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Adaptive thermal comfort and sustainable thermal standards for buildings

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Abstract

The origin and development of the adaptive approach to thermal comfort is explained. A number of recent developments in the application of the theory are considered and the origin of the differences between adaptive thermal comfort and the 'rational' indices is explored. The application of the adaptive approach to thermal comfort standards is considered and recommendations made as to the best comfort temperature, the range of comfortable environments and the maximum rate of change of indoor temperature. The application of criteria of sustainability to thermal standards for buildings is also considered.

Keywords: Comfort standards; Thermal comfort; Sustainability; Adaptive approach

1. Introduction

Thermal comfort standards are required to help building designers to provide an indoor climate that building occupants will find thermally comfortable. The definition of a good indoor climate is important to the success of a building, not only because it will make its occupants comfortable, but also because it will decide its energy consumption and thus influence its sustainability. A standard which seeks to define acceptable indoor climates should consider all these factors. In the past, the designers of standards have not seen it as part of their task to consider sustainability. With increasing pollution and climate change, a thermal standard which ignores sustainability will at best fall into disrepute and at worst share responsibility for unsustainable buildings.

People have a natural tendency to adapt to changing conditions in their environment. This natural tendency is expressed in the adaptive approach to thermal comfort. This paper introduces the adaptive approach and explores some of the recent research bearing upon it. It then suggests ways in which the findings of adaptive thermal comfort can help frame sustainable standards for indoor climate for buildings in the future.

2. Adaptive thermal comfort

2.1. Field studies and rational indices

The adaptive approach to thermal comfort is based on the findings of surveys of thermal comfort conducted in the field. In the field survey researchers gather data about the thermal environment and the simultaneous thermal response of subjects going about their everyday lives. The thermal response of subjects is usually measured by asking them for a 'comfort vote' on a descriptive scale such as the ASHRAE or Bedford scale (Table 1). Interventions by the researchers are kept to a minimum. The well-known early work of Bedford [1] and the more recent Tropical Summer Index of Sharma and Ali [2] are examples of this approach. The researcher uses statistical methods to analyse the data using the natural variability of thermal conditions. The aim is to find the temperature or combination of thermal variables (temperature, humidity, and air velocity) which subjects consider 'neutral' or 'comfortable'. This analysis is then used to predict the 'comfort temperatures' or 'comfort conditions' which will be found acceptable in similar circumstances elsewhere.

There are problems with using a field study in this way. Firstly, the environmental conditions are inherently variable and difficult to measure accurately and errors in the input data can give rise to errors in the relationships predicted by the statistical analysis [3]. Secondly, it is difficult to generalise from the statistical analysis the results from one survey

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Table 1
Descriptors for the ASHRAE and Bedford scales

ASHRAE descriptor	Numerical equivalent	Bedford descriptor
Hot	3	Much too hot
Warm	2	Too hot
Slightly warm	1	Comfortably warm
Neutral	0	Comfortable
Slightly cool	−1	Comfortably cool
Cool	−2	Too cool
Cold	−3	Much too cool

Although, the two scales are semantically different, especially in the implication of preference in the Bedford scale, experience has shown that subjects use the two scales in a very similar way.

often do not apply to the data from another even in similar circumstances.

The 'rational' approach to thermal comfort seeks to explain the response of people to the thermal environment in terms of the physics and physiology of heat transfer. An 'index' of thermal comfort is developed which expresses the thermal state of the human body in terms of the thermal environment including allowances for temperature, humidity, air movement, clothing and activity. Current standards such as ISO 7730 [4] and ASHRAE 55 [5] are based on this approach. The indices are based on the responses of subjects measured in stable conditions in climate chambers, but it is assumed that such an index will express the response of people in the variable conditions of daily life. The results from field surveys should therefore be predicted by the index.

When rational indices are used to predict the thermal comfort of subjects measured in field surveys they are found to be no better at predicting the comfort vote [6] than simpler indices such as temperature alone. In addition the range of conditions which subjects find comfortable in field surveys is much wider than the rational indices predict. This is partly because the rational indices require a knowledge of clothing insulation and metabolic rate which are difficult to estimate in the field but there are a number of other possible explanations.

The reasons for the discrepancy between rational indices and field measurements have been the subject of considerable speculation and research, most of which have concentrated on the context in which field surveys are conducted. Nicol and Humphreys [7] suggested that this effect could be the result of a feedback between the comfort of the subjects and their behaviour and that they 'adapted' to the climatic conditions in which the field study was conducted.

2.2. The adaptive principle

The fundamental assumption of the adaptive approach is expressed by the adaptive principle: *if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*. This principle applies to field surveys conducted in a wide range of environments and thus legitimises meta-analyses of comfort surveys such as those of Humphreys [8,9], Auliciems and deDear [10] and deDear and Brager [11]. These meta-analyses have been used to generalise from the results of a number of thermal comfort surveys.

By linking the comfort vote to people's actions the adaptive principle links the comfort temperature to the context in which subjects find themselves. The comfort temperature is a result of the interaction between the subjects and the building or other environment they are occupying. The options for people to react will reflect their situation: those with more opportunities to adapt themselves to the environment or the environment to their own requirements will be less likely to suffer discomfort.[1]

The prime contextual variable is the climate. Climate is an overarching influence on the culture and thermal attitudes of any group of people and on the design of the buildings they inhabit. Whilst the basic mechanisms of the human relationship with the thermal environment may not change with climate, there are a number of detailed ways in which people are influenced by the climate they live in and these play a cumulative part in their response to the indoor climate. The second major context of nearly all comfort surveys has been a building, and the nature of the building and its services plays a part in defining the results from the survey. The third context is time, in a variable environment such as will occur in most buildings occupants will respond to changes in the environment. They will do this by taking actions to suit the environment to their liking or by changing themselves (for instance by posture or clothing) to suit the environment. This implies that the comfort temperature is continually changing. The extent of these changes and the rate at which they occur is an important consideration if the conditions for comfort are to be properly specified.

This paper will present findings in all these areas and discuss the implications for the development of more sustainable standards for the indoor climate of buildings.

2.3. People and indoor climate

Nicol and Humphreys [7] presented data suggesting that the mean comfort vote changed less with indoor temperature from climate to climate than might be expected. Humphreys [8] confirmed this from a wider variety of climates. The rate of change of comfort vote with temperature is characteristically much lower from one survey to another than it is within any particular survey (Fig. 1).

The corollary of this finding is that in field surveys the comfort temperature is closely correlated with the mean temperature measured. This was found to be the case in surveys conducted over a wide range of indoor climates (Fig. 2a).

[1] In these terms, the climate chamber is a very particular environment where conditions and occupant action are closely controlled by the researcher for the period of the experiment.

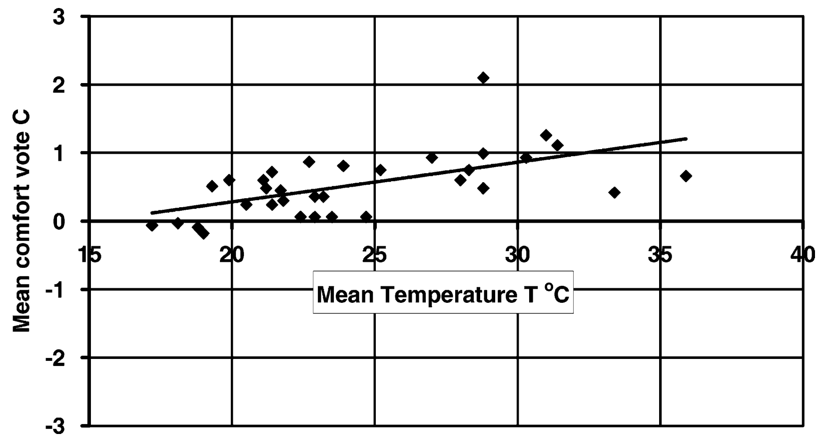

Fig. 1. The variation of mean comfort vote with mean indoor temperature. Each point is the mean value from a comfort survey (using data presented in [8]).

A similar effect was found when data were collected throughout the year from a particular group. Surveys in Pakistan [12] and Europe [13] were conducted at monthly intervals throughout the year (Fig. 2b). The variety of indoor temperatures, particularly in Pakistan, is remarkable. The strong relationship with comfort temperature is clear.

As an example of how effectively adaptive actions can be used to achieve comfort, Fig. 3 shows the actual proportion of subjects comfortable among office workers in Pakistan at different indoor temperatures. The data were collected over a period of a year so the comfort temperature was continually changing, as was the indoor temperature [12]. The major methods these workers had to control their comfort were by changing their clothing and using air movement, fans being universally available in Pakistani offices. The curve shows the mean probability of comfort calculated using probit regression. Each point represents the proportion comfortable in a particular city in a particular month.

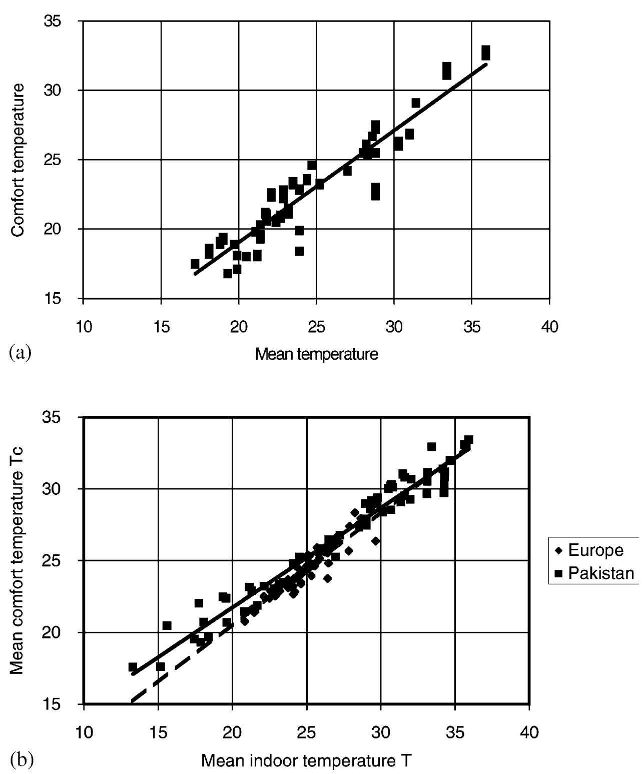

Fig. 2. The variation of comfort temperature with mean indoor temperature: (a) from surveys throughout the world (from data presented in [8]); (b) from within a particular set of climates (Europe (dashed line) and Pakistan) but at different times of year.

2.4. The relationship with outdoor climate

Humphreys [9] took the indoor comfort temperature determined in a number of surveys conducted world-wide and plotted them against the outdoor monthly mean temperature at the time of the survey. The results are shown in Fig. 4. He found a clear division between people in buildings which were free-running at the time of the survey and those in buildings that were heated or cooled. The relationship for the free-running buildings was closely linear. For heated and cooled buildings the relationship is more complex.

deDear and Brager [11] make a division between buildings which are centrally air-conditioned and those which are naturally ventilated. They argue that occupants of building which are air-conditioned have different *expectations* than the occupants of naturally ventilated buildings. It seems unlikely that people using a building should modify their responses to it on the basis of their expectations of its building services. Nor is this distinction supported by evidence from the field [6]. Whilst expectation does have a part to play in the interaction between people and their environment, it is more in defining the temperature they will expect in a particular situation than in their attitude to the building services.

Probably the difference is due to an accumulation of the small effects caused by a wide variety of adaptive actions which together amount to a large difference in conditions for comfort. In a re-analysis of the data of deDear and Brager, Humphreys and Nicol [14] argue that using Humphreys' original distinction (between free-running and heated or

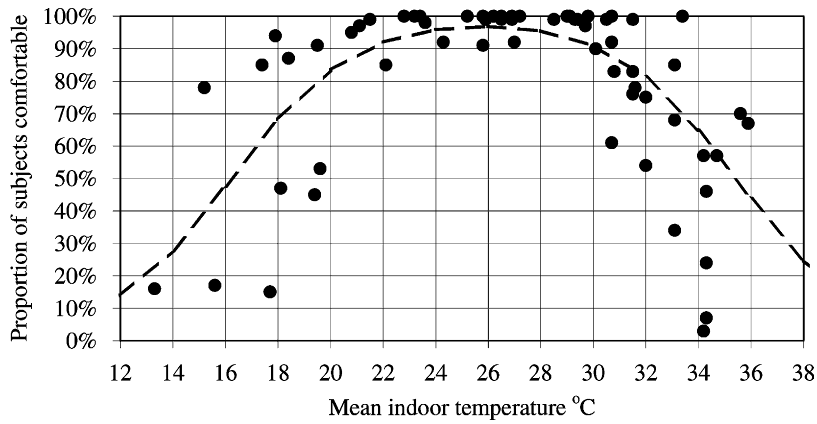

Fig. 3. Pakistan: the proportion of office workers who were comfortable at different indoor temperatures. It will be noticed that on many occasions the subjects recorded no discomfort. With a continually changing indoor temperature and comfort temperature, Pakistani buildings were found comfortable at temperatures ranging between 20 and 30 °C with no cooling apart from fans (from [12]).

cooled buildings) increases the precision of the relationship both in free-running buildings and those which are heated and cooled. Fig. 5 shows how the comfort temperatures changes with outdoor temperature in buildings which are free-running and with heated or cooled from Humphreys [9] in the 1970s and from the ASHRAE database [15] in the 1990s.

It has been argued that using just the outdoor temperature to calculate comfort temperatures ignores a whole lot of other factors such as the humidity and air movement. The comfort temperature is clearly a function of more than just the outdoor temperature. But people's clothing insulation also depends on outdoor temperature [12], as does the use of building controls [16]. Other instances are posture, which Raja and Nicol [17] have shown to vary with temperature, and metabolic rate for a given activity which Baker and Standeven [18] among others [7,19] have suggested may also vary with temperature. It is the *feedback* between the climate and these adaptive actions which means that only the outdoor temperature need be considered in real situations in real buildings. The relationship is to some extent an empirical 'black box' because the inter-relations are not all fully defined.

2.5. People in buildings

Buildings differ in a number of ways: in addition to their individual physical form, they differ in their services; in what sort of heating or cooling system is provided and whether it is used; in the possibilities they offer for occupants to control their environment and in the policies of management about whether there is a dress code and so on.

There are other aspects of building services which affect the comfort of occupants. Leaman and Bordass [20] have demonstrated that there is more 'forgiveness' of buildings in which occupants have more access to building controls.

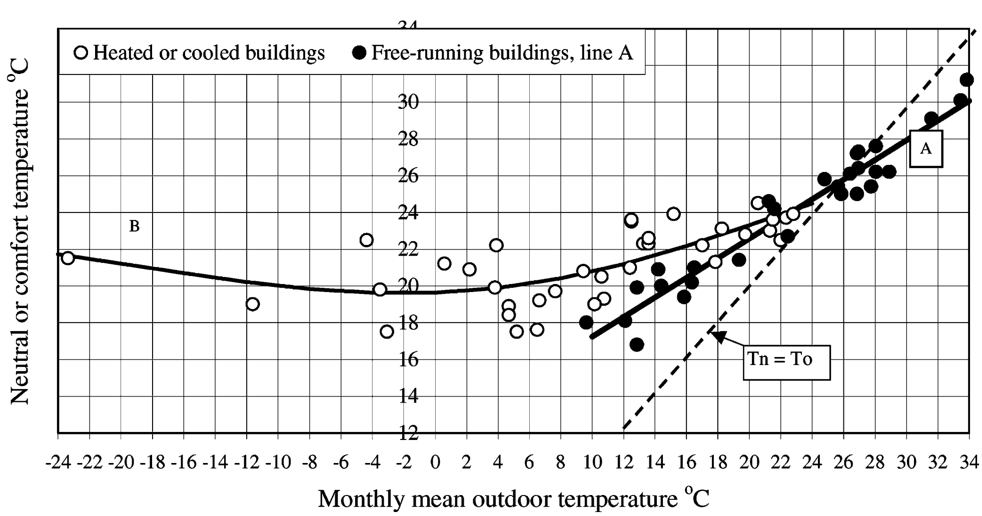

Fig. 4. The change in comfort temperature with monthly mean outdoor temperature. Each point represents the mean value for one survey. This graph is from Humphreys [9]. The buildings are divided between those that are heated or cooled at the time of the survey and those that are free-running. Subsequent analysis of the ASHRAE database of comfort surveys [14] showed similar results (see Fig. 5).

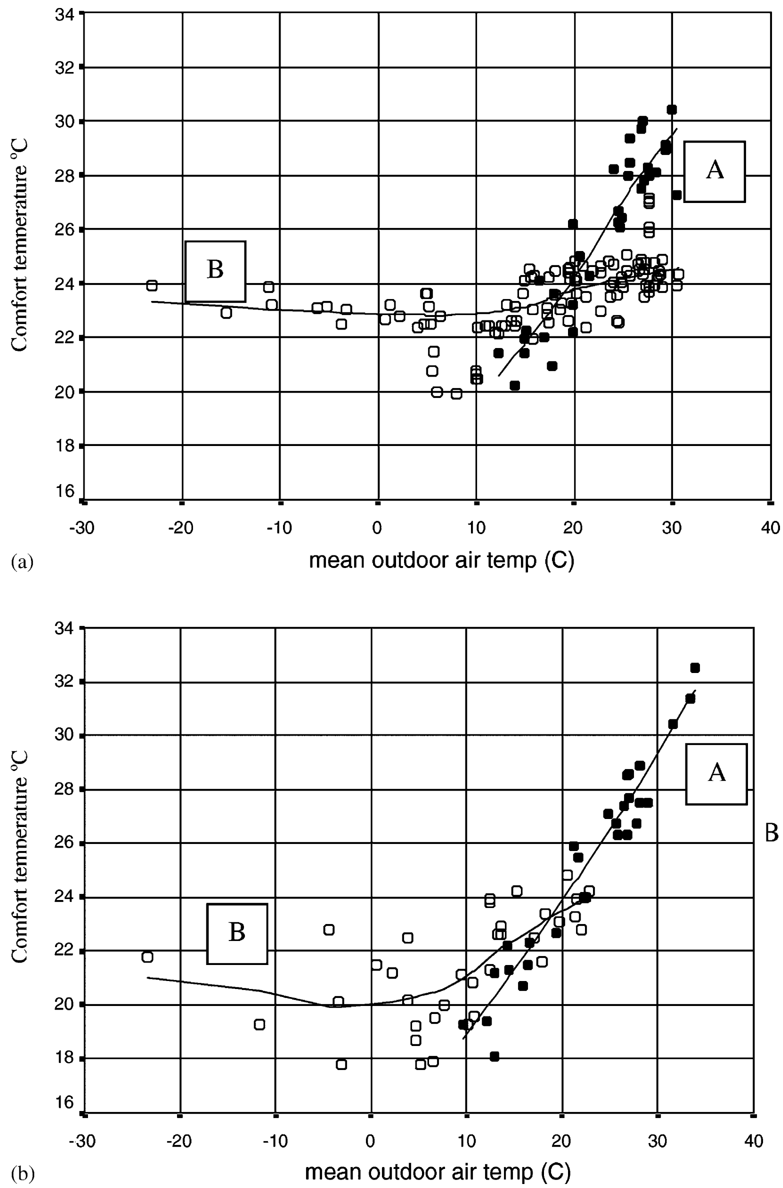

Fig. 5. Comfort temperatures as a function of outdoor temperature for buildings which are free-running (A) and with heating or cooling (B): (a) from the ASHRAE database [15]; (b) from Humphreys [9] see Fig. 4. These graphs first appeared in [14].

By forgiveness, they mean that the attitude of the occupants to the building is affected so that they will overlook shortcomings in the thermal environment more readily. This can be explained as a function of who is in control. Variability is generally thought of as a 'bad thing' in centrally controlled buildings because occupants are adapted to a particular temperature. Much change from this and they become uncomfortable. In buildings where the occupants are in control, variability may result from people adjusting conditions to suit themselves. A certain amount of variability then becomes a 'good thing'. Many naturally ventilated buildings give their occupants a certain amount of control over their environment. If the control is left to the building manager (through the HVAC system) there is a smaller envelope of acceptable conditions, comfort changes more quickly with temperature and the occupants appear less forgiving.

A more robust characterisation is that of Baker and Standeven [18]. They identify an 'adaptive opportunity' afforded by a building that will affect the comfort of its occupants. Adaptive opportunity is generally interpreted as the *ability* to open a window, draw a blind, use a fan and so on, but must also include dress code working practices and other factors which influence the interaction between occupant and building. Changes in clothing, activity and posture and the promotion of air movement will change the conditions which people find comfortable. Many of the adaptive opportunities available in buildings will have no direct effect on the comfort conditions but will allow the occupants to change conditions to suit themselves. Actual adaptive behaviour is an amalgam of these two types of action—changing the conditions to accord with comfort and changing the comfort temperature to accord with prevailing conditions. The range of conditions considered comfortable is affected by the characteristics of the building and the opportunities for individual adaptation by occupants.

In reality, it has been found difficult to quantify the adaptive opportunity in terms of the availability of building controls. Nicol and McCartney [21] showed that the mere existence of a control did not mean that it was used, and that merely adding up the number of controls does not therefore give a good measure of the success of a building or its adaptive opportunity. It would seem that as well as the existence of a control a judgement is needed as to whether it is useful in the particular circumstances. For example, solar shading may be useless on one face of a building, but essential on another. In addition the perceived usefulness of a particular control will change from time to time depending on conditions [22].

The feedback mechanisms embodied in the adaptive principle create order in the relationship between outdoor climate and comfort temperature. In a free-running building the indoor climate is linked by the building to outdoor conditions. When the building is being heated or cooled the relationship changes, because the indoor climate is decoupled from that outdoors. In these circumstances the building occupants control comfort temperature either locally as in most naturally ventilated buildings or centrally when the building is centrally air-conditioned.

2.6. Time as a factor in the specification of comfort temperatures

When people take actions in response to a thermal environment which is causing discomfort these actions take time to accomplish. There are a number of actions which can be taken: some like opening a window, take little time, others such as the change of fashion from winter to summer clothes take longer. The change is fast enough to keep up with the fluctuations in the weather from season to season but not always quick enough to account for all the changes in the local microclimate [23]. In his comparison between outdoor temperature and the comfort temperature indoors (see Fig. 4), Humphreys [9] used records of the monthly mean of the outdoor air temperature as the defining variable. deDear and Brager [11] use the mean of outdoor effective temperature without defining the period over which it has been measured. The weather can change dramatically within a month and both people and the buildings they inhabit change at a rate which will not be reflected by a monthly estimate.

Recent surveys [24,25,13], have tried to determine the rate of change of comfort temperature using longitudinal comfort surveys conducted over a period of time. Unfortunately, comfort surveys do not produce data which are sufficiently coherent for a statistical determination of the best time-series to use. Therefore, an appropriate time-series was assumed. Humphreys [26], suggested that the exponentially-weighted running mean of the temperature would reflect the time-dependence of the comfort temperature or clothing insulation.

The equation for the exponentially-weighted running mean at time t is

$$T_{\mathrm{rm}(t)} = (1-\alpha)\{T_{t-1} + \alpha T_{t-2} + \alpha^2 T_{t-3} \ldots\} \quad (1)$$

where α is a constant such that $1 > \alpha \geq 0$, $T_{\mathrm{rm}(t)}$ the running mean temperature at time t, T_t the mean temperature for a time t of a series at equal intervals (hours, days, etc), T_{t-n} the instantaneous temperature at n time-intervals previously. The time-interval used to calculate T_{rm} in this paper is a day. The rate at which the effect of any particular temperature dies away depends on the constant α. The time series gives a running mean temperature that is decreasingly affected by any particular temperature event as time passes. The larger the value of α the more important are the effects of past temperatures.

The aim is then to find the value of α which gives the best correlation of outdoor running mean with the comfort temperature. Fig. 6 shows how the correlation of comfort temperature (solid line) with running mean temperature varies with the value of α. It might be argued that this is a chance effect arising from the serial correlation between the daily mean temperature and the running mean temperature. Today's temperature is likely to be closer to yesterday's temperature than to last week's or last month's. Fig. 6 also shows (hatched line)[2] how the correlation of daily mean temperature (T_{od}) with running mean temperature changes with the value of α. There is clearly a difference in the shape of the two curves. The correlation with T_{od} falls consistently with increasing α, the correlation with comfort temperature rises gradually until α reaches about 0.8 and then starts to decrease. This suggests that though the peak in the correlation with comfort temperature is small, there is a real effect. The correlation with T_{od} ($\alpha = 0$) and with the monthly mean of outdoor temperature ($\alpha \cong 0.95$) are both less than the correlation with T_{rm} where $\alpha = 0.8$.

2.7. An adaptive algorithm for indoor temperature control

Humphreys and Nicol [27] suggested that an algorithm could be constructed which could determine the optimal indoor temperature to be provided by a HVAC system (or a free-running building). They predicted the comfort temperature indoors in terms of the outdoor temperature. The algorithm was based on the work done by Humphreys [9] on the relationship between comfort temperature and the outdoor temperature (see Fig. 3), but using a mixture of the instantaneous and the running mean out door temperatures rather than the monthly mean as the predictor variable. At the time this could only be presented as a tentative proposal.

[2] Note the scales are different for the two curves which are illustrative.

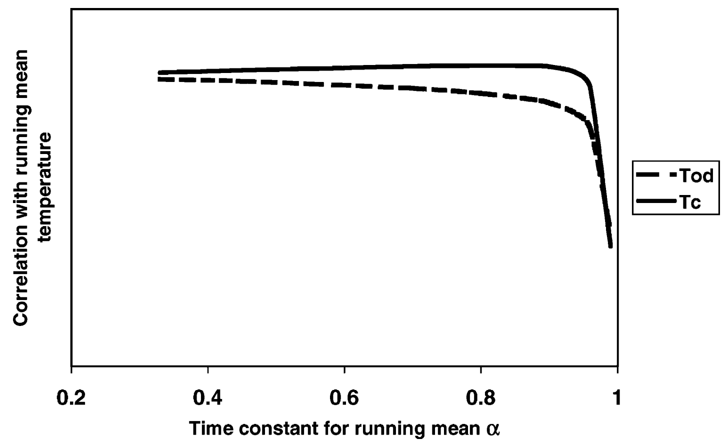

Fig. 6. Showing the changing correlation between the exponentially-weighted running mean temperature and the comfort temperature (T_c). The serial correlation with the daily mean temperature (T_{od}) is shown for comparison. The measure of the running mean temperature shown is the constant α (see Eq. (1)).

It was necessary to confirm that the exponentially-weighted running mean was an appropriate measure of outdoor temperature for predicting comfort temperature indoors. In addition, information was needed to help determine the best value of α to use in Eq. (1). Subsequent work [23] has suggested that the instantaneous outdoor temperature adds little to the predictive strength of the running mean temperature. Recent work suggests that the use of a control regime which provides a set-point temperature changing with the running mean of the outdoor temperature does not increase discomfort among occupants as compared with a constant set-point, but can result in substantial savings in energy use [13].

3. Defining an adaptive standard

3.1. What kind of standards?

Standards can be divided into those that standardise a methodology and those that define good practice. An adaptive standard will most usefully be of the latter type. Adaptive practice is context dependent. A different standard will be needed for defining temperatures for different circumstances. For example

- Buildings—indoor comfort conditions to help decide on the design and the sizing of heating or cooling systems or passive strategies.
- Outdoors—how to define comfort in an outdoor context (availability of shade, wind speed and direction, etc.)
- Vehicle designers—design of air-conditioning, ventilation, etc.

Here, we outline the basis for a standard to define good practice in the definition of temperatures in buildings. Such a standard would indicate

- The indoor environments most likely to provide comfort.
- The range of acceptable environments.
- The rate of change of indoor environment which is acceptable to occupants.

The standard should help the designer make decisions about successful strategies in terms of the design of the building, the controls it provides and its services

3.2. The most likely comfort temperature

This paper has presented evidence that the comfort temperature in free-running buildings depends on the outdoor temperature as shown in Fig. 3. Humphreys and Nicol [14] showed that this relationship between comfort temperature T_c and outdoor temperature T_o for free-running buildings (Eq. (2)) is remarkably stable as between data presented by Humphreys in the 1970s [9] and in the 1998 ASHRAE database [15] (see Fig. 5). The equation for comfort temperature is almost exactly

$$T_c = 13.5 + 0.54\,T_o \qquad (2)$$

where T_o in this case is the monthly mean of the outdoor air temperature. The correlation coefficient r for the relationship was 0.97 for 1978 data and 0.95 for ASHRAE database.

The relationship in buildings which are heated or cooled is more complex, and less stable. It is less precise because when a building is heated or cooled the indoor temperature is decoupled from the outdoor temperature and the indoor temperature is more directly governed by the custom of the occupants (or their building services manager). This custom is not absolute as is shown by the wide range of comfort temperatures for heated and cooled buildings shown in Figs. 4 and 5. There is also a difference of some 2 °C in indoor comfort temperatures for heated and cooled buildings between two databases [9], one compiled in the late 1970s and the other [11] compiled in the 1990s (see Fig. 5). Whilst it is not clear whether this is due to a change in preference over time or to other differences between the two databases, the preferred indoor temperature may need to be determined from time to time or between one group of people and another. It should be noted that this does not put the adaptive standard at a disadvantage vis-à-vis the rational indices. These also assume a knowledge of clothing behaviour and working practices if they are to reflect changes in comfort temperatures.

3.3. The range of comfortable conditions

It is difficult to define the range of conditions which will be found comfortable. The adaptive approach tells us that variability in indoor temperatures can be caused by actions taken to reduce discomfort, as well as those which are not controlled locally and hence more likely to cause discomfort. Adaptive thermal comfort is, therefore, a function of the possibilities for change as well as the actual temperatures achieved. The width of the comfort 'zone' if measured purely in physical terms will therefore depend on the balance between these two types of action. In a situation where there was no possibility of changing clothing or activity and where air movement cannot be used, the comfort zone may be as narrow as $\pm$ 2 °C. In situations where these adaptive opportunities are available and appropriate the comfort zone may be considerably wider.

3.4. Using the standard to design buildings and their services

The adaptive relationship between comfort temperature and the outdoor temperature can be used to help design comfortable buildings. An example is shown in Fig. 7. Here, the indoor comfort temperature is calculated from the mean outdoor temperature and plotted on a monthly basis together with the monthly mean of the daily outdoor maximum, minimum and mean air temperatures. Such a diagram helps the designer to judge whether passive heating and/or cooling are a possibility in the climate under consideration. The relationship between the desired indoor temperature and the range of outdoor temperatures shows whether, for instance, night cooling is likely to be a viable way to keep the building comfortable during the day in summer, or to calculate whether passive solar heating will be enough in winter. This method has been used to define comfort indoors in a recent book. [28].

3.5. The case of heated and cooled buildings—the adaptive algorithm

The comfort temperature in heated or cooled buildings is a matter of custom, but so long as the change is sufficiently slow, people will adapt to a range of temperatures. The indoor comfort temperature will naturally change with the seasons as people adjust their clothing to the weather. Thus, the idea of an 'adaptive algorithm' [27] (see Section 2.6) to define a variable indoor temperature in terms of the running mean of the outdoor temperature is attractive. A crude form of such an algorithm is already used in ASHRAE Standard 55 [5], which describes different indoor set points for 'summer' and 'winter'. These seasonal set-points are based on crude assumptions about the seasonal change in clothing insulation and the metabolic rate. The adaptive algorithm changes continuously in line with the results from comfort surveys. It does not rely on the vague description of 'season' but relates the set-point directly to the running mean of the current outdoor air temperature. A recent project [13] suggests that such a variable indoor standard does not increase occupant discomfort, yet does significantly reduce energy use by the cooling system compared to a constant indoor temperature.

3.6. Sustainable comfort standards

One aim of this paper is to introduce the notion of sustainable comfort standards. There is an advantage, when presented with two otherwise equal possible standards, in preferring the more sustainable one. A number of attempts have been made through simulation [29,30], to predict the

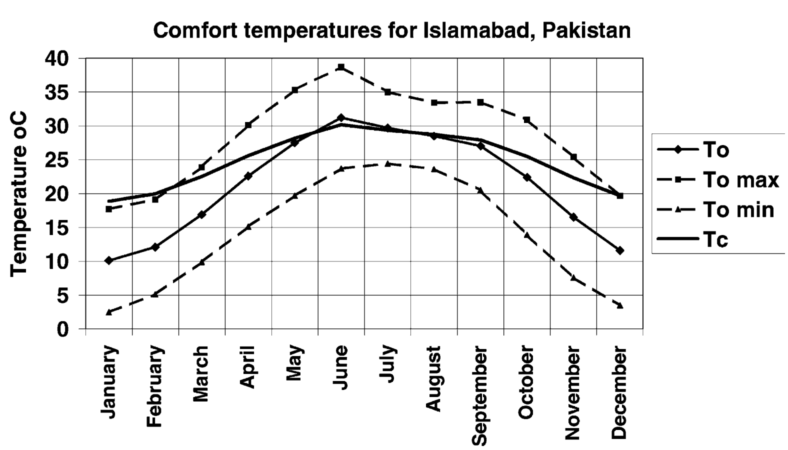

Fig. 7. Showing the seasonal changes in mean comfort temperature T_c in Islamabad, Pakistan and its relation to mean daily maximum, minimum and mean outdoor temperatures T_o. The relationship used to calculate comfort temperature from outdoor temperature is from [9] for free-running buildings.

changes in energy use which will result from the use of a variable indoor temperature in an air-conditioned buildings and many have suggested that energy savings will result. The extent of energy savings has been estimated in the region of 10% of the cooling load in UK conditions. In a recent European project [31] estimated energy savings were in the region of 18%. It is as well to remember, however, that a 'low energy' standard which increases discomfort may be no more sustainable than one which encourages energy use. This is because of the 'sting in the tail' of the adaptive principle: occupants may well use energy to alleviate their discomfort.

Naturally ventilated buildings typically use about half the energy of ones which are air-conditioned [32]. The temperatures in free-running buildings are constantly changing in line with outdoor conditions. A constant-temperature standard therefore militates against the use of natural ventilation. A variable indoor temperature standard will help save energy by encouraging the use of naturally ventilated buildings. Note that, though it will save energy in an air-conditioned building, a 'seasonal' temperature change such as is suggested by ASHRAE Standard 55 [5] may be almost as hard to achieve in a free-running building as a single constant temperature throughout the year.

3.7. And finally... do we really need to specify indoor climate?

This paper has made the case that optimal indoor environments in a building are a function of its form, the services it provides and the climate in which it is placed. This implies that, given a full understanding of the mechanisms at work, it may eventually be possible to produce thermal standards for building which do not resort to specifications of the indoor climate. The characteristics of a building (in terms of controls and building management) in relation to the local climate may be sufficient. Such standards will be more meaningful to building designers and consequently it will more likely to be used.

4. Conclusions

This paper explores the use of results from the field to inform thermal standards in buildings.

(1) Field studies suggest that rational indices are difficult to use in real situations and are poor indicators of comfortable conditions in buildings.
(2) This suggests that relationships based on laboratory experiments should be tested in the field before inclusion in standards.
(3) The adaptive approach allows building designers to estimate the indoor temperature which building occupants are most likely to find comfortable, particularly in free-running buildings.
(4) There are a number of small ways in which people can adapt to their environment. People use these adaptive mechanisms or opportunities to achieve their desired conditions. The cumulative effect of these adjustments can explain the differences between the responses of people in buildings with different servicing regimes and levels of available control.
(5) The range of conditions which will be found acceptable at any one time is in the region of ± 2 °C. Giving occupants the control necessary to make themselves comfortable can increase this range.
(6) The building should give occupants the chance to adjust the conditions to suit themselves. Discomfort is increased if control is not provided, or if the controls are ineffective, inappropriate or unusable.
(7) The rate of change of comfort temperature can be characterised by the running mean of the outdoor temperature. This means that an adaptive algorithm can be formulated which can be used to calculate a variable indoor set-point, related to the outdoor temperature. Early indications are that such a variable set-point does not increase discomfort and allows significant reductions in energy use in buildings.
(8) Sustainability needs to be considered in the framing of standards. Such standards can have an effect on the energy use by buildings. Where acceptable low-energy solutions are available they should be preferred.

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