Title

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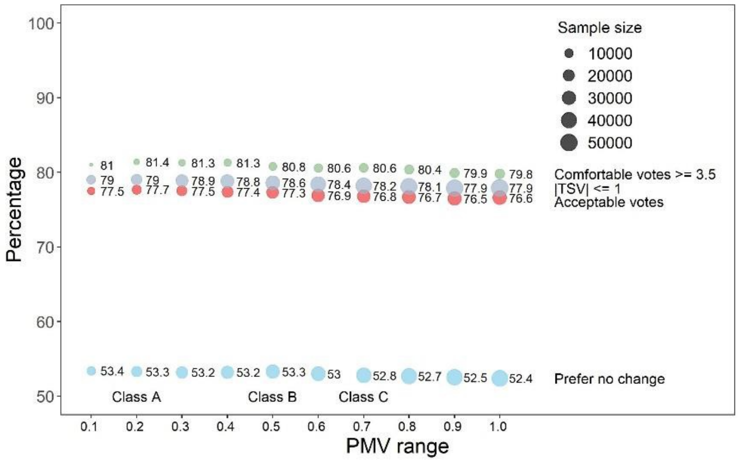
Abstract

Current thermal comfort standards use Predicted Mean Vote (PMV) classes as the compliance criteria despite previous critiques. The implicit assumption is that a narrower PMV range ensures higher thermal acceptability among building occupants. However, our analysis of a global database of thermal comfort field studies demonstrates that PMV classes are not appropriate design compliance criteria, and reinforces the need for a new and robust approach to thermal comfort compliance assessment. We compared two statistical methods to derive acceptable temperature ranges from occupant responses applied one to the ASHRAE Global Thermal Comfort Database II. Derived acceptable temperature ranges in real buildings (7.4K-12.2K) using this new method are wider than the current standards mandate (2K-6K). Our findings support the call for a relaxation of suggested temperature ranges in thermal comfort standards so as to minimize unnecessary space conditioning. The proposed data-driven statistical methods to determine temperature design compliance criteria are viewed as an important step forward in the age of continuous and pervasive monitoring and the associated large databases of building comfort measurements.

Key words

Thermal comfort, compliance, temperature, PMV-PPD, standards

Graphical Abstract



Highlights

- Observed satisfaction showed no significant difference between the 3 PMV classes.
- We used observed individual neutral temperatures as the compliance criteria.
- The observed acceptable temperature ranges are wider than in ISO and EN standards.
- Some reasons are inaccuracy of PMV-PPD model and variance in PMV input variables.
- The generalization of European context where ISO is primarily used is problematic.

1 Introduction

International standards like ASHRAE 55 [1] and ISO 7730 [2] define the compliance criteria for an acceptable thermal environment in buildings. These are normally expressed as either setpoint temperatures which inform the specification of heating, ventilation and air conditioning (HVAC) systems in the design phase, or comfort temperature ranges during the operational phase. This provision of comfort by HVAC systems accounts for a significant proportion of the total building energy consumption. For example, 39% in Australian office buildings [3], 44% in U.S. commercial buildings [4], and 48% in U.S. homes [5]. The demand for air conditioning is only set to increase, with the International Energy Agency predicting the number of air-conditioners worldwide to total 5.6 billion units by 2050 from 1.6 billion units today [6]. This is being driven largely by the combined effects of global warming, economic growth, and swelling populations in emerging economies in hot climates such as India. Addressing this escalating source of greenhouse gas emissions requires both a reduction in unnecessary space conditioning (heating and cooling) as well as improving the energy efficiency of HVAC systems.

Whilst technological innovations and energy rating schemes have worked to improve efficiencies, much less attention has been given to scrutinising the way we use HVAC in buildings. Building energy simulations have shown that simply widening HVAC temperature setpoints can significantly reduce energy consumption without impacting occupant comfort [7]. Yet such deviations in indoor temperature would contravene the comfort criteria found in international standards. To address this, the present paper examines the temperature design compliance criteria in relevant thermal comfort standards in the context of occupant comfort. Two distinct data-driven methods to defining temperature compliance criteria are tested using the ASHRAE Global Thermal Comfort Database [8]. We then apply the recommended method to field measurements of occupant comfort and compare the resulting acceptable temperature ranges to those in standards. The principal aim is to demonstrate the limitations of the temperature compliance criteria in current standards while highlighting the methodological issues in developing them.

2 Thermal comfort compliance

The predicted mean vote (PMV) proposed by Fanger in 1970 [9] is the dominant steady-state heat balance model that serves as the basis for almost all thermal comfort standards. The Analytical Comfort Zone Method in ASHRAE 55:2017 [1] sets the comfort range as $-0.5 < \text{PMV} < +0.5$, corresponding to 80% acceptability based on 10% whole body dissatisfaction from the predicted percentage of dissatisfied (PPD), plus an assumed additional 10% local dissatisfaction. ISO standard 7730:2005 [2] prescribes three classes of thermal comfort: Class A (PMV ±0.2), Class B (PMV ±0.5), and Class C (PMV ±0.7). EN 15251:2007 [10] adopts the same three classes (but named Class I, II, and III respectively) for mechanically conditioned buildings.

These classes function as the design compliance criteria for thermal comfort which have to be specified in the design phase of a new building. An implicit assumption of the tiered compliance criteria is that a narrower PMV range ensures higher thermal acceptability among the occupants i.e. lower predicted percentage of dissatisfied (PPD) in Table 1. Yet the comprehensive analysis of three large databases of field studies by Arens et al. [11] showed that Class A (I) does not ensure any satisfaction benefit in office buildings. In fact, pursuing narrower PMV ranges in offices promotes the widespread use of air-conditioning, leading to a higher chance of sick building syndrome and increased energy costs and greenhouse gas emissions [12]. Despite the evidence showing no tangible benefit of tighter temperature tolerances on occupant comfort, the tiered PMV compliance criteria remain in use.

In addition to concerns around the energy costs and comfort implications, there are significant challenges in operationalizing the tiered PMV classification. d'Ambrosio Alfano et al. showed that the narrow range of environmental conditions required for the different PMV classes in ISO 7730 and EN 15251 are difficult to reliably determine due to the measurement uncertainty of common sensors, making classification a random operation in many instances [13]. In an acknowledgment of the effect of measurement accuracy of the PMV input variables, both ISO 7730 and EN 15251 also recommend operative temperature ranges based on the PMV model with assumptions of the activity level (met) and clothing (clo) in different building types. For a typical office in summer, the recommended temperature ranges for three classes are 2K, 3K, and 5K (Table 1), assuming air temperature is equal to operative temperature, 0.5 clo (thermal insulation for a typical combination of garments in summer), 1.2 met (sedentary office activity), and 60% relative humidity (moderate environment). Although these assumptions are likely to differ from what is experienced in most office buildings, expressing the compliance criteria as a temperature range has the advantage of being more readily understood and implemented by practitioners. Whether these recommended temperature ranges, derived from their equivalent PMV ranges, actually represent the comfortable range of conditions for building occupants is still unclear.

Table 1 Three classes of indoor thermal environment in ISO 7730

Class	PMV range	Temperature range (°C) for a typical office in summer	PPD (%)
A	–0.2 < PMV< +0.2	24.5 ± 1	<6
B	–0.5 < PMV< +0.5	24.5 ± 1.5	<10
C	–0.7 < PMV< +0.7	24.5 ± 2.5	<15

Increasing criticism of the accuracy of the PMV model to predict comfort in real buildings served as a backdrop for the development of alternative methods to derive comfort temperature ranges from field studies rather than laboratory studies. Most notable are the adaptive comfort models [14–16] which regress neutral operative temperatures with the prevailing mean outdoor temperature. The development of the adaptive models involved the use of occupant survey responses to determine the neutral temperature (either at the building or individual level), and the resulting tool is a predictive model requiring outdoor air temperature as the sole input variable. There is no doubt that much of the success of the adaptive model can be attributed to its simplicity, as well as that it's based on field data rather than the artificial laboratory conditions. As such, we thought it would be valuable to explore the field data even further, to determine acceptable indoor temperature ranges using occupant responses directly, rather than a predictive model.

A large dataset of subjective evaluations of the indoor environment with contemporaneous physical measurements across different contexts (e.g. climate, culture, building types, etc.) is required to comprehensively explore the psychophysical relationship between thermal acceptability and temperature. Such a resource is now available with the release of the ASHRAE Global Thermal Comfort Database II [8]. Combining the original ASHRAE RP-884 database [17] with newly compiled data from field studies around the world, it is the largest global database of thermal comfort field studies to date: 107,583 records contributed from 66 publications from 1982 to 2016 covering 98 cities in 28 countries across 16 Köppen climate types. Table 2 summarizes information about the database, referred to hereafter as the "ASHRAE database".

Table 2 Summary of basic parameters in ASHRAE database

Season	Building type	Cooling strategy at building level	Age	Gender
Autumn: 17,161 Spring: 12,680 Summer: 40,876 Winter: 36,625 Records: 107,342	Classroom: 17,852 Multifamily housing: 10,401 Office: 67,755 Others: 6,555 Senior center: 821 Records: 103,384	Air Conditioned: 32,372 Mechanically Ventilated: 180 Mixed Mode: 26,519 Naturally Ventilated: 47,285 Records: 106,356	Min.: 6 Median: 29 Mean: 32 Max.: 95 Records: 43,576	Female: 30,895 Male: 36,140 Records: 67,035

One of the challenges of using a large database to define acceptable temperature ranges is that different statistical methods, including the selection of input and output variables and algorithms, will produce different outcomes with the same data. Such methodological considerations have not been widely discussed in the research literature, and are even less well-understood when using occupant survey data compared to instrumental measurements. Arens et al. [11] used different psychometric scales from three distinct databases to determine the percentage of acceptability in binned operative temperatures. Zhang et al. [18] analyzed the percentage of thermal acceptability votes compared to binned operative temperature measurements. Ryu et al. [19] determined the comfort zone (indoor temperature and relative humidity range) on the psychrometric chart using the criteria -1 < thermal sensation vote < 1, -3 < comfort sensation vote < 0, and 0% < percent dissatisfied < 20%. These slight differences between studies highlight the hitherto unexplored implications of such decisions and the sensitivity of the selected analytical procedure to the determination of acceptable comfort temperature ranges. As the number of thermal comfort field studies continually increases, a comparison of data-driven approaches is necessary to determine the most appropriate method for deriving acceptable temperature ranges from psychometric data.

The objective of this paper is to perform a metanalysis of the ASHRAE database to determine a method of deriving acceptable temperature ranges based on occupant responses. The specific aims are:

1. Test the validity of tiered PMV classes as the compliance criteria by repeating the analysis by Arens et al. [11] on a large, contemporary thermal comfort database;
2. Recommend a method for deriving acceptable temperature ranges from occupant survey data and discuss the advantages of such an approach from a methodological perspective;
3. Compare the recommended comfort temperature ranges found in ISO 7730 and EN15251 standards to the newly derived acceptable temperature ranges.

3 Analysis of PMV classes

The research team used the ASHRAE database to assess the validity of thermal comfort classification based on the PMV method outlined in ISO 7730. The ASHRAE database includes four common psychometric scales: thermal acceptability, thermal sensation, thermal preference, and thermal comfort. Table 3 summarizes responses to these questions from the database.

Table 3. Summary of subjective answers in ASHRAE database. Thermal sensation is a continuous scale from -3 (cold) to 3 (hot) with 0 being neutral. Thermal comfort is a continuous numeric scale from 1 (very uncomfortable) to 6 (very comfortable).

Thermal acceptability	Thermal sensation	Thermal preference	Thermal comfort
0 (unacceptable): 14,045	Min.: -3	Cooler: 27,725	Min.: 1
1 (acceptable): 48,399	Median: 0	No change: 43,256	Median: 5
Records: 62,444	Mean: 0.1679	Warmer: 14,518	Mean: 4.31
	Max.: 3	Records: 85,499	Max.: 6
	Records: 104,454		Records: 34,481

Since thermal comfort standards, as well as the PPD index, refer to "satisfaction", but surveys don't ask about this directly, we had to make the following assumptions to equate each of the four different scales to "satisfaction":

- "Acceptable" votes.
- "Thermal sensation" votes between -1 and 1 (sometimes referred to as the central points).
- "Thermal preference" votes of "no change".
- "Thermal comfort" votes equal to or greater than 3.5 (between neutral and very comfortable).

These assumptions are widely used in thermal comfort research, and whilst their statistical validity may be challenged it is beyond the scope of this paper to do so. For this analysis, we dropped records without one of these four scale responses or a corresponding PMV, and used the resulting data to calculate the observed percentage of satisfaction in each PMV class using the assumptions noted above.

Table 4 Observed percentage of satisfaction in three PMV classes

	PMV Class (range)		
	A (0±0.2)	B (0±0.5)	C (0±0.7)
Sample size (inclusive)	11,200	21.650	26,853

Thermal acceptability	% of acceptability	77.7	77.3	76.8
Thermal sensation	Sample size (inclusive)	17,163	34,080	42,902
	% of -1 ≤ TSV ≤ 1	79.0	78.6	78.2
Thermal preference	Sample size (inclusive)	15,296	29,989	37,424
	% of no change	53.3	53.3	52.8
Thermal comfort	Sample size (inclusive)	4,006	8,319	10,621
	% of comfort (vote ≥ 3.5)	81.4	80.8	80.6

Table 4 shows the percentage of votes corresponding with thermal satisfaction within the three PMV classes. For thermal acceptability, even the narrowest PMV of Class A does not achieve acceptability levels above 80%. The table shows the same result for thermal sensation and thermal preference. Satisfaction as expressed through thermal comfort votes was the only metric to reach levels above the 80% threshold. Importantly, there was no significant difference between the three PMV classes for any of the four psychometric scales tested. This confirms the analysis by Arens et al. in 2010 [11] and supports the general critique by Roaf et al. [12] that PMV classes only encourage greater energy expenditure without necessarily improving occupant comfort.

To investigate whether this was the result of the PMV class thresholds themselves, as specified in the standards, we calculated the percentage of satisfaction for ten PMV ranges (from ±0.1 to ±1.0). Figure 1 shows that as the PMV range widens, the percentage of satisfaction only very slightly declines across all scales (about 1% decrease from PMV ±0.1 to ±1.0). This contradicts the claim made in the standards that one will see a decrease of 9% in satisfaction (reciprocal of an increase of PPD) as the PMV ranges from ±0.2 to ±0.7 (i.e., an association determined by the PMV-PPD relationship). The difference between the scales will be discussed in a later section.

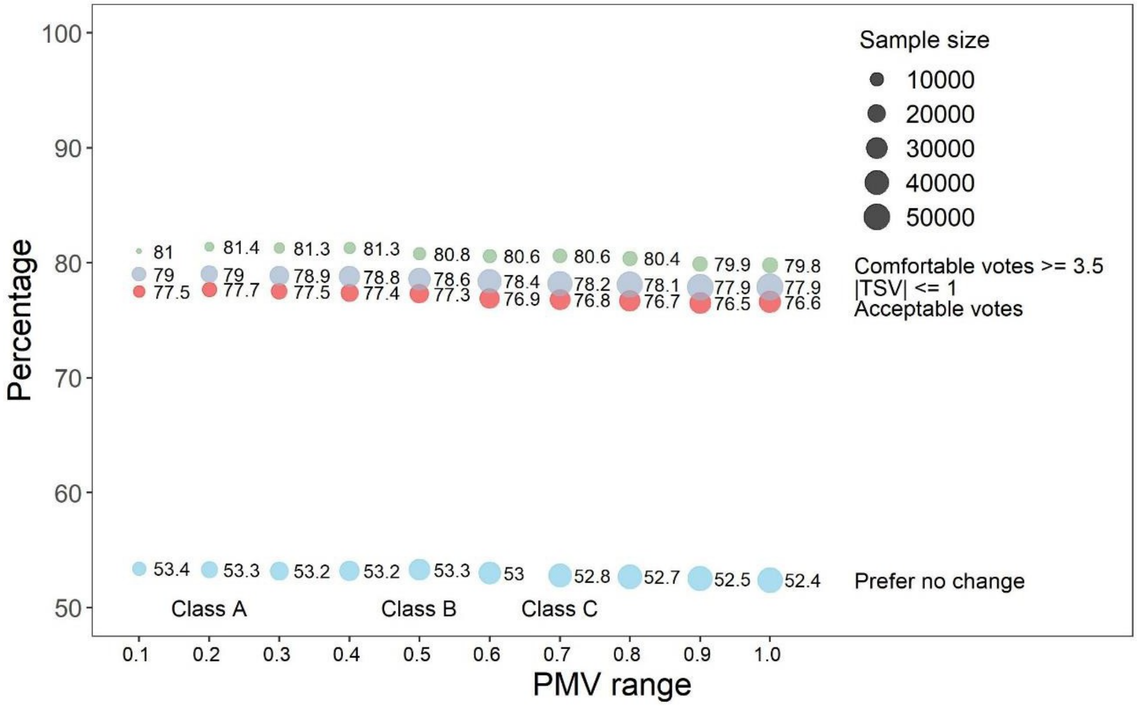


Figure 1 Observed percentage of satisfaction in PMV ranges (e.g. 0.1 means |PMV|≤ 0.1)

To further explore the validity of the PMV-PPD model, the observed percentage of dissatisfied (OPD), the reciprocal of percentage of satisfaction, is shown in Figure 2. The classic PMV-PPD curve is superimposed for reference. Each dot represents the percent dissatisfied for the corresponding scale in the PMV bin (size = 0.1) and the smooth curves are quadratic regression models weighted by sample size. The OPD is not as sensitive to thermal sensation as the PMV-PPD predicts, shown by the flatter slopes of the curves compared to the PPD. This reinforces the earlier finding that – for the purpose of creating PMV classes for comfort standards - narrower PMV ranges around a neutral point do not provide greater levels of satisfaction.

It is interesting to note that in addition to the flatter slopes of the dissatisfaction curves shown in Figure 2, the lowest OPD - based on any of the four subjective scales and in relation to the PMV metric - is approximately 20%. This is much higher than the 5% minimum predicted by the conventional PMV-PPD relationship. It is difficult to offer a conclusive explanation for this finding given the diverse range of field studies contained in the ASHRAE database, but a related analysis of the PMV-PPD model using the same database may shed more light on the discrepancy [20]. There it was found that PMV may be a greater source of error than the PPD metric. That study found that the field-based OTS_{bin}-OPU (observed thermal sensation bin against observed percentage of unacceptability) curve and the lab-based PMV-PPD curve are comparable, suggesting that if the actual thermal sensation vote is known (or the PMV prediction is accurate) then the predicted dissatisfaction level using the PPD curve is somewhat reliable.

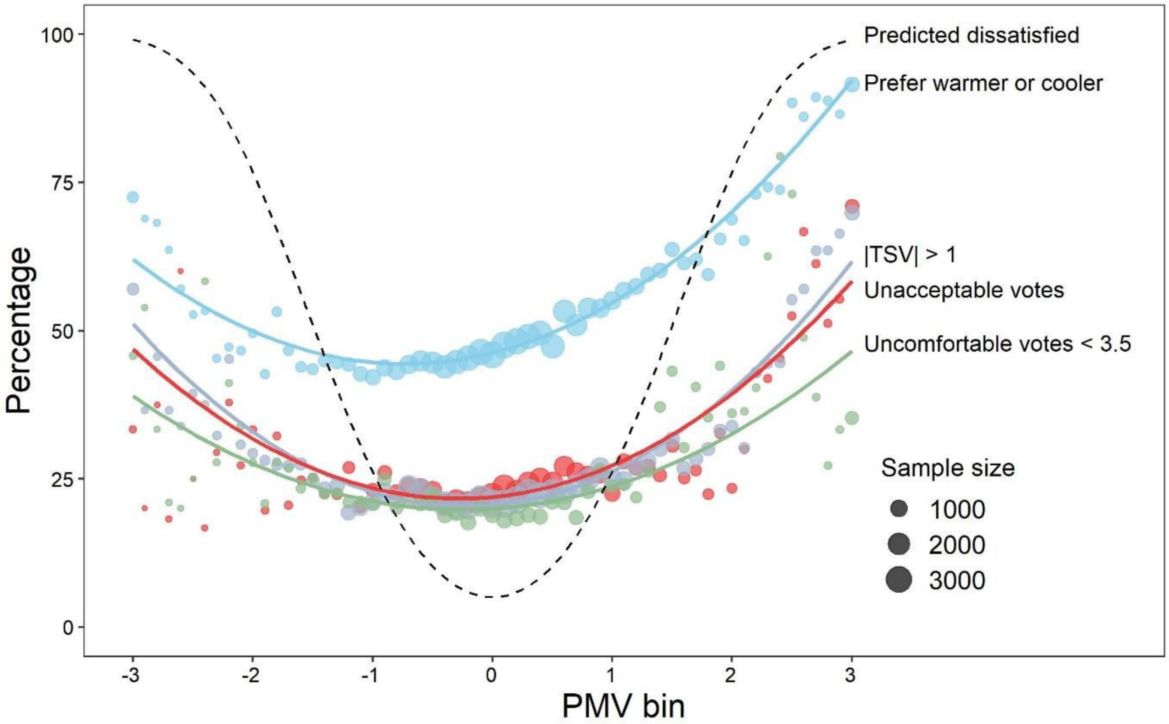


Figure 2 Observed vs. predicted percentage of dissatisfied. Quadratic smooth curves are weighted by sample sizes.

4 Methods to derive acceptable temperature ranges

The analysis in the earlier section demonstrated that PMV classes are unhelpful in defining an acceptable thermal environment, likely due to the role of PMV inaccuracies in the PMV-PPD relationship, suggesting that a new approach is required. Practically speaking, methods to derive comfort ranges should limit the necessary input parameters to simplify the measurement and implementation for practitioners utilising them in building operations. For specifying comfort ranges, operative temperature has the advantage of combining the radiant and convective heat exchanges that characterise non-uniform exposures in buildings. However, the number of operative temperature measurements in the ASHRAE database (n = 37,963) is much smaller than that of air temperature (n = 99,911). Moreover, preliminary comparative analysis showed that using air temperature vs. operative temperature resulted in a difference of less than 1K for the derived acceptable temperature range. For these reasons, the present analysis expresses comfort ranges using air temperature, which has the additional advantage of being the most commonly controlled parameter in buildings and routinely measured by building management systems. The following section discusses two statistical methods to derive the acceptable temperature range using occupant survey data: one used in previous studies and a new method.

Method 1: percentage of acceptability in temperature bins

Used in earlier studies [11,18], method 1 involves binning temperature into intervals of 1°C and using the "Acceptability" scale directly to calculate the percentage of acceptability within each of those temperature bins. Temperature bins with 80% or greater acceptability votes are considered to represent a comfortable temperature, and the range is defined by the upper and lower temperature bins achieving such levels of acceptability.

Figure 3 (a) shows the acceptable temperature ranges defined by method 1: 18˚C – 29˚C for classroom, 16˚C – 31˚C for housing, 23˚C – 24˚C for office, and 19˚C – 29˚C for other building types. The advantage of this method is that it strictly follows the conventional definition of an acceptable thermal environment – over 80% of occupants deeming a given thermal environment to be acceptable. However, the tight acceptable temperature range found for office buildings (only 2K wide) seems to contradict the now-routine finding from field studies conducted around the world that building occupants accept much wider temperatures than the PMV-PPD model predicts. This raises the obvious question of whether 80% acceptability – as measured by the binary Acceptable-Unacceptable scale - is an appropriate or realistic threshold for contested spaces with limited controls such as an office. Whilst this might seem discouraging, it does lend support for the uptake of personal comfort systems as a potential solution to the fallacious one-size-fits-all approach that has dominated thermal comfort thinking. This will be discussed in a later section of this paper.

Method 2: neutral temperature range

We propose a novel method which involves determining the neutral temperature corresponding to each individual occupants' vote of neutrality on the thermal sensation scale (TSV = 0) and defining the acceptable temperature range based on the population distribution. We calculated the neutral temperature for each record in the ASHRAE database based on measured air temperature and thermal sensation votes according to the Griffiths method [21]. The range of air temperatures containing 80% of the populations' neutral temperatures defines the acceptable range. Neutral temperatures below the 10th percentile and above the 90th percentile are considered outliers, i.e. occupants with extreme thermal preferences. Humphreys and Nicol [22] suggested 0.4 to be an appropriate constant for the Griffiths method but later used 0.5 when developing the European adaptive model [16]. Both constants were tested and 0.4 was selected as it derived temperature ranges closer to those found when using method 1.

An implicit assumption of method 2 is the equivalence of a neutral sensation and thermal acceptability despite the fact that people may not necessarily consider neutral as their preferred thermal comfort condition [23–25]. Figure 3 (b) shows that method 2 derives wide ranges for classroom, housing and other building types that are generally narrower than the ranges from method 1. Most importantly, the acceptable temperature range for offices is wider than the 2K found using method 1. A similar range was found in classrooms. This is an encouraging result as offices and classrooms are similar thermal contexts – contested spaces with fewer adaptive options - compared to homes and other building types.

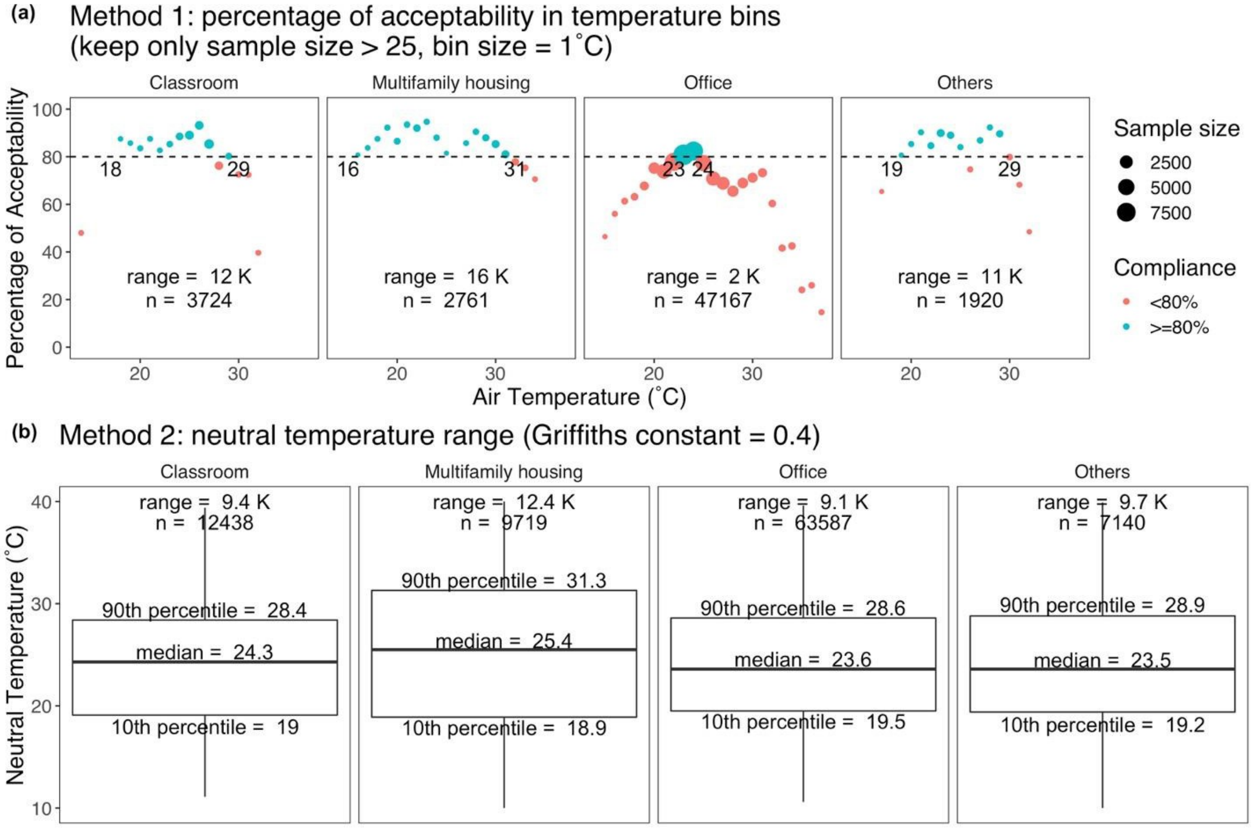


Figure 3 Acceptable air temperature range derived by (a) method 1 and (b) method 2

Performance measures of methods

The two methods used to derive acceptable temperature ranges in the present analysis are not predictive models *per se*, so conventional metrics of prediction accuracy are not applicable. However, we conducted a test of the reliability of the two methods to compare their performance. The reliability test involved randomly partitioning the database into training and testing sets (80%

and 20% of samples, respectively), using both method 1 and 2 to derive the acceptable temperature range for different building types, and then calculating the absolute difference between the resulting ranges found in the training and testing sets. This is somewhat representative of the systematic error of the method in determining acceptable temperature ranges. The test was run 500 times in order to achieve stable mean differences.

It was found that the error (or difference) between ranges using method 1 was 5.3K for classrooms, 2.6K for multifamily housing, 0.5K for offices, and 2.6K for other building types. The differences were substantially smaller using method 2, with differences of 0.2K for classrooms, 0.2K for multifamily housing, 0.04K for offices, and 0.2K for other building types. The test results show that the derived temperature ranges from method 2 are more reliable than method 1, which appears to be highly dependent upon the subset of data being used to derive the range. The error reported for office buildings is the lowest of all building types regardless of the method used. This is likely due to the large number of measurements available from offices compared to other building types, underlining the importance of larger datasets when conducting metanalyses of subjective votes.

The large difference found in acceptable temperature ranges between building types when using method 1 seems to suggest that the individual building may influence the acceptability of occupants. Since the ASHRAE database does not identify buildings, we used heuristics to develop a proxy building-level unit of analysis based on several different parameters. Records with a unique combination of publication source, city, building type, and cooling strategy were classified as being from the same building. Although this approach is coarse, we deemed it to be sufficient for the current analysis. Once buildings were identified, we used the same methods for deriving acceptable temperature ranges at the building level, rather than by building type across the entire dataset.

Bars in Figure 4 display the number of buildings for each acceptable temperature range using method 1 (left) and method 2 (right). The total number of buildings applicable to method 1 is far smaller than those applicable to method 2 because of the fewer acceptability votes in the ASHRAE database. The method 2 result is close to a normal distribution while using method 1 the number of buildings decreases as the range widens. In fact, 23 out of the 37 “buildings” in Figure 4 (a) are office buildings. This explains why narrow ranges dominated in Figure 4 (a).

The red lines in Figure 4 show the reverse cumulative percentage of buildings, indicating the number of buildings (y%) in the database that would be deemed as having acceptable thermal environments if the temperature range threshold is set to be xK. This may be helpful in the discussion of an appropriate temperature range threshold. For instance, the cumulative percentage of buildings in Figure 4 (b) with a >6K air temperature range is nearly 80%, i.e., the number of buildings with range 6K, 7K, …, and 14K accounts for 80% of the total number of buildings. This may be interpreted practically by saying that a 6K acceptable temperature range specified in the standards would correspond to 80% of building occupants expressing satisfaction with that temperature range. However, for 80% of buildings to be deemed as acceptable using method 1 the acceptable temperature range threshold should be 2K (see red line in Figure 4 (a)).

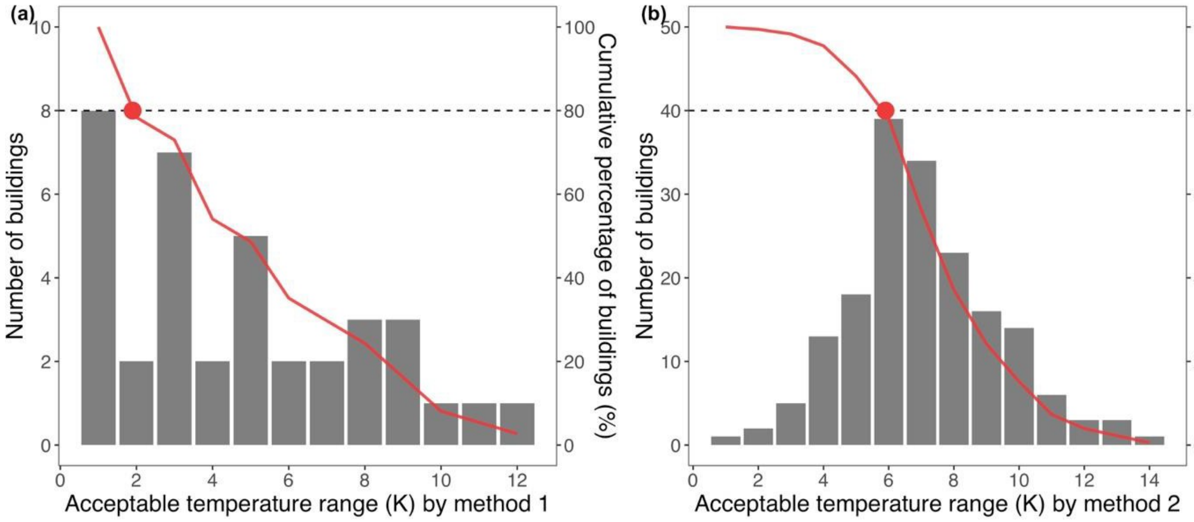


Figure 4 Acceptable temperature range for each "building" using (a) method 1 and (b) method 2

The results in this section suggest that although method 1 is conceptually sound, the results are greatly influenced by the dataset used, the sample size, and the building type. Method 2 uses a pragmatic statistical approach that leverages the larger sample size afforded by the more widely used thermal sensation vote. The resulting temperature ranges show strong agreement with method 1 for classrooms, residential houses, and other building types. The major difference occurs in office buildings, but it is argued that the wider temperature ranges from method 2 are more realistic and align with results reported in thermal comfort field studies. It is clear from these findings that the approach to defining temperature ranges should depend on the features of the dataset being used. Method 2 is therefore used in the following sections as it is more suitable for use with large datasets comprised of diverse contexts.

5 Results compared to standards

Both ISO 7730 and EN 15251 recommend informative indoor temperature ranges during heating and cooling seasons for a range of building types. In order to compare the results of this analysis with these standards, we used method 2 to determine the acceptable air temperature ranges for different building types for summer and winter (swing seasons were dropped). It is recognised that a binary classification of season is not necessarily a robust approach for considering the effects of prevailing weather or climate. However, this coarse level of differentiation is what is used in the standards and we felt was therefore applicable for such a comparison. The analysis first compared the derived ranges following method 2 with the middle class (Class B/II) of comfort temperature ranges given in ISO 7730 and EN 15251. The building type classification in the ASHRAE database is not as detailed as what is published in the standards. Therefore, Figure 5 only compares the temperature ranges for classrooms, multifamily housing, and offices, and shows the acceptable temperature ranges by building type and season using method 2 alongside those specified in the standards.

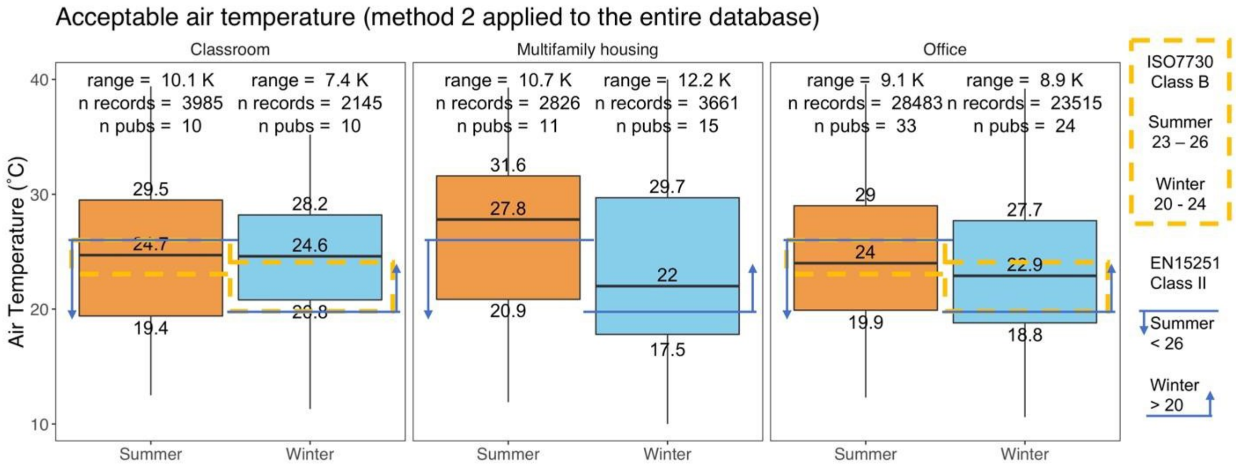


Figure 5 Acceptable air temperature ranges by method 2 compared to the standards. ISO 7730 does not specify temperature ranges for homes. n pubs = number of publications.

The figure shows that – for winter - there is relatively close agreement between the lower limit of temperature ranges found in the standards and those determined through method 2 using the ASHRAE database. However, the upper limits for both summer and winter are too conservative in the standards, with field study data showing much greater tolerance to warmer temperatures by building occupants in both seasons. One possible explanation for this discrepancy is that the temperature ranges in standards were developed using the PMV model with assumptions of some physical and personal parameters. First, it was shown earlier in this analysis (section 3) that the PMV-PPD relationship does not correctly model the observed satisfaction in real buildings; there is very little change within the range of $-1.0 < PMV < 1.0$. Second, the assumptions of both the environmental and personal input parameters into the PMV model used in ISO 7730 and EN 15251 for their summer and winter designations appear to differ to those observed in buildings.

Uncertainty analyses have shown clothing insulation level and metabolic rate to be the two largest sources of uncertainty in the inputs for PMV [25–29]. For the specification of comfort temperature ranges in the standards, clothing level was assumed to be a fixed 0.5 clo in summer and 1.0 clo in winter in the standards. Figure 6(a) shows that although the mean and median clothing level in summer in real buildings is close to 0.5 clo, there is large variance in clothing across the database ranging from just above 0 clo to over 1 clo. In winter, people generally dress below the 1.0 clo assumed by European standards, which may explain why occupants were found to accept higher temperatures in winter than the standards suggest. The metabolic rate of occupants in the ASHRAE database was found to be close to the assumed level in the standards (1.2 met). This is likely to be attributable to the near universal use of lookup tables for met estimation due to the significant technical requirements to properly measure metabolic rate.

While the fixed assumptions made by the European standards of the two personal PMV inputs likely contribute to the discrepancy between the predicted and the observed comfort temperatures, a similar issue for some environmental parameters may further compound those errors. EN 15251 assumes a “low” air velocity and ISO 7730 specifies the maximum mean air velocity to be 0.19 m/s in summer and 0.16 m/s in winter. The empirical basis for these assumptions is unclear, but Figure 6(b) shows that measured air velocity in real buildings can be much higher than those speeds, particularly in classrooms and homes. Such elevated air speeds could also help explain the higher acceptable temperatures found in all building types for both summer and winter. Moreover, the large variance in relative humidity in all building types will exert some influence over the range of acceptable temperatures.

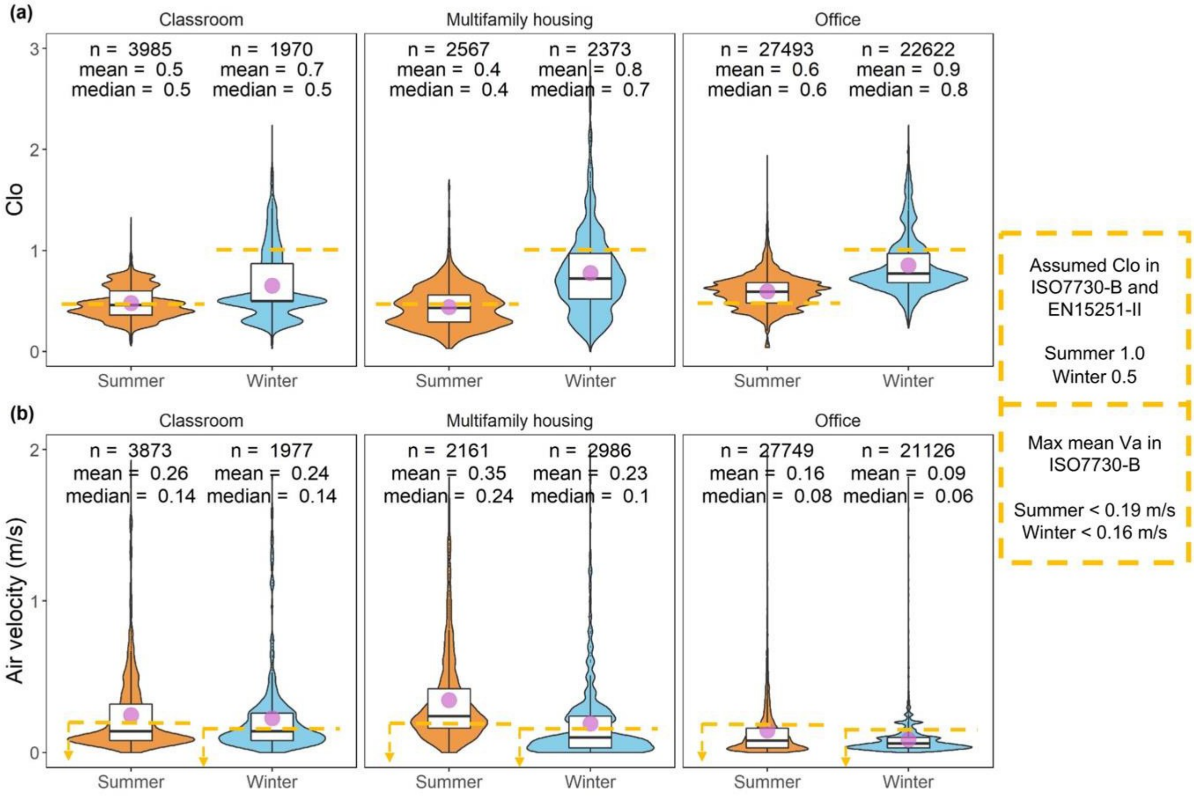


Figure 6 Clothing level (a) and air velocity (b) in different spaces and seasons. Pink dot is the mean. Boxplot shows 25th percentile, median, and 75th percentile. Violin plot shows the density of records.

It is understandably necessary for standards bodies to make assumptions about the PMV input parameters in order to specify acceptable temperature ranges. Yet, the present analysis has shown that discrepancies between those fixed assumptions and the thermal exposures characterised by field studies in real buildings are likely to contribute to the determination of different neutral temperatures for occupants. Whilst it is impossible to consider all possible permutations within a single temperature range, our analysis suggests that there appears to be a cultural bias in the assumptions of both personal and environmental parameters within the standards. Both ISO 7730 and EN 15251, although prepared for the European contexts, are widely used in other parts of the world. To investigate potential cultural differences in the field measurements, Figure 7 shows the acceptable air temperature ranges using method 2 for separate Asian and European subsets of the ASHRAE database. When compared with the analysis of the full dataset in Figure 5, the European acceptable temperature ranges are shifted towards the cooler side whilst the Asian subset is shifted towards the warmer side. This is unsurprising given the predominant climates in the Europe cities in the database are temperate or cold, whilst the entire database encompasses a variety of climate types particularly from tropical climates (e.g. Asia). Interestingly, the lower temperature limits for homes and offices determined using method 2 are below the 20°C suggested by the standards for the European subset. More significant adaptive opportunities afforded to people in homes, such as different clothing levels, are likely to substantially explain the cooler limits. Psychological factors associated with the ability to utilise natural ventilation through operable windows, modify window furnishings to influence connectedness to outdoors, or even the material and color selection of the interiors may also affect thermal sensation. Unfortunately the ASHRAE database does not contain the requisite information to explore the relationship between these factors and thermal sensation.

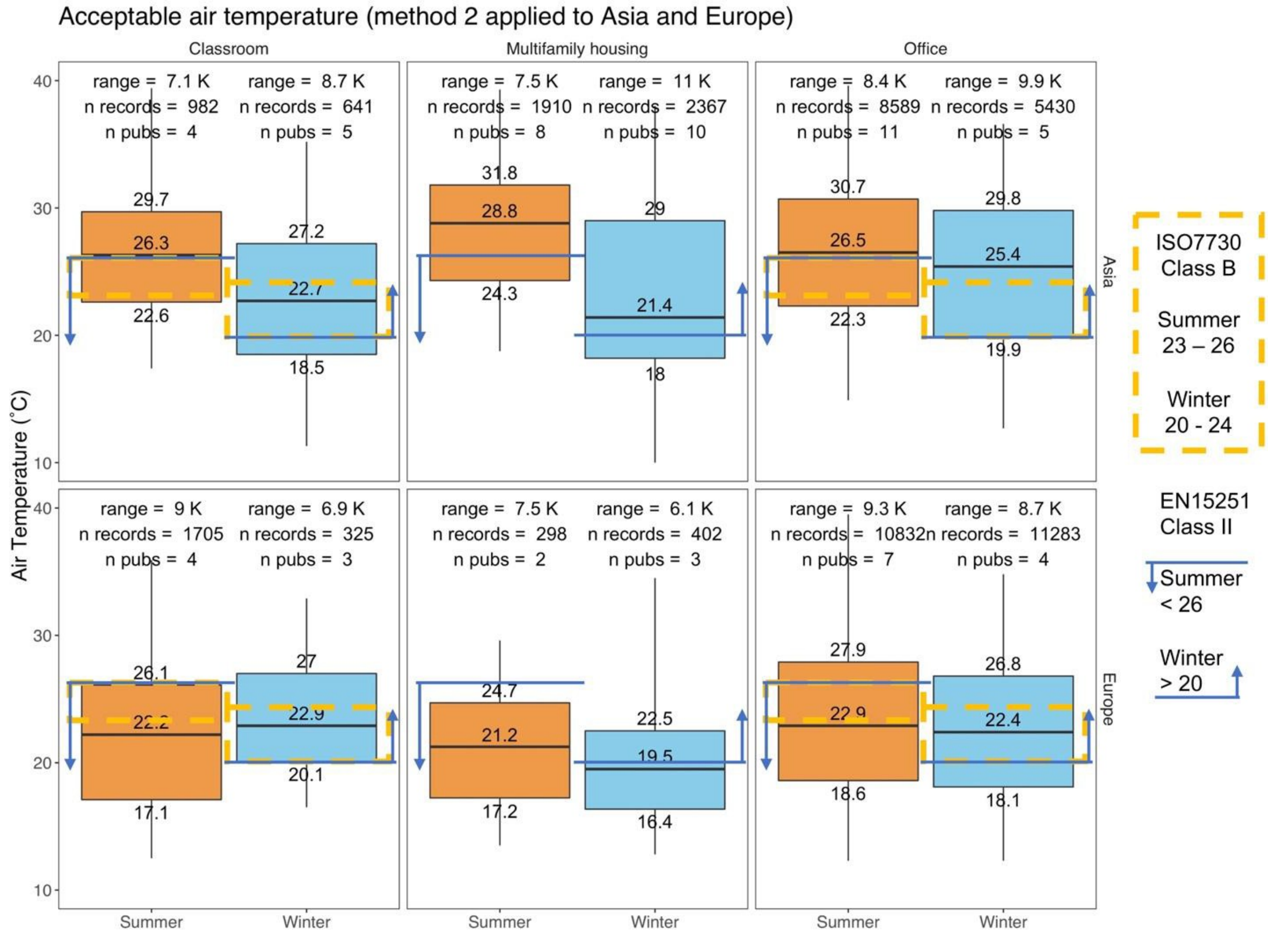


Figure 7 Acceptable air temperature ranges for Asian (top) and European (bottom) datasets compared to the standards. ISO 7730 does not specify temperature ranges for homes. n pubs = number of publications.

In summary, the recommended temperature ranges in ISO 7730 appear to be too narrow, particularly when expanded beyond the European context. The widest compliance class (Class C) - 5K for summer and 6K for winter – is conservative compared to the 7.4K-12.2K neutral temperature ranges derived in this paper based on field studies in different building types and season (Figure 5). Possible reasons for these discrepancies include the inaccuracy of PMV-PPD model, variance in the input variables of PMV model, and the generalization of a context-specific model. These should all be considered before endorsing the universal use of such temperature ranges for thermal comfort compliance assessments of buildings.

6 Discussion

The PMV-PPD model marked a significant step forward in thermal comfort understanding by establishing an empirical relationship between thermal sensation and the associated satisfaction. However, countless field studies have shown the shortcomings of this deterministic approach in many different contexts [30–33]. Humphreys and Nicol attribute this failure to three important factors: the uncertainties of input variables, the structure of the equation itself, and its application to non-steady-state conditions [34]. These all indicate that a heat-balance model in practice requires significant simplifications that reduce important contextual aspects of thermal perception and ignore the adaptive processes of building occupants. The aim of this paper is not to simply demonstrate the inaccuracies of the PMV model itself, but instead to argue that these shortcomings have flow-on effects to the specification of the thermal comfort compliance requirements, and particularly the PMV classes, that falsely assume a narrower PMV range leads to higher occupant satisfaction. Not only is this specious connection between tighter indoor temperature tolerances and improved comfort untrue, it promotes energy-intensive HVAC use that significantly contributes to the problems of greenhouse gas emissions.

In addition to the model uncertainties of PMV-PPD, the variant terms used in thermal comfort field studies present challenges to determining the level of thermal satisfaction of occupants that the PMV model aims to predict. ASHRAE Standard 55 uses “acceptability” as the target outcome and “satisfaction” as part of the definition of comfort, but laboratory and field studies have primarily used “thermal sensation” scales, leading to the PMV model having to use assumptions to equate specific thermal sensation responses with thermal satisfaction. This raises important questions around the semantic equivalence of acceptability, satisfaction, and sensation that have yet to be addressed adequately by the thermal comfort research community. The same problem applies to other common psychometric scales like thermal preference and thermal comfort, which similarly require assumptions and rule-of-thumb techniques when converting to satisfaction.

It was anticipated that the percentage of thermal preference votes of “no change” would be the lowest among the four common psychometric scales, and the percentage of acceptability would be the highest. This was based on the assumption that preference represents the ideal condition for the occupant while acceptability refers to a broader notion of tolerance [24]. In the analysis of Figure 1, percentage of “no change” votes is indeed the lowest as anticipated, but the percentage satisfied using the thermal acceptability scale is not the highest – it is lower than the sensation and comfort scales, suggesting that TSV between -1 and 1 and comfort are even broader requirements than thermal acceptability. However, this interpretation needs further examination, since the reason why TSV between -1 and 1 seems to have broader meaning than acceptability could partly be due to the fact that people may not perceive thermal sensation scale as equidistant [35], and/or the effects of language and context on the interpretation of words [36]. Clearly the choice of scales, and the widely-used conversion rules, lead to different outcomes and may not be directly translatable.

These considerations are an important acknowledgement of the challenges of using psychometric scales for thermal comfort research, and reinforce the importance of selecting the appropriate scale for the research question. Rather than directing attention towards understanding the nuanced semantic difference between scales, perhaps a more pragmatic effort would be to standardise the use of scales for thermal comfort research. If the standards continue to define comfort as an acceptable thermal environment, then “thermal acceptability” scales should be used in field studies, particularly when focused on thermal comfort compliance assessment. If a laboratory study is investigating a particular aspect of the human thermoregulatory system, then the thermal sensation scale may be more appropriate. Thermal preference is more helpful in building control applications, with emerging technologies like Comfy asking occupants’ thermal preference to appropriately adjust the HVAC system [37]. Carefully selecting the scale for the particular research question or practical application would reduce the need to convert between metrics.

Based on the laboratory-derived relationship, the lowest predicted percentage dissatisfied (PPD) is 5% when PMV is neutral. In the standards, the oft-cited aim is for greater than 80% thermal acceptability in offices – accounting for 10% of occupants experiencing whole body discomfort (assumed to be thermal sensations greater than +/-2), and 10% more are presumed to be uncomfortable due to local discomfort (e.g., draft, asymmetry). However, the results presented in this paper suggest that office workers are generally difficult to satisfy (Figure 2), and 5% dissatisfaction is unlikely to be achieved by any centrally-conditioned building. Luo et. al. found that occupants quickly increase their thermal comfort expectations and rarely compromise once raised [38]. Occupants becoming accustomed to, or even demanding, tighter temperature tolerances might explain why tight temperature ranges do not necessarily improve thermal comfort. Thermal influences on positive vs. negative overall environmental assessments can also vary. Kim and de Dear [39] showed that the thermal environment has a clear negative impact on overall satisfaction when occupants are unhappy with the conditions, but contributes less to positive evaluations when conditions are satisfactory. These studies, along with the analysis presented here, raise the question of the appropriateness of the 80% acceptability threshold for office buildings without some type of personal control. The large inter-individual distribution of thermal preferences and the physical constraints of centralized HVAC systems to deliver bespoke conditions effectively preclude the provision of ideal thermal environments for all occupants. Continuing to encourage unrealistic levels of thermal satisfaction using such systems seems certain to increase HVAC energy use without any tangible improvement in occupant comfort.

Rather than the U-shape curve defining the PMV-PPD relationship, occupants in real buildings appear to be more tolerant of non-neutral indoor environments as defined by the standard-based PMV metric. The regression lines in Figure 2 have an almost-flat bottom and gradually increase towards the ends of the thermal sensation scale. These lines indicate that the thermal satisfaction of a population is similar across a wide PMV range, and therefore a wide range of air temperatures. This contradicts the popular idea of an optimum or ideal temperature that has been promoted by the steady-state heat balance approach to thermal comfort, and in turn the comfort standards. Rather than a single controlled body temperature with a fixed setpoint, contemporary thermophysiological theory instead promotes the concept of a thermoneutral zone where vasomotor tone is able to regulate against body temperature fluctuations without initiating shivering or sweating [40,41]. Very few indoor environments would push occupants’ thermoregulatory system beyond the thresholds of the thermoneutral zone, and it is very likely that the comfort zone exists within this range of body temperatures [42]. This conceptual model of human thermoregulation supports the observed flatter dissatisfaction curves found in the present analysis, and further discourages the pursuit of an optimum comfort temperature or even narrow temperature ranges.

The major finding of this analysis is that it is difficult to specify a universally-applicable comfort temperature range for different contexts without resorting to heavy HVAC requirements that promote profligate energy use. The results in Figure 7 suggest that for the European context both the upper and lower temperature limits for offices can be relaxed by 2K i.e. cooling setpoint of 28°C instead of 26°C, and a heating setpoint of 18°C instead of 20°C. The recommend temperature ranges for classrooms in EN 15251 appear to be in line with neutral temperatures found using the ASHRAE database. While the results for residential housing in Figure 7 are somewhat aligned with one residential comfort study [43] and appear to suggest a widening of the temperature range, some caution should be taken when interpreting this due to the relatively small sample size. Interestingly, Cheung et al. [20] tested a simple model that predicts thermal sensation based solely on air temperature. The neutral temperature band of this simple model ranged from 18°C to 30°C, similar to what was reported in Figure 5, and the overall prediction accuracy was higher than the PMV-PPD model. So whilst a universal prescription of a comfort temperature range is neither possible nor desirable [40], the current recommendations for offices found in international standards such as ISO 7730 appear to be too narrow and could be relaxed to still maintain comfort while avoiding encouraging unnecessary energy expenditure on space conditioning.

Strategies to widen the permissible temperature ranges in offices are more likely to succeed when coupled with the availability of local control options that recognise individual differences [44] and allow for the creation of bespoke microclimates. The theoretical basis and design solutions for such an approach to thermal comfort in buildings can be found in research studies of thermal adaptation and personal control systems [45–47]. Both chamber studies [48] and field studies [49] have demonstrated the overwhelmingly positive effect of individual control on thermal comfort whilst potentially reducing HVAC energy use by 32% - 73% [7]. Personal comfort systems such as desk fans or footwarmers can deliver comfort to occupants whilst allowing for a relaxation of the room air temperature range to 18°C-29°C [50–52]. Unfortunately, the ASHRAE database utilized here does not contain sufficient information on personal controls to perform such an analysis. It is likely that the majority of buildings surveyed in the database did not have personal comfort systems, so the derived temperature ranges in Figure 5 and Figure 7 may even be conservative if the corrective potential of personal comfort systems are considered [53]. Therefore, instead of demanding ever-increasing central control over the environment, standards should aim to link performance criteria to thermal adaptation opportunities, such as access to and degree of personal control [54]. This is particularly important given the number of emerging technologies around personal comfort systems, such as thermally responsive clothing fabric [55] or a heating and cooling robot [56]. Perhaps a more promising approach is the development and use of personal comfort models based on physiology or behaviour that can dynamically control HVAC setpoints based on occupants' comfort profile and energy use restrictions [57–60].

7 Conclusion

This paper builds on data analyses of the largest-to-date global database of thermal comfort field studies and focuses on the design compliance criteria of a thermal environment. First, the observed thermal satisfaction (based on any of the four thermal scales) showed no significant difference between the three PMV classes currently included in international standards, meaning that tiered PMV classes are not appropriate compliance criteria. This demonstrates a need for other compliance criteria, such as the direct use of temperature ranges given that air temperature is the most commonly controlled environmental parameter in buildings. As the field-based global database becomes more widely utilized, data should be able to inform the acceptable temperature range directly rather than predicting the temperature range from traditional laboratory-based thermal comfort models. However, one should exercise caution when using data-driven techniques as different statistical methods yield different results. The methodological discussion led to our recommending method 2 - using individual neutral temperatures calculated from corresponding air temperature and TSV to determine the acceptable temperature range from the 10th percentile to the 90th percentile - in an attempt to standardize the data-driven methods of deriving acceptable air temperature range. The resulting acceptable temperature ranges (7.4K-12.2K) are wider than the ISO 7730 (2K-6K) and EN 15251 (maximum 26°C and minimum 20°C) mandate, and the reason may be three-fold: inaccuracy of PMV-PPD model, variance in the input variables of PMV model, and the generalization of the European context where ISO was predominantly used. Wider acceptable temperature ranges are not only valid in reality, but also favorable because of their energy savings, particularly when combined with increasingly-popular solutions to personal comfort systems. Wider temperature ranges also acknowledge and better cater to the dynamics of indoor thermal environments arising from synoptic-scale weather patterns, temporal and spatial differences, individual physiological differences (including activity levels and clothing levels), and differences in thermal preference between individuals. Researchers and practitioners are encouraged to develop context-specific compliance criteria that are suitable for inclusion in relevant comfort standards, i.e. in a specific region, for a specific type of building, etc.

Declaration of interest

None.

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