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Authors
Arens, Edward
Humphreys, Michael A
de Dear, Richard
et al.

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Are ‘Class A’ Temperature Requirements Realistic or Desirable?

Edward Arens, Center for the Built Environment, University of California Berkeley, USA
Michael A. Humphreys, Oxford Institute for Sustainable Development, Oxford Brookes University, UK
Richard de Dear, Faculty of Architecture, University of Sydney, Australia
Hui Zhang, Center for the Built Environment, University of California Berkeley, USA

Abstract
It requires more energy to maintain a narrow indoor temperature range than a broader range, in which the building may be allowed to float with reduced conditioning for longer periods of time. A narrow range should presumably be preferable to the building occupants to justify its increased energy cost. At what widths are temperature ranges detected, preferred, or judged unacceptable? Three databases of occupant satisfaction in buildings are used to examine the acceptability of three classes of temperature range currently employed in the ISO and European standards, and proposed for the ASHRAE standard. These are alternatively identified as Class A, B, and C, or Category I, II, and III, but their specifications are identical. The A class (I category) is found to confer no relative satisfaction benefit to individuals or to realistic building occupancies. In addition, the differences in B and C class satisfaction are small.

Keywords
Standard, PMV, acceptability, category, class A, setpoint temperature

Introduction
We are facing the need to reduce building energy use dramatically. Reductions of 50-70 -90% are being called for in both existing and new buildings over the next 30 years. This will not be technologically or financially easy to accomplish. From the climate perspective, early reductions are more valuable than later ones, so there is a particular need for measures with immediate impact.

Since over 15% of US energy use goes to heating and cooling interior space, it is prudent to examine our requirements for interior space conditioning to make sure that truly unnecessary conditioning is minimized, and that potentially energy-efficient space conditioning technologies are not penalized in present and future buildings.

Background
ISO standard 7730 [1] and CEN 15251 [2] include three Categories of environmental quality for mechanically cooled buildings: I, II, and III, in which Category I requires the tightest control of interior conditions. This schema has been proposed for ASHRAE Standard 55 as well [3], using the terms Class A, B, and C to represent the three Categories (see Table 1 for their thermal specifications). In this paper we will use the Class terminology. Class A if adopted would require tighter control than the existing Standard 55, whose specifications are now at the B level.

Class categories have been created for several aspects of indoor comfort. One addresses the overall thermal environment surrounding the occupant, as it affects the average heat balance of the occupant. Several others address localized environmental variables that might cause local discomfort: draught, vertical air temperature difference, floor temperature, and radiant temperature asymmetry. A ‘predicted percent dissatisfied’ (PPD) is associated with each class level for each variable, ranging in all from 3-35%.

In this paper, we address occupants' comfort and acceptance of the overall thermal environment surrounding them. In all three standards, this is quantified in terms of the variable 'predicted mean vote' (PMV), the outcome of a human heat balance model. The PMV model [4] incorporates the four basic environmental variables that affect human heat balance: temperature, humidity, thermal radiation, and air movement. It predicts the mean thermal sensation of a group of people exposed to that environment, assuming they all have the same clothing insulation and activity level. The mean thermal sensation values range from negative (cold) through neutral to positive (hot).

Thermal acceptability (or its complement, PPD) is typically indirectly inferred from PMV. The three classes in ISO 7730 and CEN 15251 each have a PMV range whose center is zero, with Class A being defined by the tightest band (Table 1) [5, 6]. The PPDs associated with the three PMV ranges vary from 6-15%.

It should be noted that the PMV/PPD relationship has been derived from climate-chamber studies. There have been few rigorous tests of PPD or thermal acceptability for actual occupants in office buildings (e.g. [7], [8], [9], [10]). In the case of draught, the PPD from climate chamber experiments has been found to differ substantially from dissatisfaction data gathered in actual buildings [11], [12].

Table 1. Thermal requirements of the three classes of indoor environment .

Class (Category)	PMV	Temperature Range (for typical clo and met)	PPD %
A (I)	-0.2 < PMV < +0.2	2K	<6
B (II)	-0.5 < PMV < +0.5	4K	<10
C (III)	-0.7 < PMV < +0.7	6K	<15

Table 1 also gives temperature ranges for a typical office occupancy. In practice it is possible to represent PMV ranges in terms of temperature by assuming the occupants' clothing insulation and metabolic activity levels. In still-air internal environments with moderate humidity, the thermal environment can be adequately characterized by operative temperature or globe temperature, combining the air and surface radiant temperatures. When air and interior surface temperatures are roughly the same, it is sufficient to measure air temperature alone. Building thermal control is ultimately implemented in terms of the temperature measured in a thermostat, a combination of air and radiant temperatures.

Maintaining a narrow PMV or temperature range requires more HVAC energy than maintaining a broad range. In commercial buildings, heating/cooling energy-use changes roughly 7% for each degree K change in interior temperature range (space-temperature-setpoint deadband), starting from a Class B baseline [13]. In residences, the change per degree is conservatively 10%, exceeding 20%/K in the vicinity of the baseline [14]. Therefore, the difference between adjacent classes translates to about 12% of annual heating+cooling energy use for commercial buildings. For residential and small commercial, it is closer to 20-30%.

This invites the questions: is the so-called Class A thermal environment worth its inherent energy penalty? Is it even more comfortable than Class B (or C) in a realistic environment?

Statement of the problem

To date there has been very little critical analysis of how the three Classes' PMV ranges are accepted by occupants in real buildings. There are a number of considerations: 1) Individuals have their own acceptable temperature ranges. These differ from those of other individuals based on personal characteristics, clothing and activity levels. 2) Building occupancies consist of collections of such differing individuals who often have to share common thermal environments. How do real occupancy acceptances relate to the Standard's three PMV ranges, bearing in mind that the PMV and PPD values are based on uniform occupancies (i.e. sedentary activity and uniform clothing in laboratory studies)?

Until recently, few laboratory or field studies included the direct question about whether an environment was acceptable or not. Dissatisfaction, acceptability, and general thermal comfort have all been inferred from whole-body thermal sensation votes. The relationship between these different metrics of subjective comfort has yet to be successfully established.

There may well be other factors determining thermal acceptance that are outside the parameters of a heat balance model, such as perceived access to environmental controls, or freedom of dress code.

1) Individuals' acceptance range.

If occupants were in individual rooms with individual thermostats which they could adjust according to their clothing, met, and personal preferences, would they control their temperature around a narrow band as in Class A, or would they control to a band more like Class B or C? If, rather than controlling the temperature themselves, it were controlled for them, would they really prefer Class A control to Class B control? Would they notice the difference?

These simple but important questions can be tested using observations of acceptance and satisfaction from field studies in which comprehensive indoor environmental measurements were recorded, as well as occupants' clothing and met rate. From these, an occupant's PMV values can be calculated, allowing individual observations to be placed in Class A, B, and C relative to the occupant's personal ideal (neutral) temperature. The occupants' acceptance of their state would indicate the extent of their *individual* need for tight environmental control as imposed by the HVAC system.

2) Variability in building occupant populations.

In many cases we would expect multiple occupants to be in zones controlled by a single thermostat. The thermostat's temperature setpoint will not be ideal for each of the occupants because in addition to normal person-to-person variability people vary in their clothing and metabolic rate. These variations cause each individual's acceptable temperature range to differ from those of the other occupants with whom they share the space. Is it then possible to find any narrow band of control setpoints (e.g. Class A, with a width of 2K) that a substantial majority of an occupant population finds acceptable?

Here again, we can test these questions directly from field studies in which building *populations* have been directly asked about thermal acceptability (or in its absence, thermal sensation). Are there temperature bands that are acceptable to a substantial percentage of occupants? How wide are these temperature bands? Do they differ with seasonal variations of the outdoor temperature? The portions of the acceptability variation caused by *clothing* and *metabolic rate* could be obtained from the same field study databases. It would be useful to know how much these clothing- and metabolic-rate-related acceptable-temperature variations compare to the 2K, 4K, and 6K sizes of the Class A, B, and C bands of setpoint control.

Method

We use three databases of field studies in which detailed occupant surveys are matched with coincident measurements made with high-grade instrumentation. The field studies use a variety of question formats, so that the analyses use subsets of the available data that have high compatibility.

1) The ASHRAE RP 884 database [7]. This public-domain database contains quality-controlled data from thermal comfort field studies conducted in various countries and climate zones around the world. We excerpted three field studies from the database; ASHRAE RP-702 in Townsville Australia, ASHRAE RP-921 in Kalgoorlie-Boulder Australia, and ASHRAE RP-821 in Montreal Canada. All 45 buildings in these three field surveys were centrally air-conditioned office buildings.

The three studies represent three distinct climate zones, and both summer and winter surveys were conducted in each location.

The 3,350 questionnaires were accompanied by simultaneous and local indoor climate measurements (air temperature, mean radiant temperature, air speed and humidity) made in accordance with ASHRAE Std 55 [3] and ISO 7726 (1985) [15] requirements. Each questionnaire included estimates of the subject's clothing ensemble insulation and metabolic rate.

2) The SCATs database (Smart Controls And Thermal Comfort) [16]. This database includes subjective survey and occupants' environmental data on 26 office buildings in 5 European countries, France, Greece, Portugal, Sweden, and UK, and different building types. The total number of environmental questionnaires, accompanied by simultaneous indoor climate measurements and estimates of clothing insulation and metabolic rate, exceeds 4,600, and covers the entire year. Experimental protocols were uniform across all surveys, apart from the language of presentation of the questionnaire.

3) Berkeley City Center (BCC) Project database [15]. This is a modern naturally ventilated building that was monitored and surveyed in great detail for three-week periods during both summer and winter. The total number of surveys was 2,075, with 38 subjects in each season repeating the survey throughout the day.

Individual occupants' acceptance of the three classes

The three databases were examined to compare *individuals'* ratings of acceptability against which PMV ranges they were in.

1) *ASHRAE database*: PMV-based ranges

The PMV comfort index calculations in the ASHRAE RP-884 database were performed with a standardized software package distributed by ASHRAE [18]. The PMV calculations were based on five minute averages across all three levels (0.1, 0.6 and 1.1m) of the measured environmental parameters (ta, tr, rh and v). Occupant acceptance of the measured thermal environments was assessed directly with this questionnaire item:

Is the thermal environment acceptable to you? ACCEPTABLE / UNACCEPTABLE

In the discussion below, we equate the terms 'accept' and 'acceptable' with 'being satisfied with' and 'satisfactory' (conversely 'unacceptable' is equated to 'dissatisfied with'). We do not know whether there should be a distinction made here. It seems that for practical purposes there is no difference. The term 'satisfied' is rarely used in questionnaires, even though PPD (Predicted Percent *Dissatisfied*) is a commonly invoked metric. The acceptability percentages for the three classes in the three studies are presented in Table 2.

Table 2: Results of the ASHRAE RP-884 database enquiry. Observed acceptability percentages (sample sizes indicated in parentheses) within the three office quality ratings defined in terms of PMV.

Office Rating	PMV Range	Townsville Summer Wet Season	Townsville Summer Dry Season	Kalgoorlie-Boulder Summer Season	Kalgoorlie-Boulder Winter Season	Montreal Summer Season	Montreal Winter Season
Class A	± 0.2	74.4% accept (n = 160)	84.2% accept (n=203)	88.9 % accept (n=163)	86.7% accept (n=166)	81.2% accept (n=129)	86.3% accept (n=102)
Class B	± 0.5	77.5% accept (n=346)	81.0% accept (n=394)	87.8 % accept (n=320)	84.5% accept (n=373)	84.2% accept (n=272)	86.0% accept (n=250)
Class C	± 0.7	77.2% accept (n=425)	79.2% accept (n=476)	88.3 % accept (n=393)	84.3% accept (n=452)	84.4% accept (n=333)	86.0% accept (n=321)

The results suggest that it does not matter to the occupants of these buildings whether the physical environmental conditions inside their air conditioned office building comply with Class A, B or C specifications; there is a fairly constant level of dissatisfaction across all grades of about 20%. The small differences between the three classes are not statistically significant. There is some variance between studies, with the general level of acceptability lower in Townsville's wet season and higher in Kalgoorlie's summer, but there is no consistent pattern of satisfaction between the Classes A, B and C.

One might conclude that occupants' sense of acceptability is unrelated to the narrow temperature ranges defined by the Classes, or that PMV lacks the discriminatory power to predict acceptability within these ranges.

2). *SCATs database*. We did a similar study for the 26 buildings in the SCATs database (Table 3). There are several differences, however. Here the acceptability metric is replaced by a right-now measure of 'comfort', which the subjects could interpret to include thermal, acoustical, lighting, and air quality effects. In addition, percentage of occupants voting within the central three categories of the ASHRAE thermal sensation scale is also shown, since this is the operational definition of comfort within PPD, and integral to the way PMV has been proposed as the basis for grading office environments. The three central categories have often been interpreted as equivalent to acceptability although the linkage is tenuous and has not been well-established in the published field studies.

Table 3. Results of the SCATs database enquiry. The percentages voting comfortable, and voting within the three central categories of the ASHRAE thermal sensation scale

PMV range	N	% voting in central 3 categories of ASHRAE scale (±std error)	% comfortable overall comfort>= 4
-0.2 <PMV<0.2	966	87.2±1.1	80.0±1.3
-0.5 <PMV<0.5	2210	87.9±0.7	78.6±0.9
-0.7 <PMV<0.7	2902	87.3±0.6	78.2±0.7

(Notes to table 3: 'Overall comfort' (in column 5) is based on a six-point scale: 1. very uncomfortable 2. moderately uncomfortable 3. slightly uncomfortable 4. slightly comfortable 5. moderately comfortable 6. very comfortable. The numbers are the percentages on the comfortable portion of the scale.)

Again the SCATS results show that there is little if any advantage in restricting the PMV range to ±0.2. The differences between the comfortable percentages within the PMV bands ±0.2, ±0.5, and ±0.7 are not significant on either measure ('comfort' or 'central 3 categories of the ASHRAE sensation scale').

As with the ASHRAE database, the conclusion must be that either PMV does not have the necessary discriminatory power, or that it does not matter to the occupants which of the three classes the environment belongs to.

3). BCC database. We did a similar analysis for the BCC database, shown in Table 4. Here thermal acceptability was directly assessed, as with the ASHRAE RP-884 analysis in Table 2. There is a small increase in acceptability with tightening range, but the differences between the three classes are not statistically significant. The warmer/cooler preferences are also shown, showing that the building conditions were not equally distributed around neutral. Almost 30% of the occupants perceived the building as being warm—three times as many people would have preferred cooler conditions than warmer. Nonetheless at least 86% regarded the environment as being acceptable.

Table 4: Results of the BCC database enquiry. Observed acceptability percentages within the three office quality ratings defined in terms of PMV ranges.

PMV Range	Sample Size (inclusive)	Thermal Acceptability (±std error)	Want warmer	No change	Want cooler
± 0.2	721	89.0% ±1.2%	9.9%	62.9%	27.2%
± 0.5	1427	87.3% ±0.9%	10.4%	61.7%	28.5%
± 0.7	1686	86.2% ±0.8%	10.7%	59.3%	29.9%

4). Summary: individual acceptability. The PMV estimates underlying the tables are necessarily imprecise, since they entail estimates of the occupants' clothing insulation and metabolic rate at the time of the survey measurements. This will result in some 'blurring' of the Class boundaries. However, such imprecision is intrinsic to any practical measurement of PMV – and a drawback to its use as a control variable.

Occupants’ ranges of acceptance appear to be broader than the narrow range of PMV that defines Class A, and perhaps also that of Class B.

Acceptable temperature ranges for occupant populations

The ASHRAE (and Class B) definition of an acceptable environment is one in which 80% of the occupants find it acceptable. For populations of individuals whose PMVs differ, the acceptable temperature range is best examined in terms of actual temperatures--operative, or globe--since temperature is the variable by which environments are usually controlled. The temperature range may be examined for various time periods, e.g., annual, seasonal, daily. The ASHRAE and BCC databases contain largely season-specific data. The SCATs data is analyzed in annual terms.

1) ASHRAE and BCC databases. Over the winter and summer test periods, the selected studies taken from the ASHRAE database showed a wide spread of operative temperatures acceptable to over 80% of the population, from 17 through 25ºC for winter (Figure 1), and from 20 through 25ºC for summer (Figure 2), although the fewness of the data makes for great uncertainty at the cold extremes. At 26ºC operative temperature, the percentage of the population voting acceptable dropped below 80% in both seasons, 72% in summer and 50% in winter.

A very similar 80% acceptability range is also found in the BCC database (not shown here). In winter the range was 19 through 25ºC, and in summer from 21 though 25ºC. In Figure 3, all the ASHRAE and BCC data are pooled to give an acceptable range for the entire year, with a greater than 7K range of acceptable temperature, from below 19 through 25ºC.

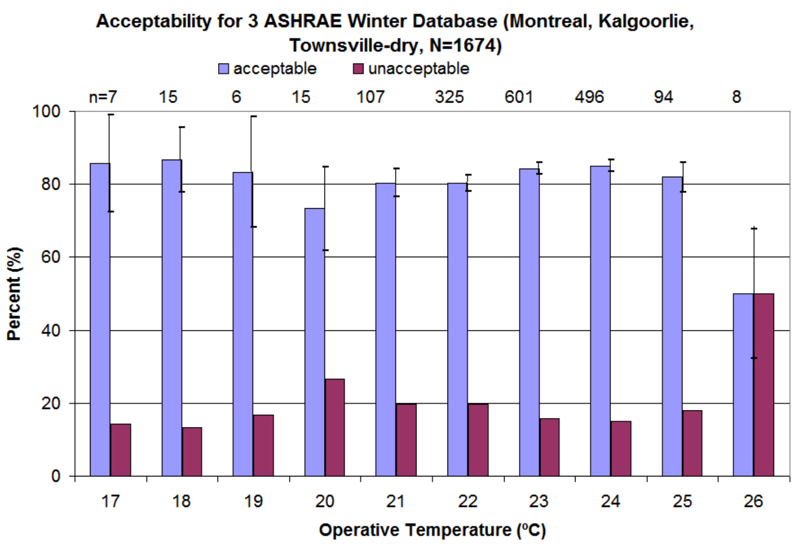

Figure 1. Acceptability against temperature at the workstation, winter season.
(Brackets represent 95% confidence intervals.)

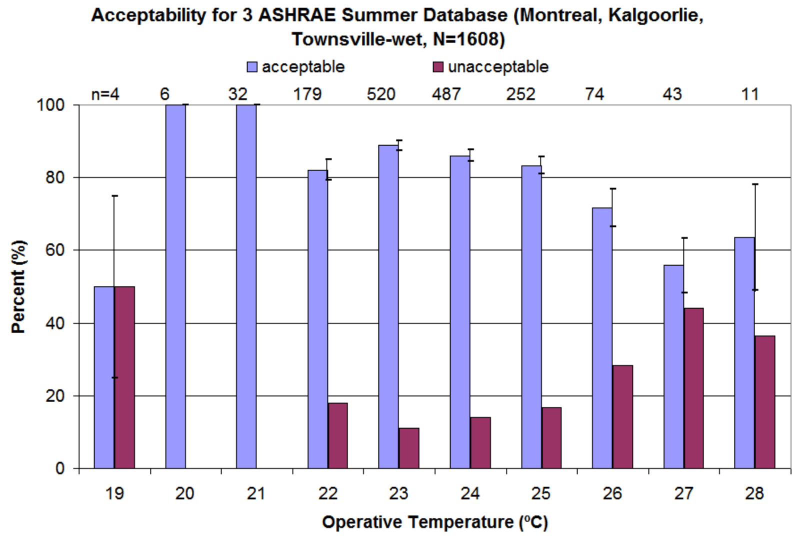

Figure 2. Acceptability against temperature at the workstation, summer season.

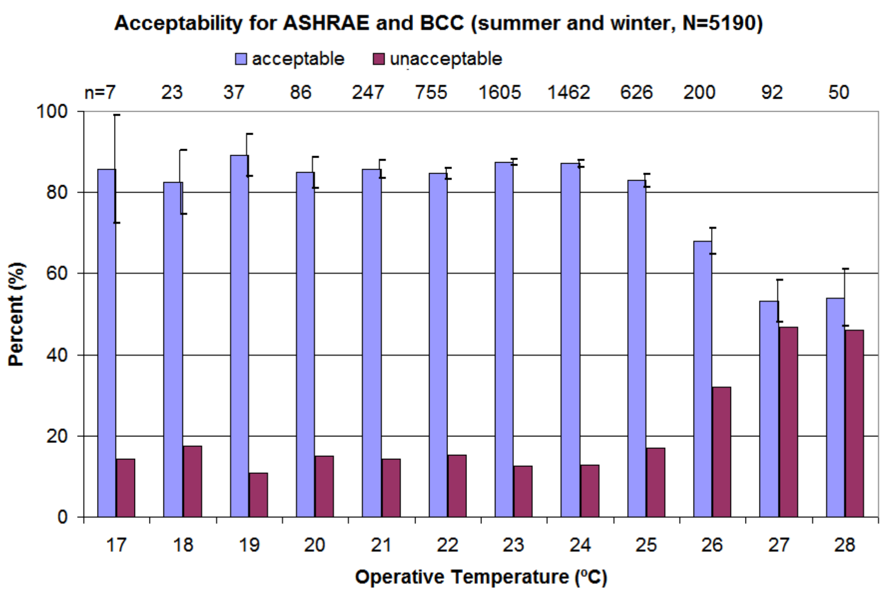

Figure 3. Acceptability against temperature at the workstation, annual, pooled ASHRAE and BCC data.

2) *SCATS database*. Figure 4, from the SCATs database, shows the relationship of comfort to annual indoor temperature variation. The horizontal axis (the standard deviation) is a measure of indoor temperature variability over the whole year. The vertical axis is the mean assessment of overall comfort. Each point represents one building. (mm=mixed mode (few of these), mv=mechanical ventilation (a requirement for offices in some European lands), pp is a building in which some spaces were air-conditioned while others were not). The error lines are 95% confidence limits for the position of the regression line.

There is little relation between tight control (low standard deviation) and overall comfort. The relation, while in the expected direction, does not reach statistical significance even over the wide (~7K) range of variability encountered.

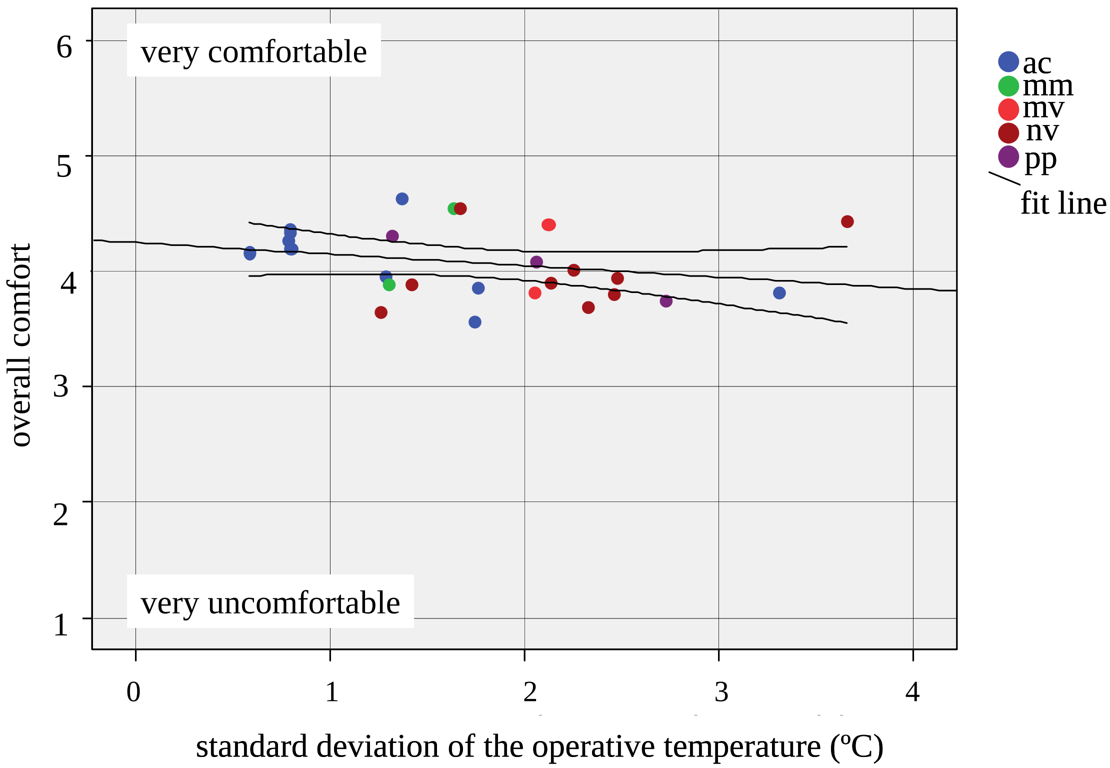

Figure 4. Annual room temperature variability versus overall comfort (entire SCATS database)

3) Summary: population acceptability. The ASHRAE data indicate that acceptability began to fall at temperatures above 25ºC, but there was no clear lower temperature limit within the range of the data. The pooled (ASHRAE + BCC) data suggest a range from 19 to 25 ºC. The SCATs data suggest that the overall variation of temperature in a building over a period of about a year makes little difference to the overall assessment of environmental comfort in that building. The generally null results of these analyses do nothing to encourage the belief that close control of the operative temperature will much improve comfort and acceptability. However, caution is necessary, because Figures 1-4 include the effects of adaptation during the course of the surveys, whether seasonally as in the ASHRAE data, or year-round in the (combined ASHRAE+BCC) and SCATs data. Thus the temperature for thermal neutrality is continually varying. If it occurred in the course of a single day, one would not expect this full range of temperatures to be acceptable.

Sources of variation in occupants' thermal requirements: clothing level

Some of the variation in an occupant's acceptable range of temperature is due to clothing. The clothing-levels observed in the 3 databases are presented in Figures 5-7. Figures 5 and 6 give the summer and winter clothing versus interior air temperature for the ASHRAE database and the Berkeley Civic Center. Figure 7 gives clothing versus indoor operative temperature from the SCATs database. From all three databases, it is very clear that at the same air or operative temperature, the clothing insulation varies by about 0.8 clo unit, from 0.4 clo to 1.2 clo.

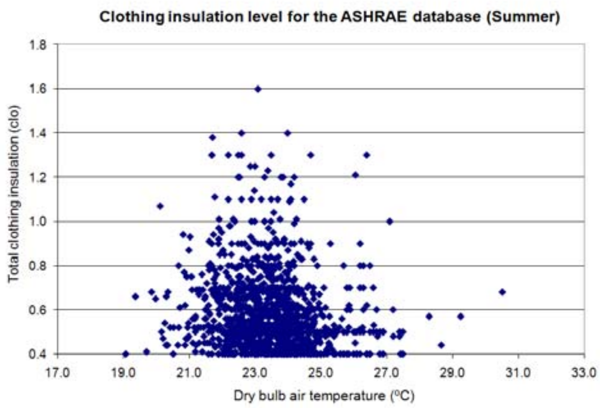

Fig.5a. ASHRAE database clothing insulation for summer

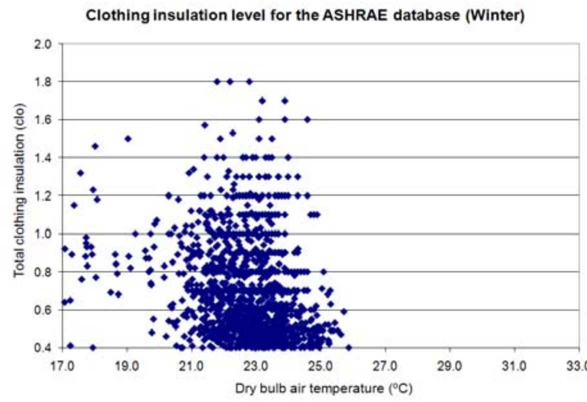

Fig. 5b**.** ASHRAE database clothing insulation for winter

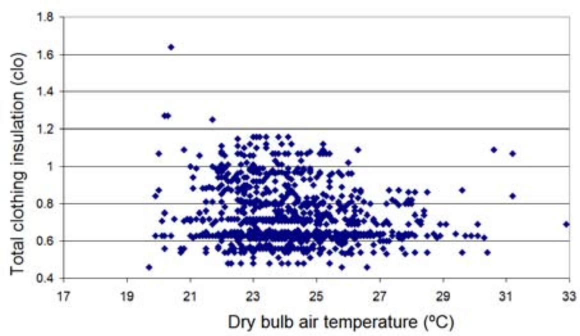

Fig. 6a. Berkeley Civic Center (a naturally ventilated building) clothing insulation for summer

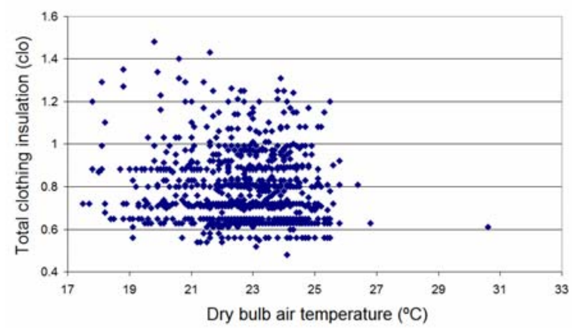

Fig. 6b. Berkeley Civic Center (a naturally ventilated building) clothing insulation for winter

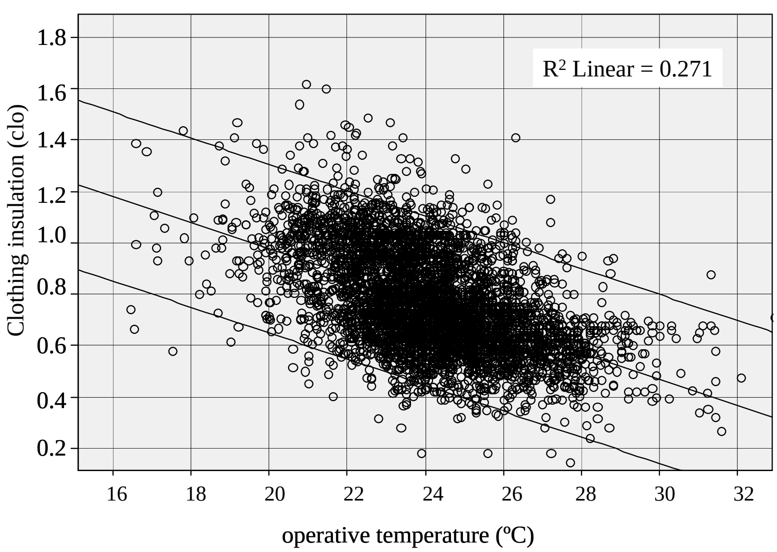

Figure 7. SCATs: clothing versus indoor operative temperature. The bands enclose 95% of the observations and show a variation of about 0.6 clo at any given temperature.

Figure 8 shows PMV simulation results for a range of clothing insulation values. It can be seen that a clothing change from 0.5 to 1 clo corresponds to a 3K air temperature change, a change that exceeds the 2K width of the proposed Class A environment. Similarly, PMV varies approximately one scale unit for this spread of clothing at a given temperature near neutrality.

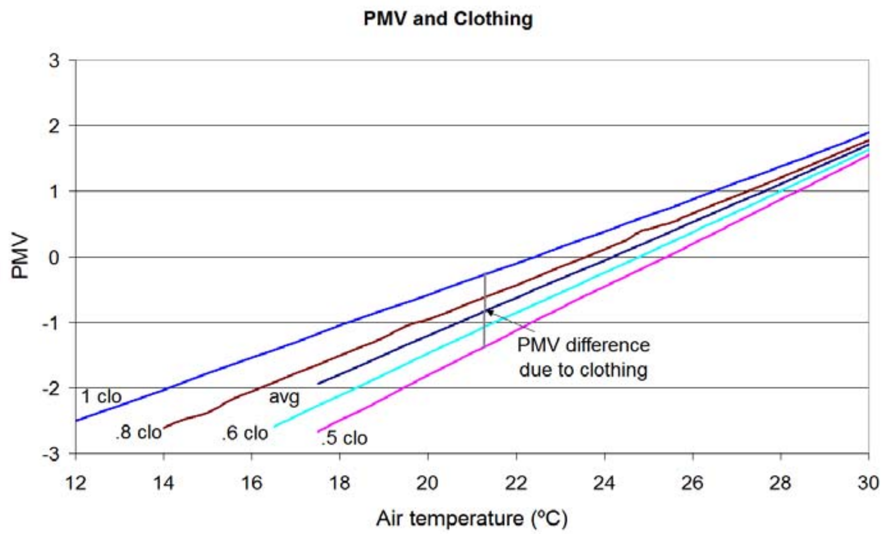

Figure 8. Clothing insulation from 0.5 – 1 corresponds to PMV variation of about 1 scale unit or a 3K air temperature difference, assuming the air and radiant temperatures are equal.

Sources of variation: activity level

Some of the variation in acceptable temperatures is due to differences in metabolic rate caused by occupants' varied activities. The results from the ASHRAE data, the Berkeley Civic Center, and the SCATs are presented in Figures 9, 10, and 11. These field data indicate large met-rate variability in realistic commercial building occupancies. The ASHRAE data cover metabolic levels from 1 to 1.8 met, the BCC metabolic range is from 1.1 to 1.4 met, and the SCATs data cover much larger range, from 1 to 2.8 met.

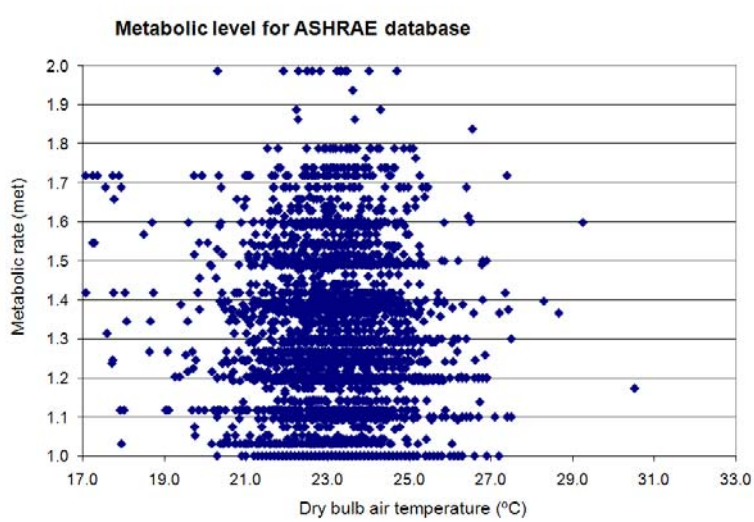

Figure 9. ASHRAE database: metabolic level varies from 1.0 to 1.8 met

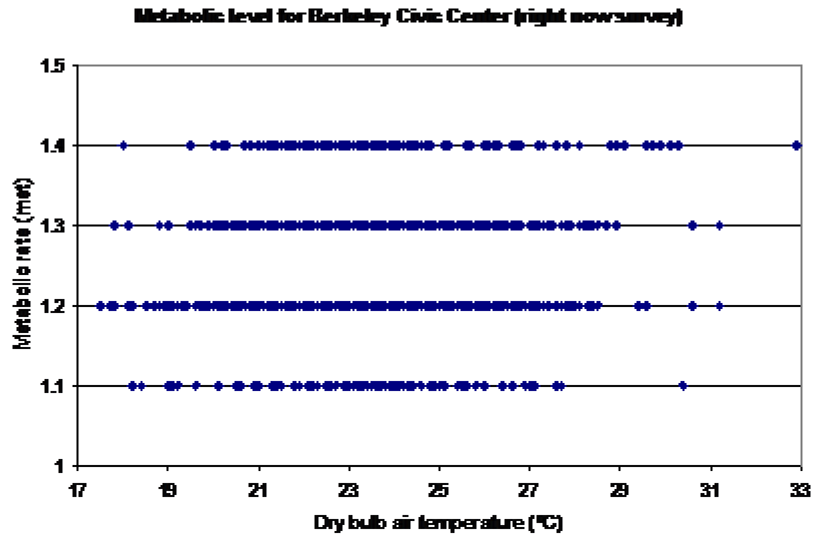

Figure 10. Berkeley Civic Center: metabolic level varies from 1.1 to 1.4 met

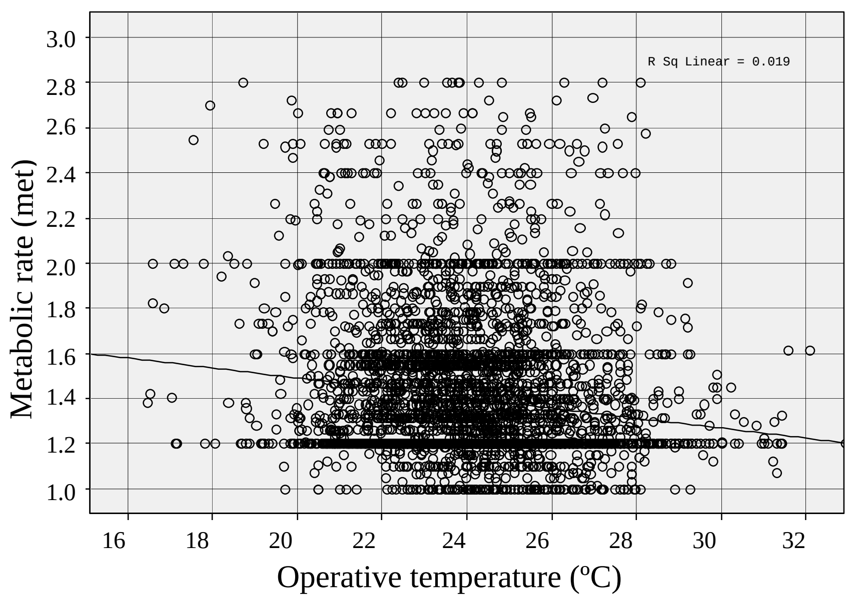

Figure 11. SCATs data: metabolic rate varies from 1.0 to 2.8 met

How much does variation in the met level affect predicted PMV values? Figure 12 shows the PMV variation over the met level from 1 (quietly seated) to 1.3 met (periodic standing and walking). The influence of met on PMV is larger when the environment is cool. At 21ºC, PMV changes about 1 scale unit when met changes from 1 to 1.3 met. The figure also shows that a metabolic change from 1 to 1.3 met corresponds to about 3K air temperature change.

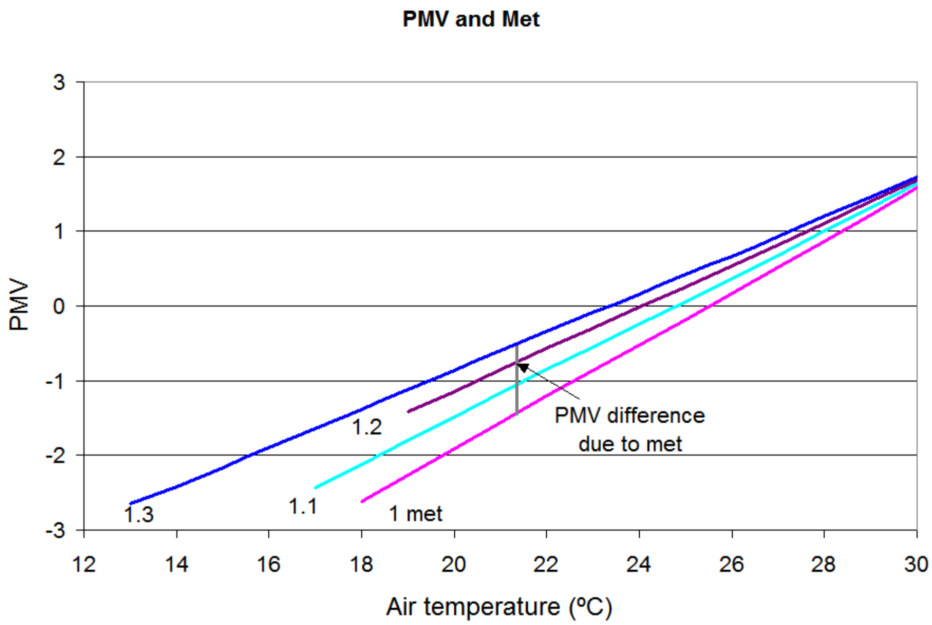

Figure 12. Metabolic level from 1.1 – 1.3 corresponds to PMV variation of about 1 scale unit, or a temperature variation of 3K, (the figure assumes the air and radiant temperatures are equal.)

Typical metabolic rate differences can be seen to cause as much change in PMV and air temperature as is caused by typical clothing variability (Fig 8).

Summary: sources of variation in predicted acceptability. The observed clothing and metabolic variation in actual occupancies (Figures 5, 6, 7, 9, 10, 11) does not allow a single PMV or PPD value to differentiate between classes, for either design or operation of buildings. Properly, PMV should be calculated for a collection of metabolic rates and clothing levels and combined in some way to account for their distributions in the population. This would require empirical evidence that does not currently exist.

Discussion: shorter time periods

This paper does not address the acceptable ranges of temperature variation within shorter timeframes, such as a week, day, hour, or minute. Acceptable range is affected by how quickly people can adapt to changing conditions. Adaptation can be due to people's clothing behavior and to changes in their physiology. In most cases, clothing insulation is fixed on a daily basis by what people choose to wear that day (unless they can add or shed a layer at work), but it can vary from day to day, and it is usual for clothing insulation to differ between the seasons. Similarly, physiological adaptation to changed thermal environments is a process requiring a few days, up to about a week. Physiology therefore also requires a more limited range over the course of a day, or from one day to the next, than over periods of a week or longer, when people may have adapted and can accept warmer or cooler conditions. Our data addresses week-and longer periods.

Conclusions

In an analysis of high-quality field studies, the three Classes do not exhibit different comfort/acceptability outcomes. The tightly air-temperature controlled space (Class A) does not provide higher acceptability for occupants than non-tightly air –temperature controlled spaces (Class B and C).

The theoretical basis of tight PMV/PPD building control is flawed. Real populations are diverse in clothing insulation and metabolic rate, causing variation in their acceptable temperature that is wider than the Class deadband. PMV itself may lack the precision needed to handle the fine distinctions needed for the three-class system of control (see [19] for a more detailed discussion of this issue).

Class A as a category is unsupportable as a basis for environmental control in office buildings, given the energy costs of designing and controlling to its specifications. The most restrictive situation for a space temperature setpoint deadband involves within-day variation, where the neutral point has been reset daily. Even for this, the Class B temperature range is the narrowest justifiable limit for control.

Building temperature ranges should be based instead on real-time empirical feedback about their occupants' requirements. In the future, one can envision measures that enhance occupant feedback capability being incorporated in normal building control and operation, and being specified in building designs.

If we do not see advantages in classifying buildings in terms of their temperature or PMV ranges, we could instead consider classifying them in terms of their energy use in providing occupant comfort [20].

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