ELSEVIER
Energy and Buildings 34 (2002) 549–561
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55

Richard J. de Dear[a,*], Gail S. Brager[b]

[a]Division of Environmental and Life Sciences, Macquarie University, Sydney, NSW 2109, Australia
[b]Center for Environmental Design Research, University of California, Berkeley, CA 94720-1839, USA

Abstract

Recently accepted revisions to ASHRAE Standard 55—thermal environmental conditions for human occupancy, include a new adaptive comfort standard (ACS) that allows warmer indoor temperatures for naturally ventilated buildings during summer and in warmer climate zones. The ACS is based on the analysis of 21,000 sets of raw data compiled from field studies in 160 buildings located on four continents in varied climatic zones. This paper summarizes this earlier adaptive comfort research, presents some of its findings for naturally ventilated buildings, and discusses the process of getting the ACS incorporated into Standard 55. We suggest ways the ACS could be used for the design, operation, or evaluation of buildings, and for research applications. We also use GIS mapping techniques to examine the energy-savings potential of the ACS on a regional scale across the US. Finally, we discuss related new directions for researchers and practitioners involved in the design of buildings and their environmental control systems. © 2002 Published by Elsevier Science B.V.

Keywords: Thermal comfort; Adaptive model; Field studies; Natural ventilation; Energy conservation; Standard

1. Introduction

The purpose of ASHRAE Standard 55—thermal environmental conditions for human occupancy, is ‘‘to specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space’’ [1]. While ‘‘acceptability’’ is never precisely defined by the standard, it is commonly agreed within the thermal comfort research community that ‘‘acceptable’’ is synonymous with ‘‘satisfaction’’, and that ‘‘satisfaction’’ is associated with thermal sensations of ‘‘slightly warm’’, ‘‘neutral’’, and ‘‘slightly cool’’. ‘‘Thermal sensation’’ is the question most commonly asked in both laboratory and field studies of thermal comfort.

What, then, influences peoples' thermal sensations? ASHRAE Standard 55 is currently based on the heat balance model of the human body, which assumes that thermal sensation is exclusively influenced by four environmental factors (temperature, thermal radiation, humidity and air speed), and two personal factors (activity and clothing). An alternative (and, we believe, complementary) theory of thermal perception is the adaptive model, which states that factors beyond fundamental physics and physiology play an important role in building occupants' expectations and thermal preferences. Thermal sensations, satisfaction, and acceptability are all influenced by the match between one's expectations about the indoor climate in a particular context, and what actually exists [2]. While the heat balance model is able to account for some degrees of behavioral adaptation such as changing one's clothing or adjusting local air velocity, it ignores the psychological dimension of adaptation, which may be particularly important in contexts where people's interactions with the environment (i.e. personal thermal control), or diverse thermal experiences, may alter their expectations, and thus, their thermal sensation and satisfaction. One context where these factors play a particularly important role is naturally ventilated buildings—the focus of this paper.

Happily, we are seeing an increasing number of architects and engineers paying attention to the plea from occupants for operable windows in non-residential buildings. Unfortunately, they have often been limited in their flexibility to pursue such options because of the relatively narrow range of interior thermal conditions allowed under earlier versions of ASHRAE Standard 55. These conditions have been assumed to be universally applicable across all building types, climates, and populations. Although, it was never intended for ASHRAE Standard 55 to require air-conditioning for buildings, it has been very difficult to meet the standard's narrow definition of thermal comfort without

* Corresponding author. Tel.: +61-2-9850-7582; fax: +61-2-9850-8420.
E-mail address: rdedear@laurel.ocs.mq.edu.au (R.J. de Dear).

0378-7788/02/$ – see front matter © 2002 Published by Elsevier Science B.V.
PII: S0378-7788(02)00005-1

such mechanical assistance, even in relatively mild climatic zones. Needless to say the energy costs of providing this constant supply of uniformly conditioned, cool, still and dry air are significant, as are the well-known environmental consequences associated with this vast energy end-use.

How can thermal comfort standards play a role in facilitating the appropriate use of energy-efficient, climate-responsive building design strategies? The first step must be to recognize that comfort depends on context. People living year-round in air-conditioned spaces are quite likely to develop high expectations for homogeneity and cool temperatures, and may become quite critical if thermal conditions in their buildings deviate from the center of the comfort zone they have come to expect. In contrast, people who live or work in naturally ventilated buildings where they are able to open windows, become used to thermal diversity that reflects local patterns of daily and seasonal climate variability. Their thermal perceptions—both preferences as well as tolerances—are likely to extend over a wider range of temperatures than are currently reflected in the old ASHRAE Standard 55 comfort zone.

As an organization representing and furthering the interests of the air-conditioning industry ASHRAE must be commended for acknowledging these subtle issues surrounding thermal perception. ASHRAE recently funded research to quantify the difference between peoples' thermal responses in air-conditioned and naturally ventilated buildings. The outcome was a proposal for a new adaptive comfort standard to complement the traditional PMV-based comfort zone. This paper briefly describes and expands on the results of that project, ASHRAE RP-884: developing an adaptive model of thermal comfort and preference, and describes how the work was recently incorporated into ASHRAE Standard 55, and how both practitioners and researcher might apply the ACS. For greater detail about the background research, previous papers describe the results of our literature search on thermal adaptation [3], the specific procedures for developing the database [4], and our analysis methods and findings [5,6].

2. Methods: developing the ASHRAE RP-884 database

In the mid-1980s, ASHRAE began funding a series of field studies of thermal comfort in office buildings spread across four different climate zones. They were specifically designed to follow a standardized protocol developed during the first in the series, ASHRAE RP-462 [7]. Since that time numerous other thermal comfort researchers independently adopted the same procedures for collecting both physical and subjective thermal comfort data in their own field studies. In 1995, ASHRAE RP-884 began by collecting raw field data from various projects around the world that had followed this standardized (or a similar) protocol, and/or where the data met strict requirements regarding measurement techniques, type of data collected, and database structure. Standardized data processing techniques, such as methods for calculating clo and various comfort indices, were then applied consistently across the entire database [4]. This enabled RP-884 to assemble a vast, high-quality, internally consistent database of thermal comfort field studies. The RP-884 database contains approximately 21,000 sets of raw data from 160 different office buildings located on four continents, and covering a broad spectrum of climate zones. The locations selected for the database and depicted in Fig. 1 include Bangkok, Indonesia, Singapore, Athens, Michigan, several locations each in California, England, and Wales, six cities in Australia (Darwin, Townsville, Brisbane, Sydney, Melbourne, Kalgoorlie) and five cities in Pakistan (Karachi, Quettar, Multan, Peshawa, Saidu). The data includes a full range of thermal questionnaire responses, clothing and metabolic estimates, concurrent indoor climate measurements, a variety of calculated thermal indices, and concurrent outdoor meteorological observations.

The buildings in the database were separated into those that had centrally-controlled heating, ventilating, and air-conditioning systems (HVAC), and naturally ventilated buildings (NV). Since the RP-884 database comprises existing field experiments, this classification came largely from the original field researchers' descriptions of their buildings and their environmental control systems. The primary distinction between the building types was that the NV buildings had no mechanical air-conditioning, and the natural ventilation occurred through operable windows that were directly controlled by the occupants. In contrast, occupants of the HVAC buildings had little or no control over their immediate thermal environment. Since most of the NV buildings were studied in the summer, in most cases, the type of heating system was irrelevant. The few that were studied in winter may have had a heating system in operation, but it was of the type that permitted occupant control. Unfortunately, there were not enough hybrid ventilation (also called "mixed-mode") buildings in the RP-884 database to allow their separate analysis. All statistical analyses were performed separately for the HVAC and NV buildings, using each individual building as the initial unit of analysis, and then conducting a meta-analysis of the separate statistical calculations done within each building. (see [5] for details of analyses).

As noted earlier, the environmental inputs to conventional heat-balance thermal comfort models (e.g. PMV) are all taken from the indoor environment immediately surrounding the building occupants. These models also require the user to have knowledge of the building occupants' clothing insulation and metabolic rates, which are often difficult to estimate in the field. But adaptive comfort models do things differently in that they use an outdoor thermal environmental variable as their input. Since presenting the early versions of our adaptive models to the engineering and comfort research community in 1998, we have often been asked to explain the relevance of outdoor temperature to the prediction of the temperature that people will find comfortable indoors. The

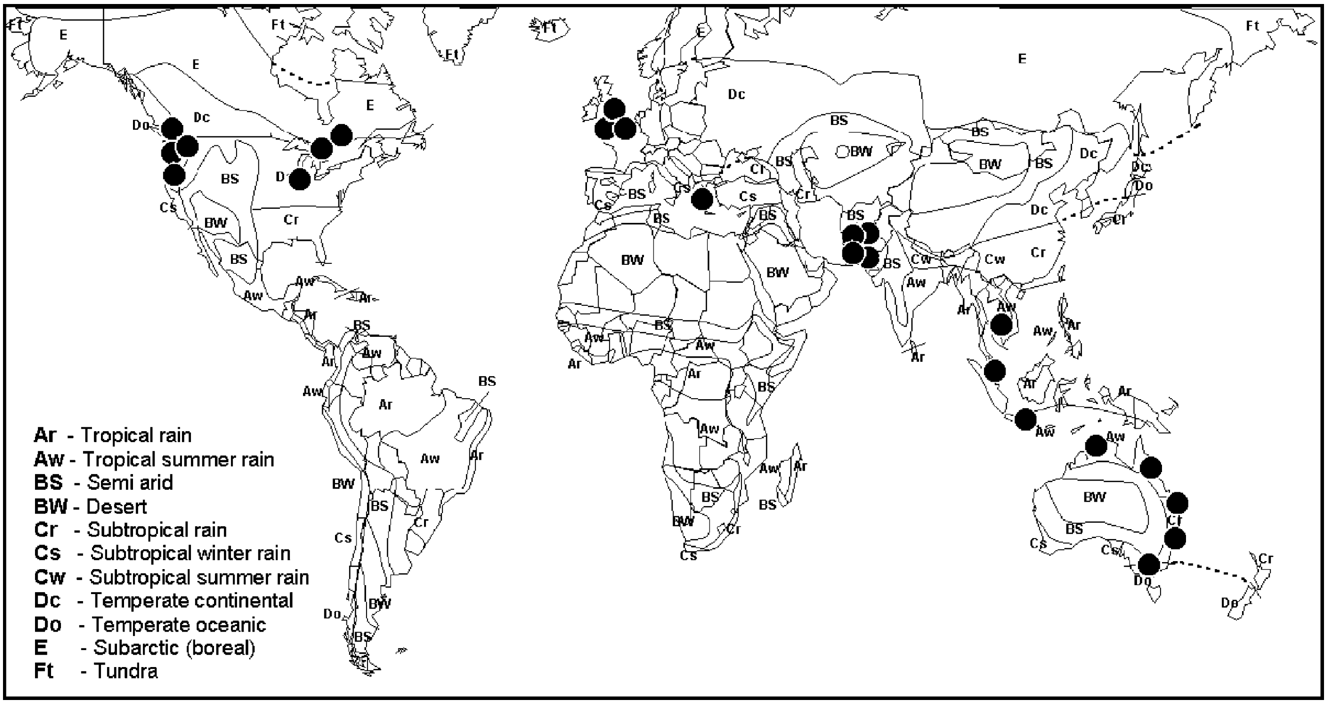


Fig. 1. The geographic distribution of building studies comprising the RP-884 thermal comfort database that formed the basis of the adaptive model and adaptive comfort standard in this paper (map adapted from Rudloff [8]).

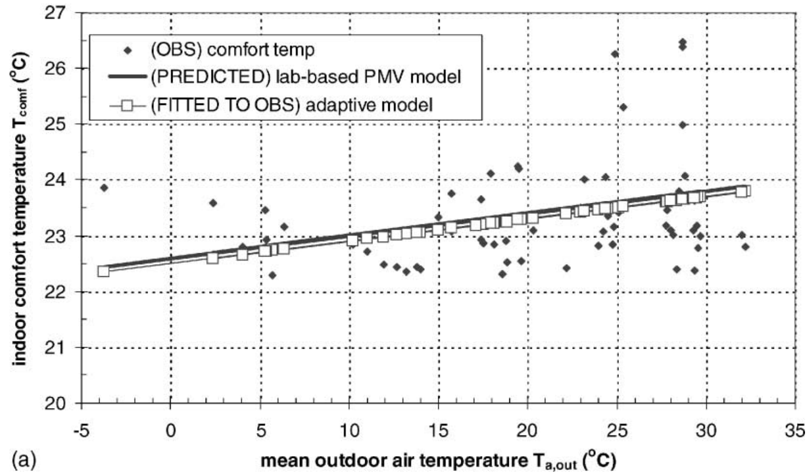
question goes to the fundamental difference of approach between heat-balance and adaptive models of thermal comfort. The former account for thermal comfort in terms of the microclimate immediately affecting the energy exchanges (i.e. heat balance) of the subject, whereas adaptive models predict comfort from broad-scale, contextual factors. But why outdoor climate? First, we believe that weather and seasons exert a pervasive influence on our behavioral adaptations to the thermal environment. For example, we typically use information about expected maximum daily temperatures along with recent experiences when making decisions about what to wear on a particular day. Secondly, we think weather, both recent past and predicted near-future, along with longer-term seasonal swings determines our psychological adaptations in the form of thermal expectations.

But the matter of how to best characterize outdoor climate remains an interesting question in the comfort research community. One might presume daily outdoor temperatures to be a more appropriate time-scale for use in predicting adaptive thermal comfort temperatures than monthly averages. Our choice of the latter was made on purely pragmatic grounds. Months represent the temporal scale most commonly adopted by national weather bureaux for collection and presentation of climatological normals. Since these form the basis of most engineering calculations they are obviously more appropriate to an engineering standard such as ASHRAE Standard 55 than some shorter time-scale, despite the loss of resolution. As is often, the case when making the transition from the researcher's world to that of the practitioner, certain sacrifices in precision are necessary in order to make models simple and useful to as many people as possible. Failure to make the sacrifice usually renders the results of research of academic interest only—a fate suffered by more than one thermal comfort model to date.

3. Results: thermal comfort in naturally ventilated buildings

Fig. 2a and b shows some of the most compelling findings from our separate analysis of HVAC and NV buildings, in the upper and lower panels, respectively. We believe that the clear differences in these patterns also vindicate our building classification scheme. The graphs present a regression of indoor comfort temperature[1] for each building against mean outdoor air temperature recorded for the duration of the building study in question. Regressions were based only on buildings that reached statistical significance ($P = 0.05$) in the derivation of their own neutral or preferred temperature. As a result, 20 buildings in the RP-884 database had to be

[1] For this analysis, "preference" was considered as a more appropriate indicator of optimum thermal conditions than the traditional assumption of "neutral thermal sensation". In the HVAC buildings, preferred temperature was slightly warmer than neutral temperatures in cooler climates, and slightly cooler in warmer climates (by up to 1 °C at either extreme end). There was no difference in the NV buildings. The indoor comfort temperature on the *y*-axis, therefore, includes a semantic correction factor to modify estimates of neutral temperatures in HVAC buildings to more accurately reflect preference.



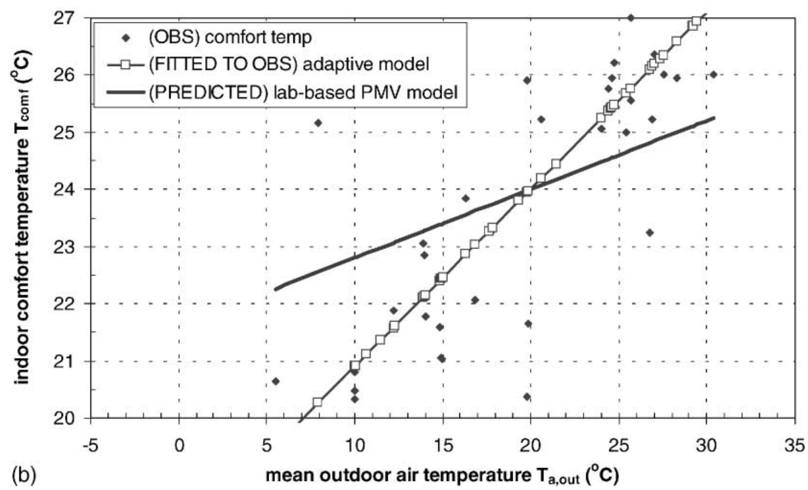


Fig. 2. (a) Observed (OBS) and predicted indoor comfort temperatures from RP-884 database, for HVAC buildings. Note that the observed comfort temperatures have been corrected for the effects of semantics (see Brager and de Dear [3]). The adaptive model fitted by weighted regression to observed comfort temperatures has an $R^2 = 53\%$ ($P = 0.0001$). (b) Observed (OBS) and predicted indoor comfort temperatures from RP-884 database, for naturally ventilated buildings. The adaptive model fitted by weighted regression to observed comfort temperatures has an $R^2 = 70\%$ ($P = 0.0001$).

eliminated from this analysis because of their small sample sizes or very homogeneous indoor climates. Use of the 20 cases would have necessitated certain assumptions about thermal sensitivities of their occupants that were unsustainable on the empirical evidence at hand. Each graph in Fig. 2a and b, shows two regressions, one based on observed responses in the RP-884 database, and the other on predictions using Fanger's PMV [9]. The latter take into account clo, metabolic rate, air speed and humidity averaged within the building in question. The original data points through which the adaptive model regression line was fitted are also shown, but it should be noted that this is a weighted regression so that outliers representing small sample sizes had a relatively smaller effect on the slope of the model.

Two strong patterns emerge from these graphs. First, the steeper gradient of observed responses in NV buildings (Fig. 2b) compared to HVAC buildings (Fig. 2a) suggests that occupants of HVAC buildings become more finely adapted to the narrow, constant conditions typically provided by mechanical conditioning, while occupants of NV buildings prefer a wider range of conditions that more closely reflect outdoor climate patterns.

Secondly, a comparison of the observed (fitted to OBS) and predicted lines within each graph clarifies the role of adaptation in these two building types. In the HVAC buildings, PMV was remarkably successful at predicting comfort temperatures, demonstrating that behavioral adjustments of clothing insulation and room air speeds (both of which are inputs to the PMV model) fully explained the relationship between indoor comfort temperature and outdoor climatic variation. In this sense, the PMV could be considered a partially-adaptive model. In contrast, in the NV buildings (Fig. 2b), the difference between these PMV-based predictions and the adaptive model (fitted to OBS) shows that such behavioral adjustments accounted for only half of the climatic dependence of comfort temperatures. Excluding gross and systematic measurement error for the time being, the unexplained residual must come from influences not accounted for by the PMV model, and our analysis suggests that psychological adaptation is a likely explanation. In particular, we hypothesize that indoor comfort temperatures in NV buildings are strongly influenced by shifting thermal expectations resulting from a combination of higher levels of perceived control, and a greater diversity of thermal experiences in such buildings.

Our hypothesis about "expectations" underlying the discrepancy between the predictions of the laboratory-based PMV model and the comfort temperatures actually observed in naturally ventilated buildings has not been allowed to pass without comment at various conferences where it has been aired. For example, it has been suggested elsewhere in this special issue of "Energy and Buildings" that the discrepancy in warm climate field studies can be accounted for by systematic errors in the estimation of metabolic rates [10]. It was claimed that if estimated metabolic rate is reduced by an average of 10%, then PMV predictions would match observed thermal sensation much more closely. However, to us this seems to underestimate the magnitude of the discrepancy by a factor of two. For example, using the "WinComf" software [11] funded by ASHRAE TC 2.1, we input the following average indoor climatic conditions, representative of measurements made in a typical tropical building in the RP-884 database, and found to be comfortable by the adaptive model in Fig. 2b:

- temperatures, $t_a = t_r = 26.7\ ^\circ\mathrm{C}$;
- air speed, $v = 0.25$ m/s;
- humidity, RH = 50%;
- clothing insulation, $I_{cl} = 0.5$ clo;
- metabolic rate, $M = 1.3$.

These inputs generated a PMV = +0.5, whereas the adaptive model in Fig. 2b indicates these conditions would be optimal (preferred and neutral). The metabolic rate would need to reduce from 1.3 to 1.05 met units in order to bring PMV back to neutral (0) and that represents a 20% reduction in met rate. In short, these subjects would need to be performing their "light office duties" with unrealistic efficiency of energy in order to explain away the 1.7 °C discrepancy between the adaptive model's comfort temperature and the counterpart predicted PMV.

Raising further doubt about the suggestion that overestimation of metabolic rate explains the discrepancy in Fig. 2b is the necessity for the overestimation to be a problem exclusively found in the tropics or other hot field study locations. Since some of tropical data in the RP-884 adaptive model database were actually collected by researchers with field study experience from the mid-latitudes (and in some cases, their mid-latitude data included in the RP-884 database), there seems to be little prospect of a procedural or instrumental explanation for selective overestimation in metabolic rates. Fanger and Toftum's [10] suggestion of a "siesta factor" explaining lower metabolic rates in warm climates is perhaps reminiscent of Ellsworth Huntington's ethnocentric spin on climatic determinism in "Mainsprings of Civilization" [12], long since discredited in the social and environmental sciences. And what about the discrepancy in milder climates to the left-hand side of Fig. 2b? The logical extension of Fanger and Toftum's "siesta factor" hypothesis is that office workers in cooler locations must expend approximately 1.6 met units to match predicted and observed thermal sensation, essentially for the same type of work activities that an office worker in the tropics would have to expend 1.05 met units on to enable a match. In short, the metabolic "siesta" hypothesis does not withstand close scrutiny.

The adaptive model findings depicted in Fig. 2b led to a proposal for an ACS that would serve as an alternative to the PMV-based method in ASHRAE Standard 55 for naturally ventilated buildings. The outdoor climatic environment for each building was characterized in terms of mean outdoor dry bulb temperature $T_{a,out}$, instead of the ET* index that was originally proposed in the first publication of the ACS [5]. The reason for the downgrade to a simpler outdoor temperature expression is that the theoretically more adequate thermal indices such as ET* require both specialized software and expertise that most practicing HVAC engineers are unlikely to possess. Optimum comfort temperature, T_{comf}, was then similar to the regression shown in Fig. 2b, but recalculated based on mean $T_{a,out}$:

$$T_{comf} = 0.31 T_{a,out} + 17.8 \quad (1)$$

The next step was to define a range of temperatures around T_{comf} corresponding with 90 and 80% thermal acceptability. Only, a small subset of the studies in the RP-884 database had included direct assessments of thermal acceptability, and the analysis of these data was not statistically significant. We were, therefore, left with having to infer "acceptability" from the thermal sensation votes, and started with the widely used relationship between group mean thermal sensation vote and thermal dissatisfaction (i.e. the classic PMV–PPD). The PMV–PPD relationship indicates that a large group of subjects expressing mean thermal sensation vote of ± 0.5 (or ± 0.85) could expect to have 10% (or 20%) of its members voting outside the central three categories of the thermal sensation scale (assumed to represent dissatisfaction). Applying the ± 0.5 and ± 0.85 criteria to each building's regression model of thermal sensation as a function of indoor operative temperature produced a 90 and 80% acceptable comfort zone, respectively, for each building. Arithmetically, averaging those comfort zone widths across all the NV buildings produced a mean comfort zone band of 5 °C for 90% acceptability, and 7 °C for 80% acceptability, both centered on the optimum comfort temperature. We then applied these mean values as constant temperature ranges around the empirically-derived optimum temperature (T_{comf}) in Eq. (1). The resulting 90 and 80% acceptability limits are shown in Fig. 3.

Oftentimes when this ACS graph has been presented in conferences and other scientific forums we have been asked to justify the constant widths for the 80 and 90%

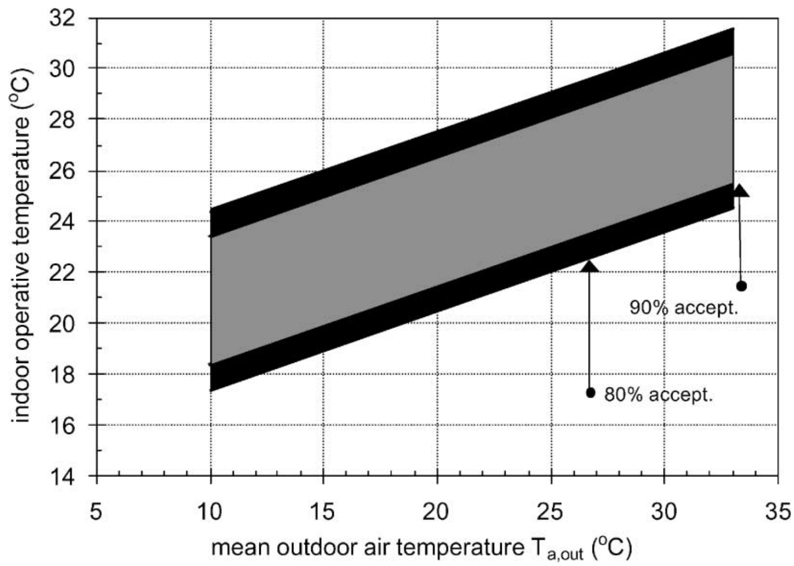


Fig. 3. Proposed adaptive comfort standard (ACS) for ASHRAE Standard 55, applicable for naturally ventilated buildings.

acceptability limits. Some commentators have hypothesized that the acceptability ranges should show some relationship with outdoor temperature. To test this hypothesis, we extracted the regression gradient terms for the thermal sensation versus indoor operative temperature models for each of the buildings that were included in Fig. 2b. We chose thermal sensation regression model coefficients because this was the parameter used to directly calculate the original 80 and 90% acceptability limits depicted in the ACS (Fig. 3). These coefficients were then plotted against the mean outdoor temperatures prevailing at the time of each building's comfort field study. The results are shown in Fig. 4 and it is clear that there is no climate-dependency for indoor thermal sensitivity, and we take this as supporting the standardization of acceptability limits across the entire range of outdoor climates, as represented in Fig. 3.

Note that Fig. 3 is slightly different than the one originally produced by RP-884 [5], but closely resembles the one included in the recently revised ASHRAE Standard 55. The decisions made to modify the original graph are described in more detail later in this paper. But before describing the process of getting Fig. 3 incorporated into ASHRAE Standard 55, it may be useful to look in more detail at the NV buildings that were included in our analysis.

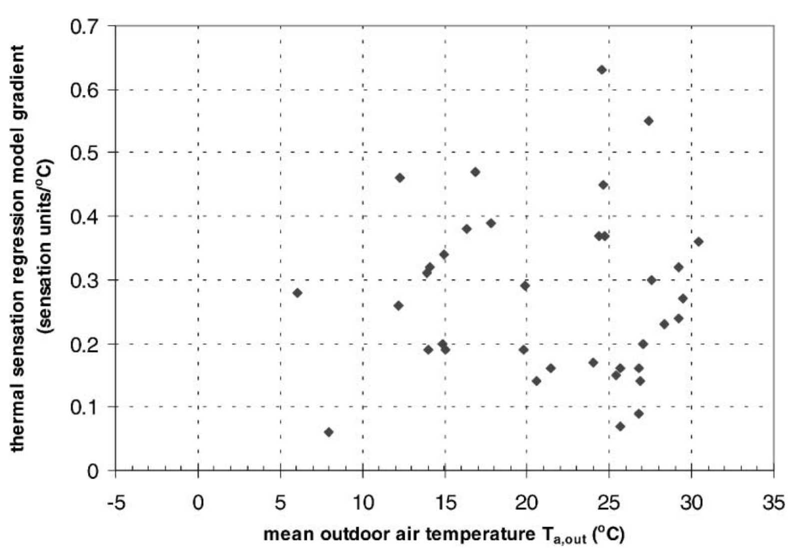


Fig. 4. The effects of outdoor climate on the indoor thermal sensation regression models for naturally ventilated buildings. Only regression coefficients meeting $P < 0.05$ significance were included in the analysis. The sensitivity of indoor thermal sensations to changes in indoor temperature (y-axis) shows no relationship to outdoor climate (x-axis), thereby supporting constant 80 and 90% thermal acceptability bands across the full range of climates represented in the ACS (Fig. 3).

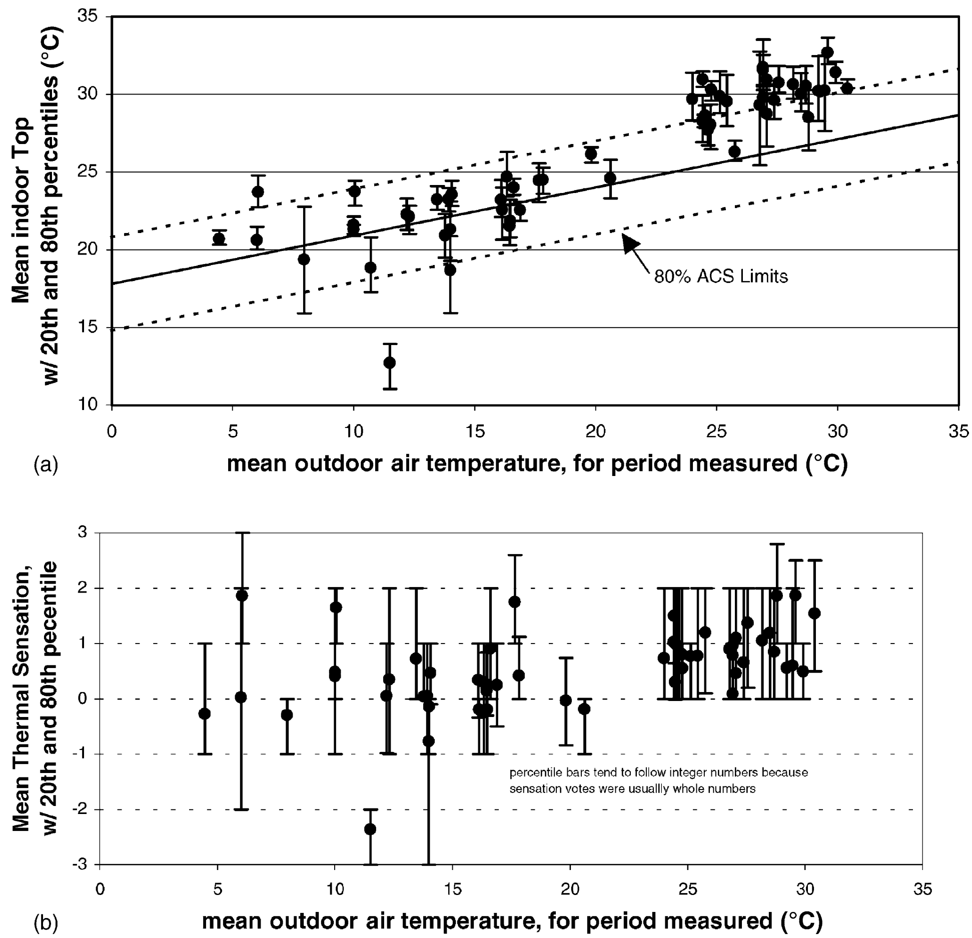


Fig. 5. (a) Indoor operative temperatures in the naturally ventilated buildings of the RP-884 database. (b) Thermal sensations in the naturally ventilated buildings of the RP-884 database.

Fig. 5a and b shows the operative temperatures and thermal sensations from each of the NV buildings in the RP-884 database,[2] as a function of the mean outdoor air temperature that existed during a continuous part of each study that took place in a given month or season. For each line, the dot represents the mean of the measurements, and the lower and upper bands represent the 20th and 80th percentiles, respectively. Fig. 5a also shows the 80% limit of the ACS model for comparison. Note that most thermal sensation votes in the database were recorded as integer numbers, and so the percentile bars tend to fall on integer numbers as well. We chose to present the 20th and 80th percentiles because they would more accurately reveal any asymmetries around the mean, as compared to using the more traditional + one standard deviation.

A couple of clear patterns are seen in Fig. 5a and b. First, below mean outdoor temperatures of 23 °C, the NV buildings were primarily operating within the limits of the ACS, and mean thermal sensations were primarily within ±0.5. This means that, despite relatively large climatic variations outside, interior conditions remained relatively stable and occupants were able to maintain neutral or close-to-neutral sensations. The few buildings that were operating above or below the ACS limits had corresponding thermal sensations that were, respectively, much warmer or cooler than neutral, as one might expect.

Above mean outdoor temperatures of 23 °C, interior temperatures frequently rose above the ACS limits, with mean indoor operative temperatures clustered around 30 °C, and simultaneous mean thermal sensations clustered around a mean vote of 1.0. So, while the neutral temperatures for these buildings were calculated to be in the range of 26–27 °C, the data suggests that these naturally conditioned buildings were not, in fact, able to maintain thermal comfort, even as defined by the ACS model, for many hours of the day. These uncomfortable buildings came from a range of climates and cultures, including various regions of Pakistan, Australia, Greece, Singapore, Indonesia, and Thailand. As a result, it is difficult to generalize about them or to cast them off as being representative of only a single region.

[2] Note that not all of the NV buildings in these figures were used in the development of the ACS shown in Fig. 3, since some buildings were eliminated from the ACS analysis if their if their regression of comfort vote on operative temperature did not reach statistical significance.

4. Agreeing on an adaptive comfort standard

Incorporating research into a thermal comfort standard is a very different process than conducting the research itself. While one expects researchers to conduct their work with rigor and impartiality, standards are produced through a process that must balance scientific evidence with expert judgment, practical experience, pragmatism, added assumptions, and compromises to compensate for the gaps in our knowledge. The ASHRAE Committee (SSPC 55) in charge of revising its thermal comfort standard is made up of members representing manufacturers, designers, building owners and users, researchers and educators. Because of the experience these members bring with them, they are expected to naturally have their own perspectives and sometimes biases (and are therefore, required by ASHRAE regulations to declare them up front when they join the committee). These biases are clearly reflected in the committee's deliberations and represent a healthy and necessary part of the process. But only by representing as many different stakeholders as possible on SSPC 55 can the revised standard have any real chance of adoption by the intended end-users. SSPC 55 minus this diversity could be expected to develop a document of little more than academic interest only.

In funding the adaptive model project RP-884, it was always intended by ASHRAE that this work would result in a proposal for what was then called a "variable temperature standard", to eventually be incorporated into ASHRAE Standard 55. A brief history of this evolution from research to standard follows:

- January 1998: The findings of RP-884 were first presented at the ASHRAE San Francisco meeting [5].
- June 1998: ASHRAE Committee (SSPC 55) passes a motion to include some type of an ACS in the next set of revisions to ASHRAE Standard 55.
- June 1998–January 2001: ASHRAE Standard 1992R continues to go through its revision process, with many issues related to the ACS raised, discussed at length, and eventually resolved through agreement, compromise, and capitulation. In January 2001, SSPC 55 votes to approve the draft for public review.
- February 2001: The Public Review Draft of ASHRAE Standard 1992R is released, and comments are collected through April 2001.
- 2001–2002: ASHRAE SSPC 55 responds to all public review comments (at the time of this writing, this is the current stage of the process). Once all comments are resolved, SSPC 55 forwards the standard through the various bureaucratic ranks for final approval by ASHRAE's Board of Directors, and the Standard is published. At the time of this writing, it is expected that this will happen in 2002.

The new ACS is presented in ASHRAE Standard 55 as "Section 5.3—optional method for determining acceptable thermal conditions in naturally conditioned spaces". Note from the title that the PMV-based prediction method is still accepted as universally applicable for all conditions, while the new ACS is offered only as an option under certain limited circumstances.

4.1. Scope

One of the most contentious issues was the scope of applicability of Section 5.3, which can be used only under the following circumstances:

- Naturally conditioned spaces where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows. It is specifically noted that the windows must be easy to access and operate.
- Spaces can have a heating system, but the method does not apply when it is in operation.
- Spaces cannot have a mechanical cooling system (e.g. refrigerated air-conditioning, radiant cooling, or desiccant cooling).
- Spaces can have mechanical ventilation with unconditioned air, but opening and closing of windows must be the primary means of regulating thermal conditions.
- Occupants of spaces must be engaged in near sedentary activity (1–1.3 met), and must be able to freely adapt their clothing to the indoor and/or outdoor thermal conditions.

Some people in SSPC 55 presented strong arguments that the ACS should be applicable to other situations where people have personal control, such as mixed-mode buildings or spaces (where both air-conditioning and operable windows are present), or task/ambient conditioning systems (TAC, where occupants have control over some aspect of local thermal conditions, and the ACS would be applied to the broader ambient conditions). The crux of these arguments was that the availability of personal control played a primary role in shifting people's thermal expectations, and so the ACS model is likely to be a more accurate representation of people's thermal responses in other realistic situations with personal control, compared to the laboratory studies. There is also evidence that people with TAC systems are comfortable over a much wider range of temperatures when they have control over those local conditions, and this pattern was very close to what was found in the naturally-ventilated buildings in the RP-884 database [13]. Other people argued that the ACS should be strictly limited to the same conditions under which the data were collected (i.e. the limitations summarized earlier). Some felt that this was placing a stricter standard of proof or interpretation for this field-based method, compared to the traditional laboratory-based comfort zone which is being universally applied to all conditions, even though it was developed under a comparatively smaller range of scenarios, and was not based on tests in any buildings at all. In the end, the more conservative positions prevailed, and the scope of Section 5.3 is limited to the conditions described earlier.

4.2. Characterization of outdoor climate

The original analysis of RP-884 expressed the ACS in terms of outdoor effective temperature (ET*). But it was agreed by everyone on SSPC 55 that ET* is primarily an index used by researchers, and that practitioners would be more likely to use the ACS if the meteorological input data was a more familiar and accessible index. The ACS was, therefore, reformulated in terms of mean monthly outdoor air temperature, defined simply as the arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry bulb) temperatures for the month in question. This climate data is readily available and familiar to engineers.

4.3. Limits

The original analysis of RP-884 extended from a mean outdoor air temperature of 5–33 °C. Several members of SSPC 55 felt the lower end was too extreme, regardless of what the data actually showed, and there was some discussion as to whether the lower end of the graph should simply be arbitrarily truncated at a higher mean outdoor air temperature, or that it showed be limited to non-heating conditions. In the end, both recommendations prevailed, and the ACS presented in Section 5.3 of Standard 55 ends at 10 °C mean outdoor air temperature. It was also discussed whether the graph should end sharply at the end points, or whether the lines should extend horizontally when outdoor temperature extended beyond the 10–33 °C. It was decided to truncate the graph at the endpoints of the range of measured data, and specify that the allowable indoor operative temperature limits may not be extrapolated to outdoor temperatures above or below the end points of the curve. An awkward consequence of this decision, however, is an unrealistic step change in allowable indoor temperatures as soon as the mean outdoor air temperature rises above 33 °C. Below this point, users of Standard 55 can refer to the wider range of acceptable indoor temperatures in Section 5.3. Above this point, the graph no longer applies and the only predictive tool available is the PMV, which not only will require significantly cooler indoor temperatures, but has already been shown to be unreliable for predicting thermal responses of people in naturally ventilated buildings under warm conditions.

5. Using the adaptive comfort standard

How might people actually use the ACS? Like any part of a thermal comfort standard, recommendations for acceptable indoor temperatures can be used during the design stage of a new building, or for the operation and evaluation of an existing building.

As a design standard (or, simply a design tool) for naturally conditioned spaces, one might first use a building simulation tool to predict what indoor conditions might be achieved. The ACS could then be used to determine whether those thermal conditions are likely to be acceptable. If they are not acceptable, then design modifications might be made (i.e. to the thermal mass or fenestration), and the process repeated. If such changes prove to be ineffectual in subsequent simulations, a decision to air-condition might then be appropriate.

If windows in a building were operated both manually and automatically, or if the ACS were eventually allowed to apply to mixed-mode buildings, perhaps it could also be used as an operating guideline. The interior temperatures might be allowed to float within the more energy-efficient acceptability limits of the ACS, and when the temperatures reached the maximum limits then the air-conditioning could be turned on in a limited way to ensure that temperatures stayed within the ACS limits (rather than switching to the narrow set-points of a traditional, centrally-controlled air-conditioned building). The ACS could also be used in mixed-mode buildings to establish the interior design temperatures used for load calculations for sizing equipment. If the building was going to be operated within the wider limits of the ACS, this would also the equipment to be downsized, resulting in potential cost-savings and space-savings as well.

If the ACS were allowed to apply to task/ambient conditioning systems, then the building's ambient environment could be allowed to float within the broader limits of the ACS, while the individual controls would allow occupants to control their local thermal conditions to achieve their preferred comfort levels.

The ACS could also be used to evaluate the predicted acceptability of existing thermal conditions in naturally conditioned spaces, in the same way that the PMV-based thermal comfort standard is used to evaluate the acceptability of thermal conditions in HVAC buildings. Some weighted time function could be devised to index the duration and intensity of temperature excursions outside the ACS zone and this might serve as a useful quality benchmarking tool for property managers.

In all these applications, one of the advantages of the ACS over the PMV-based model, at least for situations where it applies, is its simplicity. One needs to estimate what mean clo and met levels might be before using the PMV model, but the relationship between clothing and climate is already accounted for in the ACS.

The ACS is also intended for continued use as a research tool. The database is available on-line (http://atmos.es.mq.edu.au/~rdedear/ashrae_rp884_home.html), and it is expected that other researchers will continue to use it to investigate new questions, or to validate new field data from buildings with operable windows, or perhaps with other forms of personal control.

Another potential application is the use of the ACS for regional climate analysis, as a way of investigating the feasibility of using natural ventilation, and the potential energy savings that might result. If a building's interior conditions were able to be maintained within the ACS limits

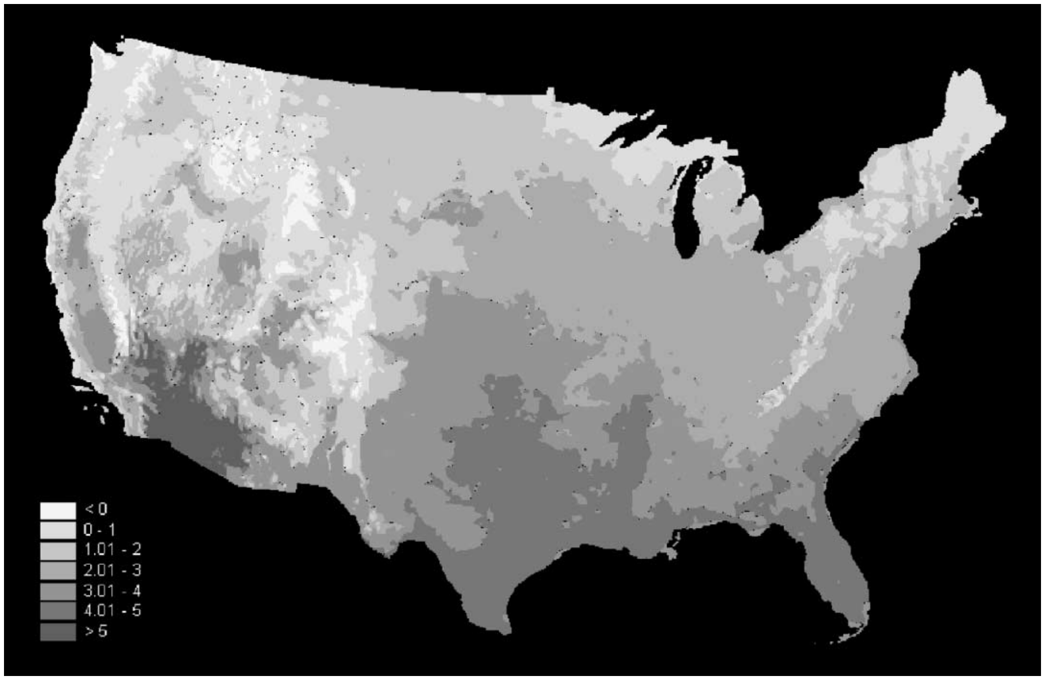


Fig. 6. Comparison of recommended indoor comfort temperatures, upper limits of ACS vs. ASHRAE Standard 55. Darker areas indicate larger differences between set-point temperatures, and therefore, larger energy savings, by switching to the adaptive comfort standard.

entirely by natural means, then one could potentially save 100% of the cooling energy that would otherwise be used by an air-conditioner to maintain conditions within the more narrow ASHRAE Standard 55 comfort zone. If one were to apply the ACS to a mixed-mode building, however, the air-conditioner might be used in a limited way to keep the more extreme temperatures from rising past the acceptability limits of the ACS. In this case, the energy savings would be proportional to the difference between set-points defined by the upper limit of the ACS, compared to typical set-points used in an air-conditioned building.

Fig. 6 presents an approach to this type of analysis, where we began with July climate data for the US, and then compared the upper 80% acceptability limit of the ACS to the upper limit of the ASHRAE Standard 55 comfort zone (based on 0.5 clo and 50% RH), which is 26 °C. The map shows the regions of the country where the difference in comfort temperatures using these two methods ranges from 0 to 5 °C. Energy savings would be proportional to the difference in these set-points. This is actually a very conservative estimate, and savings are likely to be much higher than indicated since it is more common to find buildings operating at the center of the ASRHAE Standard 55 comfort zone (approximately 23 °C) than at the upper end of 26 °C. It should be emphasized that this is a preliminary application of GIS technology to thermal comfort and is based on coarse data. However, the picture is still indicative of the large potential for saving energy by using natural ventilation instead of air-conditioning (assuming that people have direct control of the operable windows, and are also free to adapt their clothing).

6. Moving into the 21st century

Finally, we would like to address the primary objective of this special issue of ‘‘Energy and Buildings’’, and the conference from which these papers were drawn. What new thermal comfort research is needed and how can it be incorporated into the development of new standards? The collective research that has formed the basis of the ACS has exposed many significant gaps in our knowledge of thermal comfort, and we would like to highlight some key issues regarding the application of research and new standards towards improving the design and operation of buildings.

6.1. Satisfaction and inter-individual differences

In developing the ACS we applied the relationship between mean thermal sensation and % dissatisfied, as illustrated in the classic PPD versus PMV curve. In so doing, we were adopting two broad assumptions that should be investigated in future research. First is the traditional assumption that dissatisfaction is associated with votes of ±2 and ±3 on the seven-point ASHRAE thermal sensation scale (with 0 representing neutral). Is there a better way to assess dissatisfaction, or acceptability, than having to make this indirect association with thermal sensation votes? Unfortunately, field data has shown that direct assessments of acceptability often do not produce statistically significant relationships with environmental measurements, and so the nature of such questions needs further study.

Perhaps a more important research priority is the assumption that inter-individual differences are the same in both the laboratory and the field (this is at the heart of applying the lab-based PMV–PPD relationship to standards, that are then applied in the field). Is there a rational basis to this, or is it just a "leap of faith"? The early work of McIntyre [14] and Humphreys [15] examined these questions, but it has not yet affected the way we apply laboratory data to building standards. Certainly, the role of clothing is one obvious influencing factor, since there is much greater variability in occupants' clothing patterns in real buildings, compared to the standard uniforms used in lab studies, and to the single average clo value that might be chosen when using the PMV-based standards. If people dress merely for fashion, then random differences in clothing are likely to increase inter-individual differences (and increase the % dissatisfied) when a group is exposed to a single thermal environment. But if people dress in response to the expected indoor/outdoor climates, and to their own thermal sensitivities (i.e. some people are typically warmer or cooler than the group), then the inter-individual differences would likely decrease (and the % dissatisfied decrease as well). In a study of office workers in Australia, Morgan [16] found that corporate dress codes override thermal comfort considerations (i.e. building occupants start responding like climate chamber experimental subjects in a standard uniform). We also know that women typically have a significantly more weather/season sensitive clothing response than their male counterparts in the office, so this creates two quite distinct sub-populations in terms of thermal insulation. The implications of this and other clothing behavioral issues for indoor climate management need further research.

6.2. Climatic context

It is clear that outdoor climate influences thermal perceptions beyond just the clothing that we wear. It probably has a psychological effect on expectations, particularly in naturally ventilated buildings that are more closely connected to the natural swings of the outdoor climate. The ACS was developed using mean monthly outdoor temperature as the input, because this would be one of the easiest for practitioners to use—the month is the typical unit of analysis for climatological records. However, an interesting question for researchers to continue to investigate is what other characterizations of the outdoor climate might be more highly correlated to people's perception of indoor comfort? Perhaps future studies can investigate parameters such as simultaneous outdoor temperature, daily average, some measure of daily range or peak conditions, a weighted measure of the recent history of temperatures over the previous few days or weeks, etc. And what about temperature forecasts? It seems reasonable to expect that they influence clothing decisions too. While some of these questions have already been investigated (particularly noteworthy is Humphreys' [17] examination of clothing insulation patterns as a function of weighted functions of outdoor temperature) there remains more work to be done.

6.3. The role of control

An increasing number of people are accepting and even promoting the use of individual thermal control in buildings, either as operable windows, task/ambient conditioning systems, or other forms. The questions no longer center around "should we?", but instead are focused on "how?". Effort needs to be spent on developing new products and technologies, educating architects and engineers, documenting and reducing costs, and re-evaluating building fire codes that are often a significant barrier to incorporating such technologies. There are also many issues that thermal comfort researchers need to address, with the aim of providing alternative recommendations for acceptable thermal conditions when occupants themselves are able to control those conditions. In particular, previous studies have indicated that there is a difference between the effects of perceived control and utilized control [18]. This has important implications for the design and operation of products, environmental control systems, and buildings.

The assumption to date in thermal comfort research has been that heat balance is the "bottom line" and that avenues of heat gain/loss are largely interchangeable. However, recent Danish climate chamber research [19] indicates quite persuasively that 28 °C is overwhelmingly preferable to 26 °C (with fixed airspeeds of 0.2 m/s) if the subjects in the warmer environment are permitted to select their own preferred airspeed. In this scenario, higher temperatures would allow significant cooling energy savings in situations where outdoor air can be utilized for cooling with natural ventilation, or even in air-conditioned spaces with task/ambient conditioning (with control of air movement), because more use can be made of the economizer cycle.

There is also evidence that the increased availability of personal control has positive effects far beyond just thermal comfort. Hawkes [20] found that energy efficiency was actually improved when people were given control of their environment, because energy use was more closely aligned to needs rather than maintaining uniformity based on externally-imposed standards. Wilson and Hedge [21] found that fewer building-related ill health symptoms and greater productivity were achieved as the perceived level of individual control increased. Additional research has been done on this topic over the last decade and needs to be reviewed. The impact of personal control should not be underestimated, but clearly needs to be investigated further so we can understand its impact on comfort, health, productivity, and energy use, and how we can best incorporate it into buildings.

6.4. Beyond thermal neutrality

Thermal comfort standards, and mechanical engineers designing environmental control system, typically strive to provide neutral thermal conditions that are constant in time, and uniform throughout the indoor environment.

The goal is to avoid the negative (discomfort), and minimize dissatisfaction. Is it possible to move beyond this thinking? Is thermal monotony always a good thing? McIntyre [14] made an early plea for counteracting thermal boredom with fluctuating interior temperatures to meet our inherent needs for sensory stimulation. Kwok [22] reviewed research and collected anecdotes regarding the concept of thermal monotony, or thermal boredom, in indoor environments. In contrast to engineering characterizations of comfort, she found a large number of architectural educators who encourage students to explore and utilize the natural dynamic qualities of the thermal environment as inspiration for generating architectural form. We would argue that thermal qualities can and should be used in a more purposeful way to add to the richness of our indoor environments. Perhaps we should be aiming for a higher level of experiential quality in our environments, where "pleasantness" rather than "neutrality" are the goals [23]? Designers should strive to create spaces that are better than "neutral", where people can find "thermal delight", can interact with their environments, and can be refreshed and stimulated by them [24]. Perhaps this is too much to ask of a thermal comfort standard, but it is certainly an appropriate idea to place in the minds of designers. For example, in situations of high density occupancy for sustained periods of 60–90 min (like a classroom), there is typically a steady temperature ramp that, while incrementally unnoticeable, can often give rise to widespread occupant discomfort towards the end of the exposure. In such situations, it may well be appropriate to "flush" the occupied zone with periodic "bursts" of air from the mechanical ventilation system in a way that breaks thermal monotony and offsets mild but growing warm discomfort.

6.5. Beyond thermal comfort

Researchers need to take a more integrative view of the indoor environment. With few exceptions, most studies look at one outcome at a time, and try to assess what the ideal environmental conditions should be for optimizing thermal comfort, indoor air quality, energy consumption, or productivity. Is there a way to optimize them all simultaneously? Research findings often suggest conflicting goals for the indoor environment. For example, recent work has shown that perceptions of indoor air quality are improved when temperatures are cooler, and engineers can therefore, decrease ventilation rates [25] by decreasing indoor temperatures. But what are the energy implications of this finding? Although decreased ventilation rates would reduce energy consumption, cooler temperatures would either decrease or increase energy use, depending on whether it is a heating or cooling situation. Before we use these laboratory studies to promote turning down air-conditioning set-points to promote "good health", we should look closely at the numerous large-scale building studies conducted over the last two decades that have examined the connection between sick building syndrome (SBS) symptoms and ventilation system type. These studies reveal a statistically significant relationship in which buildings with air-conditioning, with or without humidification, are consistently associated with 30–200% higher incidences of SBS symptoms, compared to naturally ventilated buildings [26,27].

Air movement also appears to have an effect on perceived indoor air quality. Many practitioners report that the stillness of air within the occupied zone of most air-conditioned spaces (as mandated by current standards like ASHRAE Standard 55) is associated with complaints of poor quality "dead" air. Perhaps elevated air speeds within the occupied zone cannot only permit thermal comfort to be achieved at higher temperatures (thereby saving on refrigeration energy), but also improve perceived air quality, or at least offset the enthalpy effect referred to in [25]. The work of Toftum et al. [19], discussed earlier with regard to the role of personal control, would certainly lend support to this idea.

Many important thermal comfort questions still need answers, and a new generation of researchers need to be trained to provide them. In thinking beyond just thermal comfort, many people can easily agree on some of the more obvious recommendations for improved environmental control—reduce indoor pollution sources, deliver the air closer to the occupants, provide personal control where feasible. But tougher questions still remain. What are our objectives for conditioning the thermal environment? Is it better to provide air warmer or cooler than the "neutral" temperatures at the middle of existing standards? The answer may depend on context—are you trying to optimize comfort, indoor air quality, energy, productivity, or all of them? Is the budget the prime consideration or does one also take into account the environmental impacts of the building across its life-cycle? Is it even reasonable to think that we can create a single environment that optimizes all these outcomes for all people? Probably not. Perhaps the most appropriate goal would be to provide a variety of means for people to control their own environment. For example, this could range from a workplace culture that allows a flexible dress code and policy for taking breaks, to providing means for control of the local physical environment (task/ambient conditioning, windows, local controls, etc.), or providing areas within the building that have different thermal conditions.

One clear conclusion seems to emerge—approaches to indoor climate management based on "one-size-fits-all" and "uniform, world-wide conditioning with cool, still, dry air" are fast becoming curious anomalies of the last century.

Acknowledgements

We extend our gratitude to ASHRAE for funding the adaptive model research (RP-884) underpinning this paper, to the many researchers around the world who generously donated their raw field data, to Donna Cooper of Macquarie University for her work on the database and original statistical analysis, and to David White of University of California, Berkeley for his additional statistical analysis. Michael Humphreys, Fergus Nicol and P. Ole Fanger are also thanked for many discussions of the issues raised in this paper.

References

[1] ASHRAE Standard 55—thermal environmental conditions for human occupancy, ASHRAE Inc., 1992, Atlanta.
[2] M. Fountain, G.S. Brager, R. de Dear, Energy and Buildings 24 (1996) 179–182.
[3] G.S. Brager, R.J. de Dear, Energy and Buildings 27 (1) (1998) 83–96.
[4] R.J. de Dear, ASHRAE Transactions 104 (1b) (1998a) 1141–1152.
[5] R.J. de Dear, G.S. Brager, ASHRAE Transactions 104 (1a) (1998) 145–167.
[6] G.S. Brager, R.J. de Dear, ASHRAE Journal 42 (10) (2000) 21–28.
[7] G. Schiller, E. Arens, F. Bauman, C. Benton, M. Fountain, T. Doherty, ASHRAE Transactions 94 (2) (1988).
[8] W. Rudloff, World Climates, Wissenschaftliche Verlagsgesellschaft, Stuttgart, 1981.
[9] P.O. Fanger, Thermal Comfort—Analysis and Applications in Environmental Engineering, Danish Technical Press, Copenhagen, 1970.
[10] P.O. Fanger, J. Toftum, Thermal comfort in the future—excellence and expectation, in: Proceedings of the Conference on Moving Thermal Comfort Standards into the 21st Century, Windsor, UK, 5–8 April 2001, pp. 11–19.
[11] M.E. Fountain, C. Huizenga, ASHRAE Journal 38 (9) (1996) 39–42.
[12] E. Huntington, Mainsprings of Civilization, Mentor, New York, 1945.
[13] F.S. Bauman, T.G. Carter, A.V. Baughman, E.A. Arens, ASHRAE Transactions 104 (1) (1998).
[14] D.A. McIntyre, Indoor Climate, Applied Science Publishers, London, 1980.
[15] M.A. Humphreys, Journal of Inst. Heat. and Vent. Engineering 44 (1976) 5–27.
[16] C. Morgan, The Role of Clothing in Climatic Adaptation, Unpublished M.Sc. thesis, Macquarie University, Sydney, 2000.
[17] M.A. Humphreys, The influence of season and ambient temperature on human clothing behavior, in: P.O. Fanger, O. Valbjørn (Eds.), Indoor Climate, Danish Building Research Institute, Copenhagen, 1979, pp. 699–714.
[18] M. Paciuk, Coming of Age—Environmental Design Research Association 21 (1990) 303–312.
[19] J. Toftum, A.K. Melikov, L.W. Rasmussen, A.A. Kuciel, E.A. Cinalska, A. Tynel, M. Bruzda and P.O. Fanger, Human Response to Air Movement. Part I. Preference and Draft Discomfort, DTU International Center for Indoor Environment and Energy, Lyngby, 2000.
[20] D. Hawkes, Energy and Buildings 5 (1982) 127–134.
[21] S. Wilson, A. Hedge, The Office Environment Survey: A Study of Building Sickness, Building Use Studies, London, 1987.
[22] A. Kwok, Thermal Boredom, in: Proceedings of PLEA, Cambridge UK, 2000.
[23] S. Kuno, Comfort and Pleasantness, in: Proceedings of the Pan Pacific Symposium on Building and Urban Environmental Condition, Nagoya, Japan, 1995.
[24] L. Heschong, Thermal Delight in Architecture, MIT Press, Cambridge, MA, 1979.
[25] L. Fang, P. Wargocki, T. Witterseh, G. Clausen, P.O. Fanger, Field study on the impact of temperature, humidity and ventilation on perceived air quality, in: Proceedings of Indoor Air'99a, Edinburgh, Scotland, Vol. 2, 1999, pp. 107–112.
[26] O. Seppanen, W.J. Fisk, Association of ventilation system type with SBS symptoms in office workers, Report, LBNL-47457, Lawrence Berkeley National Laboratory, Berkeley, CA, 2001.
[27] R.J. de Dear, Sick building syndrome and appropriate design, in: A. Auliciems (Ed.), Advances in Bioclimatology, Springer, Berlin, 1998, pp. 87–109.