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Thermal comfort in the context of energy conservation.

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Introduction

With the present worry about the use of energy, not only because of cost or scarcity, but also because of its implications for the emission of carbon dioxide and global warming, a grasp of the dynamics of thermal comfort has become of increased importance. So I thought it would be useful in this chapter to give a retrospective comment on my research in this subject, conducted at the Building Research Establishment between 1966 and 1978. My aim is to pick out what seems either interesting or important for our broad understanding of thermal comfort in relation to the built environment. This chapter arises from a lecture delivered at Oxford Polytechnic, and retains something of the spoken tone of that occasion. Much of the detail, and some of the substantiation of what I say, is necessarily omitted, and all I can do is refer the reader to earlier and more detailed results and arguments (1,2,3)

Consider this quotation:

(Laura) was cold. She was too cold to wake up. The covers seemed very thin. She snuggled closer to Mary and burrowed her head under the thin covers. In her sleep she was tight and shivering, till finally she grew cosy and warm. The next she knew, she heard Pa singing. .... Laura opened one eye and peeked out from under the covers. Snow fell softly on her face, a great lot of snow.

'Ow!' she said.

'Lie still, Laura!' said Pa. 'All you girls lie still. I'll shovel you out in a minute. Soon as I get this fire started and the snow off Ma' (4)

The house had been unfinished, and there was an unexpected spring blizzard. Clearly, the 'bedroom' temperature was well below freezing, for the snow did not melt when it fell on Laura's bed. Once the snow had fallen she was cosy and warm, snuggled up against Mary. What is relevant for Laura's comfort is the temperature within the cocoon of her bed. The snow provided her with a low-energy solution for her thermal comfort requirement. Let's just say that this incident casts doubt on the need for a bedroom temperature of not less than 15 degrees!

A second quotation, this time fictional:

'The Commissaris shivered, and Silva immediately showed concern.

"You haven't caught a chill, have you? It's this damned air-conditioning. It's a comfort, of course, but a danger at the same time. This isn't the best season and the heat hits you like a hot towell when you step outside, but here, in the offices, it's too cool. I'll turn the machine down a little."

"No, no," the Commissaris said quickly, "I feel quite well, better in fact than I have for a long time. But I did, probably, shiver because of the change of temperature."' (5)

This is from a novel set in a hot and fairly humid island. Outside, your skin is moist with evaporating sweat. When you enter the air-conditioned space, the sweat evaporates, giving a powerful transient cooling. Was it sensible to set the indoor temperature so low? Shouldn't it have born some relation to the temperature outside? It calls into question the need to use fuel for refrigeration in such circumstances. Could not the (fictional) designer have designed a building to maintain a steady, slightly warmer temperature, more cheaply and more satisfactorily?

Or consider the following exchange, which took place between Thomas Bedford, the Father of thermal comfort surveys, and, I believe, Charles Webb, well-known for his work on thermal comfort in equatorial and tropical climates (6). Dr Bedford had been very uncomfortable when visiting India. This was largely because he did not adapt his dress appropriately. Charles Webb explained that, if one removed the jacket and tie, and arranged one's open-neck shirt outside the trousers, all could be well. Bedford replied "But there are limits, Webb." Here a viable strategy for comfort is rejected on cultural grounds. Such a rejection is not unusual, for although the physical effect of dress is chiefly thermal insulation, it has powerful social and cultural functions too. So the architect and engineer need to know not only the climate but the culture, or even the sub-culture of the occupants, before the temperature can be specified.

The body's temperature control

The human thermal regulation system is astonishing. The body reacts to control the temperature of its core, and especially of the brain, whose temperture is regulated to within a few hundredths of a degree on a diurnal cycle of waking and sleeping.

A small increase in brain temperature induces sweating, although the pattern and quantity of sweat production is influenced also by conditions of temperature and pressure nearer the body surface. There are pressure-points on the surface which control which surfaces will sweat, so that, for example, a person lying on one side will sweat chiefly on the upper surfaces of the body, well demonstrated by Kuno's pioneering work on human perspiration (7). Clothing suitable for a hot climate must allow free circulation of air to the skin. Evaporation of sweat or other moisture from the skin is an intensely powerful cooling force. When you start to dry your hands under a hot-air dryer, the initial feeling is cold. When the hands have dried, the airstream is too hot to bear. So in a really hot climate there is an optimum windspeed. Less that this does not evaporate all the sweat, while more than this evaporates all the sweat and then heats the skin. It was shown as early as the 18th century (in a delightfully reported experiment) that it was possible to stay in a dry oven with a temperature above boiling point for lengthy periods, so long as sweat was freely evaporating from the skin (8). (A note of caution: this is not true of an oven saturated with moisture. In this case temperatures of above about 36 degrees are lethal, there being no possibility of evaporative cooling.)

A small decrease of brain-temperature induces increases muscle tension and shivering. The process begins, for a naked resting person, at a room temperature of about 28 degrees. Shivering increases the metabolic heat-production, and so tends to stabilise the body temperature. A shivering person may double or even treble his heat production.

Along with the sweating and shivering goes the dilation and constriction of blood vessels near the body surface. So if the body core is cold, the blood flow to the surface is reduced, while if the core is hot, the blood flow to the surface is increased. This gives extra regulation, increasing the band of room temperature at which there is no obvious sweating or shivering, but just a variation of the temperature of the skin.

During exercise the body-core temperature increases, inducing sweating, which dissipates the heat generated by the excercise. During sleep, the set-temperature of the brain 'thermostat' is lower, and so when one falls asleep the brain temperature is above its new set-point, and sweating takes place until the new equilibrium is reached.

Broadly speaking, and not talking now of extremes either of body-temperature or room-temperature, conditions which tend to move the body away from equilibrium are unpleasant, while those tending to restore the equilibrium are pleasant. So people will, when free to do so, seek conditions which tend to restore their body's thermal equilibrium.

Within overall equilibrium the body becomes used to moderately different distributions of surface temperature, so quite different patterns of clothing can be comfortable, provided that the overall thermal balance is correct. The change from one clothing pattern to another produces very noticeable sensations of warmth or coolness, as, for example when one changes from long to short trousers. But the different sensation is not noticed for long, because temperature perception at the skin is much more sensitive to change that it is to steady conditions.

This is a very simplified description of a marvellous and subtle system of control. In very young babies the system is not fully operational, and in the elderly it is less effective. So it is the babies and the aged who are most prone to die from extremes of heat or cold.

Behavioural Regulation

People are not passive in relation to their thermal environment. We have already noticed that people will tend to seek out comfortable conditions. Outdoors they seek shade or sunshine, wind or shelter, as may be most comfortable - though they may trade-off comfort for some other benefit (9). They also regulate their posture, activity, clothing to obtain comfort. An Antactic survey team spent the winter in upturned tractor crates, their supply-ship with the proper huts having stuck in the ice (10, 11). A survey showed that they were comfortable at very low temperatures, their clothing being adequate to the conditions. At the other pole, eskimos reached a different equilibrium within their traditional igloos. The inside temperature was kept at about 30 degrees by oil lamps and body heat, and the clothing was very light. They opted for a 'tropical' indoor environment!

Building design itself can be regarded as part of this regulatory procedure. Over the centuries styles have been developed which perform well in tropical climates, hot dry climates, temperate climates and cold climates. These buildings can be thought of as a long-term human adaptation to the environment. And of course the buildings may themselves be adjustable by means of blinds, shutters, ventilation, and active heating or cooling systems, and they may use their mass to reduce temperature variation, so as to maintain the desired temperature or at least ameliorate the rigours of the outdoor climate. We clearly have a wide-ranging regulatory mechanism in operation, with physiological, behavioural, cultural and technical aspects all meshed together. Discomfort arises when the total effect of all these regulationary actions, for one reason or another, fails to yield easy thermal equilibrium.

It follows that in general, those things which reduce the number of strategies which a person can adopt in the quest for comfort, are likely to cause discomfort, while less restrictive circumstances are productive of comfort. Soldiers on parade have virtually no mechanisms available except the basic physiological ones. The posture, activity level, clothing and the environment are all outside their control. So it is hardly surprising that fainting on parade is common, or that military history has many instances of soldiers dying from heat stress, not because of the rigours of the climate, but because of the rigours of military discipline. Contrast this with the situation of someone in their own home. They have many strategies available, for activity, posture, clothing, and often the room temperature and the amount of radiant heat are matters of choice. Home is likely to be comfortable.

Discomfort also arises when the environment is much warmer or cooler than had been expected. This can happen because of a sudden change in weather, and one has chosen clothing which is unsuitable, and there is no opportunity to change it. It can also happen if a building is maintained at an unexpected temperature - as when a hotel bedroom is much warmer than home, and they provide a megatog duvet to ensure a sweaty night. Or when you visit friends, and they keep their house cooler than you do at home.

Conversely, comfort is greatly helped if the thermal environment is predictable. The church where I ministered for fourteen years occupied a large victorian-style chapel with a high, uninsulated roof. There was little spare money for heating, so I suggested that we should try to maintain a winter heating temperature of fifteen degrees during services. People soon learned that it was necessary to dress fairly warmly and there were few complaints. In fact they complained that a nearby church with whom we later occasionally shared services kept their chapel too warm. It was about twenty-one degrees.

The point I am trying to make is very simple. Within a wide range of circumstances, thermal discomfort is not caused by the room temperature itself, but by a mismatch between actual temperature and the desired temperature. And the desired temperature is variable, depending on a complex web of the factors already mentioned.

Research methods and results

Two principal research methods have been used in thermal comfort research this century; the climate chamber and the field-study. The former is a controlled experimental procedure, while the latter is observation accompanied by measurement. The difference of approach, although not absolute, becomes clear when the methods are considered in more detail.

Climate chambers

A climate chamber is a specially constructed room whose thermal environment can be controlled. Ideally it should be possible to control independently the air-temperature, the temperature of the room surfaces as they radiate to the occupants, the humidity of the air, and its velocity. A sophisticated chamber can also provide temperature-gradients from floor to ceiling, and different temperatures on different surfaces. It is possible to put volunteers in the chamber, in standard clothing, and performing standard activities. Either they are asked to adjust the room temperature till it is just right, or they can be asked to assess how warm or cool they feel. Good climate chamber work has been done by Ole Fanger in Denmark, the late Ralph Nevins in the USA, and Ian Griffiths and Don McIntyre in this country.

A short summary of climate-chamber research results is this: People with the same activity and clothing all like the same temperature (plus or minus a degree or so in standard deviation), irrespective of their sex, age, culture, race, season, the colour of the room, or the climate to which they are accustomed (13,14).

From results obtained in climate-chambers, a physical-physiological equation can be constructed to show what thermal environment (expressed in terms of air-temperature, thermal radiation, humidity, and air-movement) will be comfortable. One must specify the activity and the clothing-insulation.

Field studies

The alternative technique is to meet people in their normal environments, while performing their normal activities, and ask their opinion of the thermal environment. The environment is measured but not altered by the researcher. In both types of work rather similar rating scales have been used to assess people's responses to the thermal environment. Typically people are asked to say how they feel by responding to a seven-point scale ranging from much too cool to much too warm, with cental point indicating neutrality or comfort. The number of categories, the manner of presentation, and the labelling of the scales has varied considerably. The classic field-study was conducted by Thomas Bedford during the nineteen-thirties, and his original full research report is still well worth reading (15). In the late seventies I correlated the results of all the thermal comfort field-studies that I could find. Today several more studies could be added (e.g. 16, 17, 18), but as far as I can see without detailed analysis, they all tend to confirm and extend the overall picture which had emerged from the comparison of the studies available to me in the nineteen seventies.

In brief the results can be summarised as follows: The temperature which people find comfortable, irrespective of age, sex, race, can be estimated (plus or minus a degree or so in standard deviation) from the average room-temperature during the survey (Fig 1). The temperature found to be comfortable is also related to the monthly mean outdoor temperature of the country and season where the survey was conducted (plus or minus a little over a degree in standard deviation) (Fig 2). In most circumstances a simple measure of the thermal environment is sufficiently good, such as the air-temperature, or, if a source of thermal radiation is present, the temperature of a globe thermometer. But in hot climates it is common to use the cooling effect of natural or induced air-movement, and this must be allowed for. In these climates humidity becomes important if it limits the evaporation of moisture from the skin (Table 1).

Table 1: Measurement of the thermal environment
The table shows the simplest sets of measurements necessary to specify the warmth of the environment. They apply to indoor conditions where there is no great radiant asymmetry or air temperature gradient.

Set of Measurements	Restrictions upon their use
1 Air temperature	Difference between air temperature and mean radiant temperature is less than 2 degrees Air movement less than 0.2 metres/sec Sweat is freely evaporated from the skin
2 Globe temperature	Air movement less than 0.2 metres/sec Sweat is freely evaporated from the skin
3 Globe temperature* Air velocity	Sweat is freely evaporated from the skin
4 Globe temperature* Air velocity Wet-bulb temperature	None

*If the difference between the air temperature and the mean radiant temperature is small, the air temperature may be used instead of the temperature of the globe thermometer.

Conflict of results

There is nothing essentially contradictory in the above statements of the results of the two methods. The climate chamber discovers what happens in controlled conditions; the field study what happens in uncontrolled conditions.

However, a puzzling conflict does appear when we notice that in the field-studies the range of temperatures which people report as comfortable is much wider than would have been expected from the results of climate chamber research. It is not possible to explain this range, from about 15 to about 30 degrees, by means of the difference between the clothing common in cool and warm climates. People who are used to high temperatures report them to be acceptable, suggesting a substantial acclimatisation which alters the temperature that they like or accept. Physiological adaptations to heat and to cold (one may simultaneously be acclimatised to both) are well-established phenomena. However, when people are flown from hot climates to Denmark, they prefer, according to Ole Fanger's results (19), the same temperature as do the Danes. As far as I am aware, this conflict has not yet been satisfactorily resolved.

In the present state of knowledge it would be unwise to dogmatise. I believe that the climate chamber studies yield a possible combination for comfort, but not the only one, and perhaps not the best one when the climate is hot and variable, and people are moving between outdoors and indoors. It seems to me that in hot countries light sweating is normal, acceptable and not uncomfortable, provided that the clothing is suitably loose and permeable to moisture. A room temperature which is cool enough to make sweating unnecessary would also be acceptable if one were used to it, but would seem cold initially.

Design temperatures for different climates and seasons

If the above analysis is correct, it means that it is unnecessary to specify unvarying indoor temperatures for buildings throughout the year. Rather it ought to be possible to relate the indoor temperature to the average monthly outdoor temperature. Such a policy would not reduce satisfaction, provided it was done gradually enough (for unexpected changes of temperature are a prime source of discomfort), and would reduce the discomfort entailed in moving between indoors and outdoors. It could also reduce the amount of fuel used for heating or cooling. Although in theory one could lower winter indoor temperatures below those shown in the figure, this would entail the adoption of clothing customs different from those nowadays common, and would probably cause strong complaint.

It also follows that there is no need for uniformity of indoor temperatures worldwide - each region of the world could adopt temperatures suitable to the prevailing climate and season. This would reduce fuel used for heating and cooling, without causing discomfort, perhaps at some sacrifice to the comfort of international travellers. Fig 2 gives guidance on the temperatures appropriate to different outdoor temperatures. Diurnal swings of indoor temperature should preferably be kept within fairly close limits. Plus or minus two degrees might cause some discomfort, while plus or minus one degree would not produce noticeably more discomfort than a steady temperature.

Concluding comments

Here I am going beyond my expertise, and stray into the design of buildings.

It seems to me that, with judicious design, making use of solar heat gain in winter, and night-time ventilation in summer, the need to use fuel for heating and cooling of buildings can be virtually eliminated in many parts of the world.

When heating or cooling are needed, thought can always be given to the possibility of localised heating and cooling. The native Americans used to point out that European settlers built a big fire and sat a long way from it, while they built a small fire and sat close to it. The level of comfort would be the same, but the fuel consumption different. (It is even more efficient to place the heating or cooling inside the clothing, but this is not often convenient; it would be still more efficient to place it within the body itself, but still less convenient!)

There are few places in the world where the mean monthly outdoor temperature (as opposed to the mean daily maximum temperature) in the hottest month is unacceptably hot. So a massive building in almost any climate, provided the internal heat gains were small, should not need cooling.

Now that it seems at least probable that the carbon-dioxide we are generating is producing a warming of the globe, it seems to me that the reduction of the burning of fossil fuel is no longer just economically desirable, but perhaps a matter of survival for substantial parts of the world's population. (The arguments are set out in a semi-popular form in reference 19). It seems to me that we should leave the world in reasonable condition for the next generation, if that it within our power to do.

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Computing note for the Editor:
The text of this chapter is set in Locoscript 2 for an Amstrad PCW8512, and a disk is avilable from the author if required.

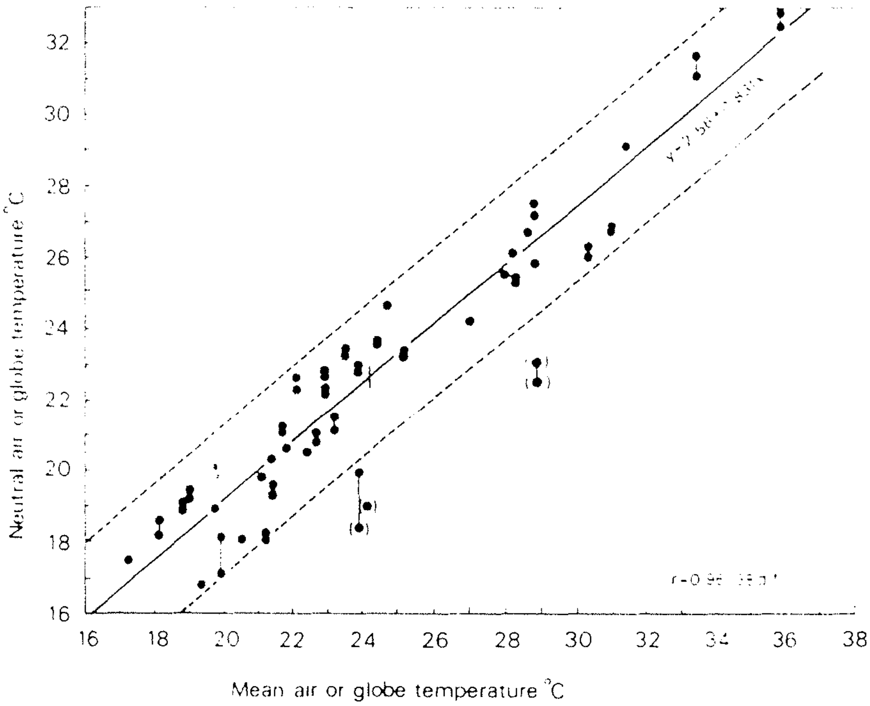

Figure 1. Scatter diagram of mean temperature and neutral temperature (the paired observations arise from two different methods of analysis, see Humphreys (1976))

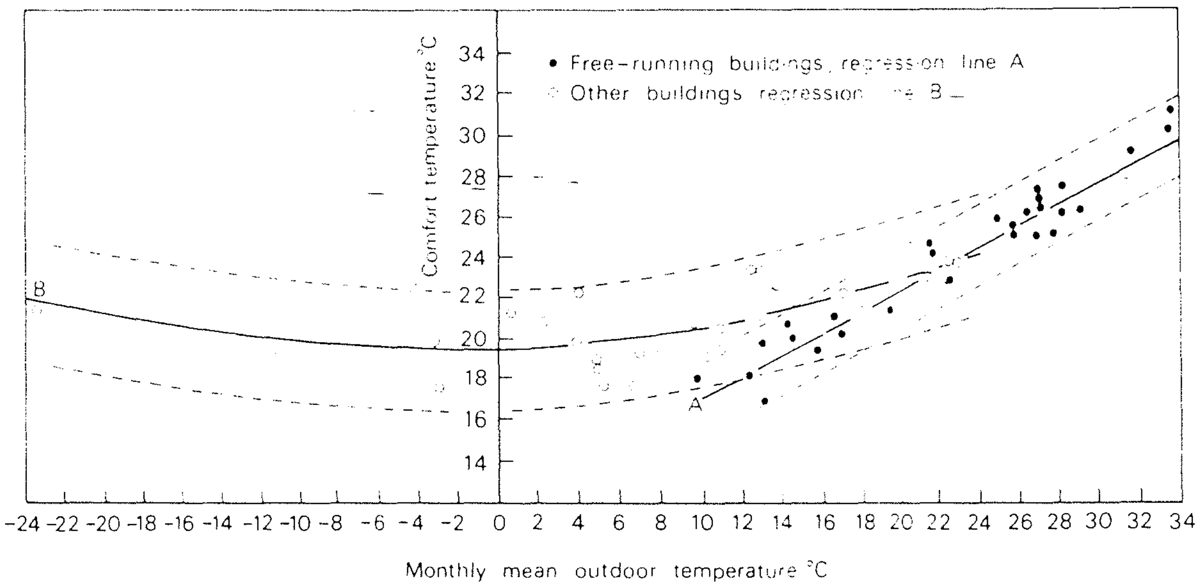

Figure 2. Scatter diagram for neutral temperature