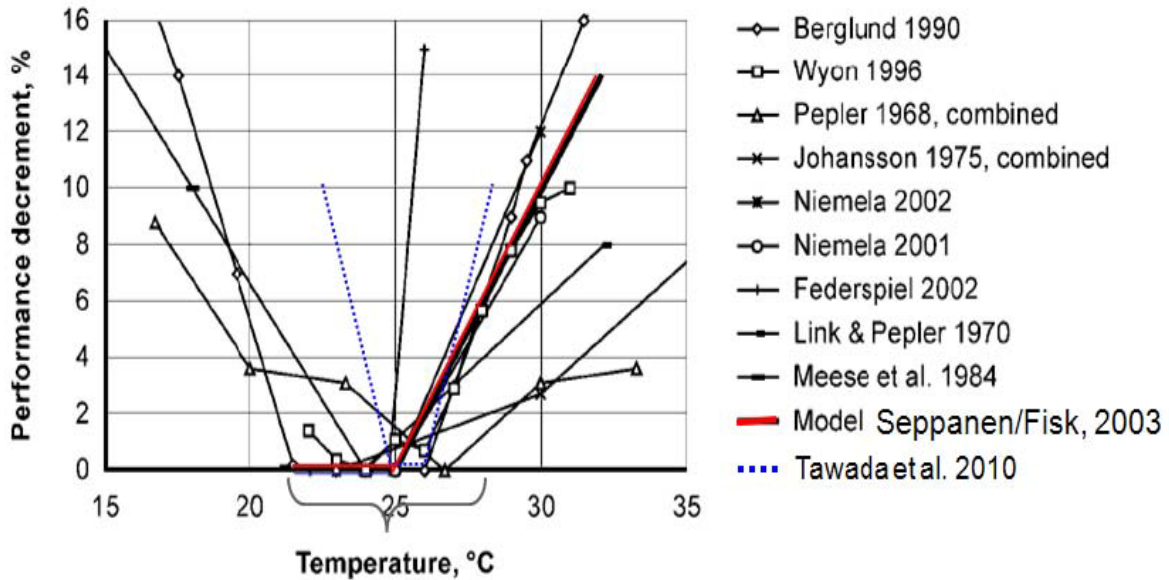


Figure 11. Summary of the studies on the effect of room temperature on decrement of performance and productivity. Sources: adapted from Seppanen *et al.* (2004), with the addition of Tawada *et al.* (2010)

A study by Uchida *et al.* (2009) shows that self-estimated performance is strongly related with thermal comfort satisfaction (Figure 12, $r=0.97$). When correlating the self-estimated performance with air temperature, the correlation is very poor, $r=-0.21$. The result shown in Figure 12 is strongly similar to that shown for PAQ in Figure 10. This might lead to the hypothesis that making people thermally comfortable is the key factor in maintaining PAQ and productivity.

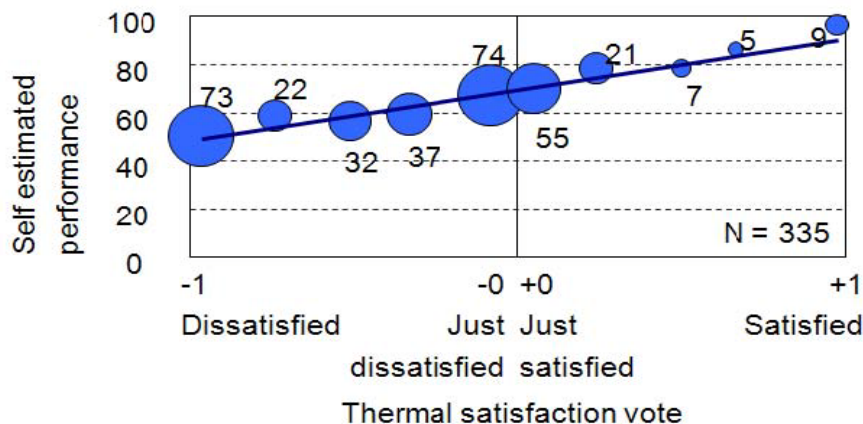


Figure 12. Self estimated performance vs. thermal satisfaction - 335 observations from workers. $R=0.97$ (Uchida *et al.* 2009)

Overcooling and overheating in HVAC buildings

Recent field studies in a large number of US office buildings (Mendell and Mirer, 2009, for 95 buildings, and Choi *et al.*, 2010, for 20 buildings) show that the average indoor air temperature is being maintained cooler in summer than in winter (22.9°C in summer and 23.4°C in winter in Mendell and Mirer; and 23.3°C and 23.5°C in Choi *et al.*). This summer overcooling works against human adaptation, the reasons for it are unclear since the practice increased both discomfort (Mendell and Choi *et al.*) 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. It is necessary 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.

Energy impacts of thresholds in HVAC buildings

By focusing on the environmental conditions outside the thresholds and not tightly controlling within them, the threshold concept encourages the design 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 13 shows that, by broadening the interior temperature thresholds in HVAC buildings, each 1K broadening corresponds to about 7 – 15% energy saving (see Figure 16, Hoyt 2009).

In addition to the operational savings seen in Figure 13, savings may be obtained by reducing the required sizes of HVAC equipment.

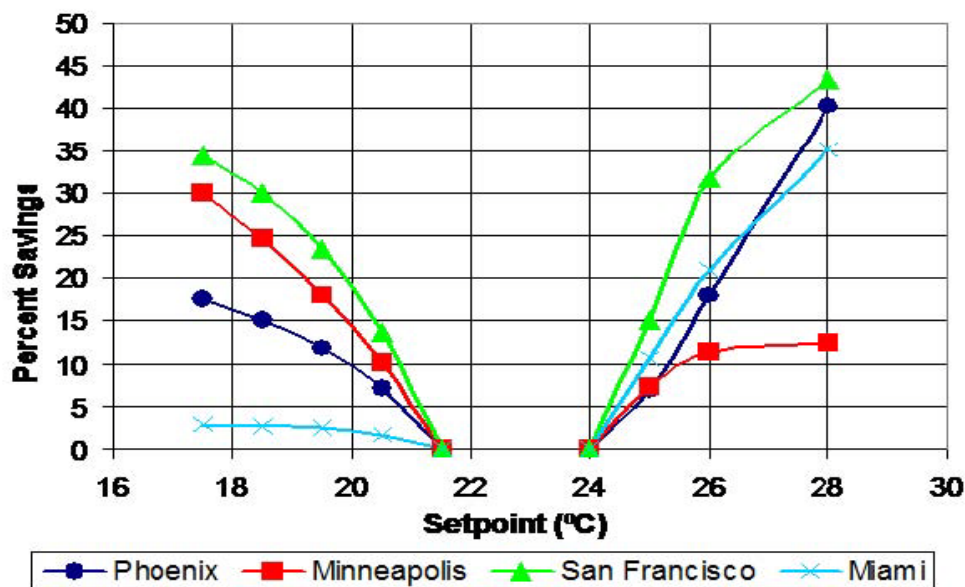


Figure 13. HVAC energy savings for widened air temperature setpoints relative to conventional setpoint range in San Francisco, Miami, Phoenix, and Minneapolis (Hoyt *et al.* 2009)

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 concept presented in this paper suggests that when indoor air temperature is within defined thresholds, there is little advantage from fine-tuning the air temperature to an optimum. The air-conditioning system should focus on bringing environmental conditions outside the thresholds within them. In NV buildings the thresholds are broad due to occupant adaptive behavior in the presence of outdoor climate. The acceptability-based thresholds presented in Figure 7 are independent of seasonal climate, and also of operable windows. The thresholds may be broadened in both HVAC and NV buildings by adding air movement and radiation to the occupied space, or the occupants directly through PEC systems. Perceived air quality in warm conditions does not appear to be a problem as long as the occupants are kept thermally comfortable. The energy impacts of broadened thresholds 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.

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