THE ELECTRICITY COUNCIL RESEARCH CENTRE ECRC/M1185

DESIGN REQUIREMENTS FOR A COMFORTABLE ENVIRONMENT

by

D. A. McIntyre

SUMMARY

The most important factor affecting thermal comfort is the general feeling of warmth. This paper presents an easy method of estimating the optimum subjective temperature as a function of activity level and clothing insulation. Subjective temperature is an index defined in terms of a standard environment, and is simply calculated from the environmental variables. The variation of thermal sensation between different people, and in the same person from time to time, is described; it is shown to have important consequences for temperature control. The findings of field surveys show that people adapt their behaviour to the prevailing conditions, and there is no universal comfort temperature.

Potential sources of thermal discomfort are discussed and wherever possible working limits are given, within which most people will be comfortable. The paper ends by discussing the concept of comfort; it is concluded that the existing concepts of acceptability need to be refined.

This Memorandum is published as part of the Electricity Council's Research Programme and any technical query on the contents or requests for permission to reproduce any part of it should be addressed to the Author.

October, 1978.

CONTENTS

1. INTRODUCTION

Decisions about the thermal environment in a building must be made at the design stage. In recent years, there has been a growing awareness of how the building structure and climate interact to determine the thermal behaviour of the building interior, and of the important part that environmental considerations have played in determining the very shape of buildings (Banham, 1969). No longer is it acceptable for an architect to design his building, and only call in the heating engineer at the last moment; in the past this has led to too many failures to control the environment inside totally unsuitable structures.

The design requirements for a comfortable environment must be specified to the design team in physical terms. It would not be reasonable simply to specify that the building should be 'comfortable'; the requirements must be set out in physical units of temperature, air speed and so on. Realistically, the requirements must include both an optimum value for the physical parameter in question, and a permitted range. The activities of research workers over the past fifty years or so have produced a great deal of information, and this paper summarises what is known about comfort requirements. Response to a potentially uncomfortable stimulus varies greatly between different people, and from time to time for the same person. Further, the strength of objection to an uncomfortable stimulus is very greatly affected by the circumstances, and it is the unfortunate experience of many office managers that the more money that is spent on a building, the greater seems to be the sensitivity of the occupants to any minor discomfort. In any modern office there is always at least one person who is more sensitive to air movement than any anemometer yet devised by man.

Experience shows that by far the most important factor determining comfort is the general feeling of warmth. Many other things influence comfort, and they will be dealt with later in this paper, but the first rule remains: get the warmth right and only then worry about any remaining causes of discomfort. They may well have disappeared.

2. WARMTH SENSATION

By comfort, we mean a state of satisfaction, i.e. a person is comfortable if he says he is comfortable. Comfort cannot be predicted from first principles, nor solely from a knowledge of physiology and the physics of heat loss. The prime data on comfort conditions is obtained by exposing subjects to different environments and asking them how they feel. Rohles and Nevins (1971) performed what has become the classic experiment on thermal sensation in the environment chamber at Kansas State University; 1600 subjects were exposed to 160 different combinations of temperature and humidity, and they rated their sensation of warmth on the seven point scale shown in Figure 1. Part of the data is displayed in Figure 2. It can be seen why so many subjects were needed; the variation between people is so great that it is necessary to work with large numbers of subjects to obtain meaningful averages. By performing a regression analysis on the data of Figure 2, we can say that the comfort temperature for sedentary people, wearing light clothing of insulation 0.6 clo units, in an air speed of 0.15 m/s, at 50% R.H. is 25.6^{o}C. Clearly it is out of the question to repeat the experiment for all combinations of clothing, activity, thermal radiation, humidity, air speed of interest, and some method of predicting comfort temperatures is necessary.

A more direct method of determining comfort temperature is that which has come to be associated with the Laboratory of Heating and Air Conditioning at the Technical University of Denmark. In this method a subject sits alone in an environment chamber, and maintains the chamber at his optimum temperature by requesting any necessary changes in temperature. The comfort temperature found by this technique is termed the <u>preferred</u> temperature; the comfort temperature found by regression analysis of warmth votes, as in Figure 2, is termed the <u>neutral</u> temperature. In some circumstances the two temperatures may not be the same (McIntyre 1978c).

The variables which affect a person's thermal sensation may conveniently be divided into two groups, termed the personal and the physical. The personal variables are the activity level and the degree of clothing insulation being worn. A more active person requires a lower air temperature for comfort; increased clothing also allows a lower air temperature. There are four physical variables affecting overall thermal sensation: air temperature, mean radiant temperature, air speed and atmospheric humidity. These parameters are described in more detail in the Appendix.

The engineer concerned with the indoor environment commonly wishes to describe the warmth of a space in terms of the physical variables under his control. Over the years, many comfort indices have been proposed; each index has normally reflected the interests of its originator, and so tends to have a limited range of application. It must be realised that all indices which combine the physical variables into a single index are theoretically inadequate as a predictor of warmth. In particular, the effects of air temperature (T_a, ^oC) and airspeed v (m/s) interact with clothing temperature (T_{cl} ^oC) e.g. an increase of air speed increases the feeling of warmth if $T_a > T_{cl}$, and vice versa for $T_a < T_{cl}$. Since T_{cl} is a function of metabolic rate and clothing insulation, the effects of T_a and v cannot be considered in isolation from the personal variables. The only entirely satisfactory way of tackling this problem is to deal with all variables at the same time, as has been done in Fanger's comfort equation (1972) or Gagge's derivation of Standard Effective Temperature (1972).

However, these relations are rather complex for normal use, and also make it impossible to describe the warmth of an environment without knowing about the people in it.

2.1 Subjective Temperature

To simplify the presentation of the comfort requirement for the indoor environment, we shall use a simple index that gets round some of these difficulties. The index is termed subjective temperature, and is defined as the temperature of a uniform enclosure, with $T_a = T_r$, v = 0.1 m/s and R.H. 50%, which would produce the same feeling of warmth as the actual environment. T_a and T_r are the air and mean radiant temperatures (^oC), and v is the air speed in m/s. This definition was proposed by Parcewski and Bevans (1966). It is implied that the personal variables are the same in the actual and in the standard environment. This definition is similar to that of ET* (Gagge et al., 1971), but does not imply the use of any particular model of heat loss.

Having got a convenient index, the requirements for comfort may be broken into two parts; firstly what subjective temperature, T_{sub} is needed for comfort, as a function of metabolic rate (M) and clothing insulation (I_{clo}), and secondly, what combinations of the physical variables will produce that T_{sub}.

The subjective temperature required for comfort is a function of metabolic rate (M W/m^2) and clothing insulation (I_{clo}, clo units) :

$$T_{sub} = 33.5 - 3I_{clo} - (0.08 + 0.05\, I_{clo})M \qquad (1)$$

This equation is plotted in Figure 3. This relation is derived empirically from Fanger's equation. Over the range of conditions $M < 150\ W/m^2$ and $I_{clo} < 1.5$ the error introduced by the simplification is less than ½ K (McIntyre, 1976). Equation (1) thus has no theoretical basis; it is a successful empirical approximation of Fanger's equation. Fanger's equation, in turn, has been shown to fit experimental data well.

Where a person is performing external work, not all of his free energy production appears as heat. In this case M in equation (1) should be replaced by the internal heat production H (W/m^2), where $H = (1 - \eta)M$, and η is the mechanical efficiency of the task performance. The efficiency of a task is normally low, but may rise to 0.1 for tasks such as sawing, or lifting. The maximum found is about 0.2 for uphill walking or cycling at a high metabolic rate.

For many indoor environments, air and mean radiant temperature are approximately equal, and the air speed is low; equation (1) then simply gives the air temperature required for comfort. For non standard conditions, we have to provide an expression for T_{sub} in terms of the physical variables. The following expressions were derived by McIntyre (1976b)

$$T_{sub} = 0.56\, T_a + 0.44\, T_r \quad \text{for } v \leq 0.1 \text{ m/s} \qquad (2)$$

$$T_{sub} = 0.44\, T_r + 0.56\, (5 - \sqrt{10v}(5 - T_a))/(0.44 + 0.56\sqrt{10v}) \quad \text{for } v > 0.1 \text{ m/s}$$

The equations represent a reasonable compromise between simplicity and accuracy. Equation (2) is supported by evidence from several experiments, summarised in McIntyre & Griffiths (1975b). The more general form in equation (3) is derived by assuming that at speeds above 0.1 m/s the convective loss varies as the square root of the air speed, and that the clothing surface temperature is 5 K above the subjective temperature. The derivation is similar to that given by Mackey (1944). Equation (3) has been checked against Fanger's comfort equation over the range of subjective temperatures from 18 to 28°C, within the range $0 < v < 1$ m/s and $|T_a - T_r| < 6$ K; the discrepancy between the predictions of equation (3) and Fanger's equation was always less than 0.6 K, and generally better than this. The relationship between the subjective temperature T_{sub} and the environmental variables is shown in Figure 4.

Figure 3 allows us to predict the comfort temperature for a person with known clothing and activity, and Figure 4 to ensure that the actual set of conditions combine to produce this comfort temperature. The figures have no theoretical basis; they are an empirical simplification of Fanger's comfort equation, which they fit with excellent accuracy for indoor conditions. Neither the equations, nor Fanger's comfort equation itself, allow the prediction of thermal sensation at temperatures which are not comfortable. This paper is concerned only with conditions near comfort, and the wider problem is not considered here. Several models have been proposed for the prediction of sensation; Fanger's PMV (1972) is based on an extension of the comfort equation, and Azer and Hsu developed a comprehensive thermoregulatory model for predicting thermal sensation (1978). In warm humid conditions thermal sensation and discomfort behave differently from each other; discomfort is well predicted by skin wettedness, which may be estimated by the SET (Gagge, 1972).

2.2 Comfort Range

Thermal comfort is not an exact concept, nor does it occur at an exact temperature. A person may be comfortable over a range of temperatures and if the temperature is changed so that it moves outside this range, the onset of discomfort is not sudden. There is nothing in the physiological system which behaves like a snap action thermostat. A person's reaction to a temperature which is less than perfect will depend very much on his expectations, his personality and on what else he is doing at the time. All this makes it difficult to talk precisely of a comfort range. The generally accepted convention is to treat thermal discomfort in terms of the scale of warmth sensation, and the comfort range is taken to be the three central categories of the seven point scales shown in Figure 1. On the Bedford scale, sensations of 'comfortably cool', 'comfortable' and 'comfortably warm' are taken to imply an acceptable thermal condition; the equivalent central three categories of the ASHRAE scale are also taken as a comfortable range.

An individual can only describe his sensation using one of the discrete categories of the scale. However it is legitimate when performing analysis to treat the scale as continuous, when deriving such statistics as means and standard deviations. On a continuous scale, the comfort range runs from 2.5 to 5.5 i.e. from the transition between categories 2 and 3, to the transition between categories 5 and 6.

A great amount of data has been collected giving the variation of warmth vote with temperature. Typically, a subject sits in an environmental chamber for a time, and then records his warmth sensation on a seven point scale. In most work that has been done, each subject attends only once. The data obtained may then be analysed to produce the best regression line. Figure 2 shows the regression line for seated, but not inactive, lightly clothed people. The regression line predicts the mean thermal vote of a group of people, as a function of the ambient temperature.

In Figure 2 the change of temperature corresponding to a change in mean vote from 2.5 to 5.5 is from 18.5 to 27.5^{o}C, so at first sight the comfort band is a surprising 9 K. However, this ignores the fact that there is a considerable variation between people. At the neutral temperature of the population, i.e. where the mean vote is 4, there are some people who are too hot, and some who are too cold. If the temperature moves above the optimum, the number of people feeling too hot increases rapidly. Knowing the standard deviation of the votes, which is 0.8 of a scale interval, it is possible to construct a curve showing the proportion of people uncomfortable, as a function of the mean vote. This is the well known curve of PPD (predicted percentage dissatisfied) produced by Fanger (1972), shown in Figure 5. It shows the PPD as a function of the mean votes of a population of people, all of whom have similar clothing and activity. Dissatisfaction is defined as a vote outside the central three categories. It may be noted that the curve must pass through 50% PPD at a mean vote of 2.5 and 5.5. If the mean vote is +5.5, then 50% of the population must be voting more than 5.5, and so are too hot.

The PPD curve shows that good temperature control is important when dealing with a large group of people. Even at the optimum temperature, 5% are dissatisfied. As the temperature moves away from optimum, the proportion uncomfortable rises rapidly. If we accept 10% dissatisfied as a working maximum, the temperature must be controlled within a band of ± 1½ K about the optimum.

The variation in warmth vote of a group of people at a constant temperature has two components. The first component is the between subjects variance. This is because people differ from each other; one person may consistently (on average) require a warmer temperature than another. The second component is the within subjects variance. A person is not perfectly consistent and will not necessarily feel the same in the same conditions on different occasions. Data from experiments in which each subject attends on several occasions enable us to estimate the two variances separately (McIntyre, 1978b); the results are surprising. The within subjects variance is no smaller than the between subjects variance, and both have a standard deviation of about 0.8 scale units. There is a real difference between people in their neutral temperature; some people are consistently warmer or cooler. However, this variation is smaller than the scatter produced by unexplained variation within subjects.

The causes of this variation have not been investigated in detail. Although we can control the activity of a subject, it does not follow that the metabolic rate is controlled; previous activity, recent food intake and emotional factors may all contribute to a variation in heat production or storage. Thermal sensation will also be influenced by vasomotor tone, which may vary under the influence of internal, as well as external, factors.

The fact that the within subjects variance is similar to the between subjects variance means that we can use Fanger's PPD curve unaltered to apply to a single individual. The ordinate, PPD, now becomes the percentage of occasions that one person will feel too hot or too cold as a function of temperature. At a temperature which is 4.5K below the optimum, the person's mean vote averaged over several occasions when he experiences that temperature, will be 2.5, i.e. on the borderline between comfort and discomfort. We would therefore expect the person to feel too cold on 50% of the occasions that he experiences this temperature. The comfort range of an individual is thus the same as the comfort range of a group of people. Taking 10% dissatisfied as the criterion, the range is ±1½ K on either side of the optimum.

2.3 Field Data

A group of people sitting in the same temperature, who all have similar clothing, exhibit a spread of warmth sensations. This is demonstrated in Figure 5, which shows that at best one can make 95% of the population comfortable at one time, and that the proportion uncomfortable increases rapidly as the temperature moves away from the optimum comfort temperature. The implication is that a room having a large number of people must be carefully controlled within a small temperature band around the optimum temperature.

In the real world, people do not wear standard clothing, and are free to modify the insulation value. The range of insulation of clothing acceptable in Western Europe and the U.S.A. is roughly 0.3 to 1.2. Inspection of equation (1) shows that this implies that an individual may adjust his comfort temperature over a range of 6 K, and it should therefore be possible for most people to achieve comfort indoors by suitable modification of clothing. To find out if this happens, we must turn to the results of field surveys.

If people are making behavioural adjustments to compensate for a change in temperature, they will act so as to reduce their thermal discomfort, and the slope of the regression line of warmth vote against temperature will be reduced below the value found in laboratory studies. Many studies carried out in environment chambers have consistently found that the rate of change of warmth sensation on a seven point scale with respect to temperature is 0.33 su/K, where su stands for scale units. Table 1 gives the regression coefficients listed by Humphreys (1976) in his important study of the results of thirty-three separate field surveys. It appears that people in real life compensate slightly for short term changes in temperature, presumably by changing clothing, and so reduce the regression coefficient to 0.23 su/K. This figure is the average of the coefficients obtained for the different studies, and thus represents the rate of change of sensation one would expect to find for a group of people in an office as the temperature changed from day to day. The position changes remarkably when long term effects are considered, and a regression of all the votes from all the surveys on temperature shows them hardly to be affected by temperature at all. This phenomenon is shown in Figure 6 where the neutral temperature for each survey is plotted against the mean temperature of the whole survey; each point thus represents the findings of a whole survey. It can be seen that the people have been remarkably successful in adjusting to their surrounding temperature. However, this adjustment seems to take some time to accomplish, since in any particular building a deviation from the neutral temperature occurring from day to day will produce feelings of warmth, cold and perhaps discomfort. The more extreme adjustments at the ends of the range may well take generations to accomplish since they involve whole patterns of life style and buildings, as well as dress. It should not, therefore, be deduced from Figure 6 that any temperature will do. Rather, the temperature provided in a building should be consistent with the local climate and culture, and should also be steady from day to day. A temperature that changes unpredictably from day to day does not allow people to wear appropriate clothing. It was noted by Humphreys (1976) that air conditioned offices, with a very steady temperature, were successful in achieving high levels of satisfaction with the temperature.

The very wide range of neutral temperatures shown in Figure 6 cannot be completely explained by clothing adjustment alone. Two possibilities suggest themselves: it is possible that people adapt to an extreme temperature in such a way that comfort corresponds to a different physiological state, so that the people who are comfortable at 34^{o}C have a different bodily state from those who are comfortable at 18^{o}C. The other possibility is that the meaning of the words of the seven point warmth scale change their meaning with a change in climate, so that people in a warm climate may wish to be 'comfortably cool', while those in a cold climate may wish to be 'comfortably warm'; this implies that the neutral temperature of Figure 6 may not in fact represent the ideal temperature. There is some evidence to support this point of view (McIntyre, 1978c), but the position cannot yet be said to be resolved.

3. NON-THERMAL FACTORS

The first section of this paper showed how the mean comfort temperature of a group of people can be predicted from a knowledge of their activity and clothing, and how this temperature is modified by thermal radiation and air speed. Several other factors might be expected to affect comfort temperature, and these are dealt with in the following section.

3.1 Age and Sex

There is little evidence to suggest that healthy old people require a different temperature from young people. Basal metabolic rate decreases with age, but this is fortuitously compensated by a decrease in insensible evaporation (Fanger, 1972). Experimental studies have not found any important difference between the comfort temperatures of young and old people (Fanger, 1972), Griffiths and McIntyre, 1973, Rohles and Johnson, 1972); the samples included people up to and over seventy years of age.

Surveys of old people admitted to hospital have shown an appreciable number with low body temperatures, and hypothermia in the elderly is recognised as a potential risk to life. It would appear that there is not a systematic shift of comfort or thermoneutral temperature with age. Rather, it seems that the ageing process results in a deterioration of both behavioural and physiological thermoregulation, which, particularly if coupled with poverty or social isolation may lead to the old person living in too low a temperature, with a consequent fall in deep body temperature.

Children have a higher basal metabolic rate per unit surface area than adults, and this does seem to lower their comfort temperature. Humphreys (1977) found that primary school children, aged between 7 and 9 years, generally felt rather warm in school, but there seemed little relationship between mean warmth and mean classroom temperature; however, over a period of some days warmth sensation did follow variations in classroom temperature. Humphreys recommended a temperature in the range 19-21^{o}C for general classwork, which encompasses a range of sedentary and standing activities.

There is no a priori reason why men and women should have the same comfort temperature; the metabolic rate per unit surface area tends to be lower for women than for men, and there are other physiological differences in temperature regulation. Nevertheless laboratory experiments in which men and women wear standard clothing have not shown any important difference in comfort temperature between the sexes (Rohles and Nevins, 1971; Fanger and Langkilde, 1975). It has, however, consistently been found that the slope of the regression of warmth vote on temperature is greater for women than for men, i.e. women are more sensitive to temperature changes away from the comfort temperature (McIntyre, 1978b).

Several surveys have found that in offices women tend to wear lighter clothing than men, particularly in summer (Gagge and Nevins, 1977), and this may be reflected in a higher comfort temperature. In practice, there is no need to differentiate between the sexes for comfort temperature.

3.2 Climate, Season, Time of Day

There are definite physiological adaptions to heat and cold in man. People moving to hot climates show changes in sweating response, and there are parallel, though less marked, changes in shivering and vasoconstrictive responses in people exposed regularly to cold.

There does not appear to be any change in preferred temperature produced by long term exposure to heat or cold. Several studies in Denmark have failed to find any variation of the mean preferred temperature of groups of cold store workers, winter swimmers or dwellers in the tropics (Fanger et al., 1976). However, the results of Humphreys (1976) survey of field studies found a de facto alteration of neutral temperature with prevailing climate. The possible implications of this were discussed above.

The same findings apply to the effects of season, and laboratory studies have generally failed to find any difference in warmth sensation between times of year (McNall et al., 1968).

Bodily functions show a definite 24 hour rhythm. Deep body temperature swings by about 0.7 K between night and day, and one would expect this to be reflected in a change in preferred temperature. There is no suggestion that this happens, and determination of preferred temperature throughout a 24 hour period found no significant variation (Fanger et al., 1974). Kansas State University found no difference between afternoon and evening (Nevins et al., 1966).

Shortening the time scale still further, it seems that the temperature which the subjects experience before an experiment has no effect on their sensation during the actual session. McIntyre (1975b) showed that half an hour's exposure to either 28 or 19°C had no influence on a person's preferred temperature measured over the next 2 hours. Similarly Rohles and Wells (1977) found that 1 hour's exposure to 16^{o} or 32^{o}C produced no effect on warmth vote when the subjects returned to a 23^{o}C standard condition; the warmth sensation returned to normal after only 5 minutes. A rather more extreme experiment by Gagge et al., (1967) exposed nude subjects to a comfortable (29^{o}C) room for 1 hour, and then transferred them to a cold (17.5^{o}C) room for 2 hours. After this period they returned to the 29^{o}C room. Their thermal sensation returned to neutral very quickly, long before skin and rectal temperatures had returned to normal.

3.3 Surroundings

Many claims have been put forward for the effects of colour on various aspects of man's feelings. In particular, it has often been suggested that the use of 'warm' colours in a room would allow a lower air temperature to be used for comfort. This has never stood up to experimental test. While a person might well prefer 'warm' colours in winter, colour does not affect thermal sensation (Bennett, 1972; Fanger et al., 1977). These results agree with the general finding that man's thermal sensation as a function of ambient temperature is little affected by extraneous variables. For instance, Griffiths and McIntyre (1975) found that mental concentration while performing a difficult reasoning task had no effect on either neutral or preferred temperature; in the experiment questions were asked about both sensation and preference, to deal with the possibility that the subjects might feel the same sensation while concentrating, but might prefer a change in sensation. In another experiment at ECRC (McIntyre and Griffiths, 1974) it was found impossible to bias the warmth vote of subjects by giving them false information about temperature changes. Recently, however, Rohles and Wells (1977) noticed a difference in warmth vote when subjects experienced the same temperature in different chambers. They followed up this observation with a further experiment and found that a chamber furnished with carpet, panelled walls and soft lighting, produced a higher warmth vote from the subjects than the same chamber with bare walls and fluorescent lighting. The difference in neutral temperature, estimated from the results on a nine point warmth scale, was 1.3 K.

4. CAUSES OF DISCOMFORT

So far we have dealt with those factors which influence a person's feeling of warmth. It is emphasised again that warmth and cold are the dominant sensation influencing thermal comfort. There is, for instance, little profit in worrying about the humidity level if the temperature is wrong. However, once the temperature is right, a person may still be uncomfortable, and we now consider what other factors might cause discomfort.

4.1 Radiation Draughts

It may be that a room which is comfortable over most of its area contains low temperature surfaces which cause discomfort to people nearby, by producing an excessive radiation loss from one side of the body. The most common instance is, of course, the 'radiation draught' felt when sitting near a cold glass surface.

Two experiments have dealt with this problem. Anquez and Croiset (1969) treated the problem directly, with subjects sitting in front of a cold window. Olesen et al. (1972) worked with unclothed subjects, but extended their results to deal with clothed subjects. It was shown by McIntyre (1975a) that if the findings of the two experiments are expressed in terms of the thermal radiation field, they show very good agreement, and the findings can be expressed as follows:

Discomfort will be experienced at positions where the plane radiant temperature facing the cold surface is more than 8 K below the mean radiant temperature in the main part of the room remote from the window. This applies to normal indoor conditions with low air speed and normally clothed people, and it is assumed that the rest of the room is comfortable.

This recommendation takes into account both general cooling, due to the reduction of mean radiant temperature (m.r.t.) near the window and the additional discomfort from local cooling on one side of the person.

The recommendation may be rewritten quantitatively as

$$F_{pg}\ (T_r - T_g) + F_{pw}\ (T_r - T_w) < 8 \tag{4}$$

F_{pg} form factor, plane element at test point to window

F_{pw} form factor, plane element at test point to wall

T_g temperature of window

T_w temperature of wall

The form factor is defined as the fraction of radiation leaving the element that reaches the other surface. Expressions for form factor are to be found in standard books on radiation transfer, and are also quoted in McIntyre (1975a). Other surface temperatures are assumed to be equal to T_r, the mrt in the room.

For design British conditions, when the outside temperature is $-1^{\circ}C$ we may take T_g to be $7.5^{\circ}C$ for single glazing; the inside wall temperature is $18^{\circ}C$, and $T_r = 22^{\circ}C$. Figure 7 shows the distance from the centre of a rectangular window which just satisfies equation (4).

4.2 Asymmetric Radiation

Most radiant heating systems produce a radiant environment that is asymmetric, to a greater or lesser degree. High levels of asymmetry may be disliked by the occupants, and it is necessary to set some sort of standard. The first step, of course, is to ensure that the heating system produces a thermally neutral environment; any problems from asymmetry will be magnified if the temperature is incorrect.

The degree of asymmetry may be quantified by the vector radiant temperature (v.r.t.) T_v. This quantity may be visualised as the difference between the average surface temperatures of opposite halves of the room. It is defined in the Appendix. Several workers have tackled the problem of relating discomfort to degree of asymmetry (McNall and Biddison, 1970; Olesen et al., 1972). It appears that a vector radiant temperature from ceiling heating of 20 K does not worsen the comfort vote of a group of people when they are asked to rate their discomfort in separate experiments. However, the subjects can detect the asymmetry, and it was found (McIntyre, 1977a) that they tended to blame the heated ceiling for causing discomfort, even though their average discomfort did not worsen when compared with a uniform environment. To be on the safe side, it is recommended that the vrt should not exceed 10 K.

When designing panel heating, it is sufficient to assume that all unheated room surfaces are at the same temperature. We can then write down relations of the m.r.t. and v.r.t. at a point in the room:

$$T_v = F_{pc} (T_c - T_u)$$

$$T_r = F_{sc} T_c + (1 - F_{sc}) T_u$$

F_{pc} form factor, plane element to ceiling

F_{sc} form factor, small sphere to ceiling

T_c ceiling temperature

T_u temperature of unheated room surfaces

The form factors are geometrical functions of the positions of the test point and the hot panel. The questions have been solved for a point under the centre of an overhead panel, and the results are shown in Figure 8.

Heated ceilings are not the only sources of overhead radiation; lighting installations may contribute thermal radiation. Measurements have shown that the illuminance and irradiance are directly related (McIntyre, 1976a), and the illuminances which produce a v.r.t. of 10 K are:

850 lux for tungsten filament lamps
4000 lux for de luxe warm white fluorescent
8000 lux for white fluorescent lamps

Radiation from fluorescent lamps is therefore unlikely to cause trouble, but tungsten filament lamps produce a considerable amount of thermal radiation.

4.3 Temperature Variations

Experiments which have exposed people to slowly changing temperatures have generally found that the mean warmth vote of a group of subjects corresponds to the instantaneous temperature, and is not affected systematically by the direction or rate of change of temperature (Griffiths and McIntyre, 1974; Berglund and Gonzalez, 1977). Nevins et al., (1975) used a cyclic change of temperature, with amplitude 10 K and a rate of change as high as 18 K/hr. The subjects rated their sensation on a seven point warmth scale, and the rate of change of sensation with respect to temperature was 0.3 scale units/K, which is only slightly less than the figure for steady temperatures. In general, then, warmth sensation is determined by the instantaneous temperature, with little effect from rate of change of temperature. It is therefore possible to use the PPD of Figure 5 when dealing with changing temperatures. In real life, people generally have the opportunity to alter their clothing insulation to compensate for changes in temperature, but there is not much evidence that they do this in the short term (Humphreys, 1976).

There is no doubt that at times a change in sensory stimulation is pleasurable, and this has been demonstrated experimentally by Haber (1958), but only for the rather restricted case of finger temperature. Temperature variation, as a pleasurable stimulus, and as a relief from 'temperature boredom' has its advocates (Gerlach, 1974), but as yet there is little convincing evidence of its desirability. Wyon et al., (1973) measured performance on mental tasks during temperature swings. Small swings of amplitude, 2 K at head level, were found to reduce arousal and depress performance. Larger swings increased arousal and restored performance back to normal. However, the large swings were found to be uncomfortable, and Wyon concluded that there was little argument for any beneficial effects of temperature swings.

4.4 Humidity

The effect of humidity on warmth is strongest at high air temperatures where a person is sweating, and consequently above his comfort temperature. The effect of humidity on comfort temperature is small; Fanger's comfort equation predicts that a change in RH from 20% to 75% would produce a reduction in preferred temperature by 1 K. Such a small effect would be difficult to detect, and experimental investigations of warmth have not shown any significant effects of humidity on warmth at steady air temperatures below about 23°C (Rohles and Nevins, 1971; Andersen et al., 1973; McIntyre, 1978d).

It is quite clear that at high air temperatures, high humidities increase both warmth and discomfort. At comfortable air temperatures, any effect of humidity on warmth is negligible; this leaves the question of whether humidity may affect comfort in other ways. Low humidities, which may occur in winter in heated buildings, are commonly held to dry the nose and skin, producing complaints of sore throats and headaches. The experimental evidence on the effects of low humidities has not yet achieved a consistent body of findings. Inhibition of mucus flow in the nasal passages at low humidities was demonstrated by Ewert (1965), yet careful experiments by Andersen (1974) failed to confirm it. Several experiments have found low (< 30%) humidities to be less comfortable than medium levels (Andersen et al., 1974; Carleton and Welch, 1971; McIntyre, 1978d) but have not always been confirmed. There is suggestive evidence that it is a combination of low humidity and atmospheric pollutants (e.g. tobacco smoke) which produces the ill effects, and so well controlled experiments eliminate the discomfort when eliminating pollutants.

The question of whether there is an upper limit for humidity at comfortable air temperatures has received less attention. There is no support for the belief in the ill effects of 'damp cold'; at low air temperatures, high humidities have no detectable effect on heat loss or warmth. If a person's activities are variable enough to produce occasional sweating, then the effect of high humidities in inhibiting sweat evaporation may be noticeable. Clothing kept in high humidities will absorb moisture, and the latent heat required to evaporate this after putting on the garment may produce a sense of chill. The arguments against high humidity in buildings lie elsewhere. Prolonged humidities above 70% encourage the growth of moulds, which, once established, are very difficult to eradicate.

There is epidemiological evidence to link the incidence of colds with low humidities. Much of the work (Green, 1974) has been in countries where the outside air temperature, and consequently indoor relative humidity, falls to values far below those found in Britain. The evidence shows an increase in incidence of infection as the RH falls from 40% to 20%.

At low humidities the act of walking on a carpet is able to charge a person to a potential of several kilovolts, and this can produce an unpleasant electrostatic shock when an earthed object is touched. A review by Brundrett (1977) showed that for most carpet materials the problem only occurs at relative humidities below 40%.

A range of humidities from 40% to 70% will prove acceptable at comfortable air temperatures, both from the point of view of comfort and other considerations.

Higher humidities bring the risk of condensation and mould growth. Lower humidities may be felt as uncomfortable, and increase the generation of static electricity. Occasional excursions down to 30% should not be troublesome.

4.5 Floor Temperature

Where people walk barefoot, floor temperature has an important effect on local comfort. Olesen (1977) investigated people's perception of floor temperature; the subjects were lightly clothed, and in general thermal comfort. As might be expected, the thermal conductivity of the floor had an important effect on comfort of bare feet; the lower the conductivity of the floor material, the wider the range of temperatures that were tolerated. Table 2 shows his recommended ranges of floor temperature, based on experiments with 10 min exposure, and with the limit taken to be 15% dissatisfied.

When people are normally shod, the flooring material turns out to have little importance. Olesen found an optimum floor temperature of 23°C for standing people, with a permitted range from 20-28°C, corresponding to 8% uncomfortable; this is a less stringent criterion of discomfort than adopted for bare feet, and suggests that floor temperature is of little importance. The results from Nevins et al. (1964) were included in the analysis.

The experiment by Chrenko (1957) and general British experience with underfloor heating suggest that Olesen's limits err on the high side, and for prolonged occupation the recommended maximum floor temperature is 25°C, with excursions up to 27°C permitted. While this is only apparently a small difference from Olesen's recommendation, it is of considerable engineering importance, since it is difficult to provide sufficient heat transfer to a heated room at low floor temperatures.

Time of exposure is important. A floor temperature that is initially pleasantly warm may, over a few hours, produce unpleasant local vasodilatation. Burton (1963) warned strongly against the danger of overheating the feet.

Cold floors are usually associated with vertical gradients of air temperature. Experience indicates that where the general room air temperature is a comfortable 22°C, a reduction in air temperature at foot level by 3 K or more will produce discomfort. Current research at the Gas Corporation laboratories in England and at the Danish Technical University should provide further data.

4.6 Air Movement

The effect of general air movement on feelings of warmth has been discussed above. In warm conditions, air movement may be employed to reduce discomfort. The disturbance of an air movement above 0.5 or 1 m/s in itself can cause annoyance, so that people given a free choice of air speed tend to under-compensate for a raised air temperature, and act to minimise the combined discomfort of warmth and air movement (McIntryre, 1978e).

The more general problem is that of localised air movement in an otherwise comfortable environment i.e. the problem of draughts. Some sort of air movement is inevitable in an air conditioned or mechanically ventilated building. Strong draughts, above about 0.4 m/s, are usually very localised, and caused by faulty design or commissioning of the system. Surveys of buildings have demonstrated a number of typical draught producing situations (Dickson, 1977). At the other end of the speed range, it is common to find complaints of draughts where there is very little air movement; usually the effect of a low floor temperature has been misinterpreted as a draught.

The specification of comfort limits for draughts has proved difficult, and is not yet completely resolved. By virtue of the natural convection loss from the body, a person produces a rising layer of warm air flowing over the head. The speed of the flow depends on the difference between body surface temperature and air temperature, but is typically 0.2 m/s; the boundary layer may be several cm in thickness (Lewis et al., 1969). Since draughts have about the same velocity as this protective layer, there is a rather complex interaction between the two. In laboratory experiments on sensitivity to air movement it is possible either to expose the subject to a free air jet (e.g. McIntyre, 1978a) or else to duct the moving air to within a few cm of the skin surface, and consequently lead it through the boundary layer (e.g. Pedersen, 1977). Experiments with a ducted draught have generally found lower discomfort thresholds than those using a free jet.
McIntyre (1978) found a 30 minute exposure to a draught of 0.25 m/s on the face to be rated significantly worse than one of 0.15 m/s; ambient and draught temperatures were both 21°C. A speed of 0.2 m/s was no worse than 0.15 m/s, and seemed quite acceptable. This agrees with the findings of Houghten et al., (1938); however Pedersen (1977) found that over 20% of his subjects would find

this speed uncomfortable. Our general experience of air movement in offices indicates that a speed of 0.2 m/s is acceptable at head level (Dickson, 1977).

In practice, air movement varies with both time and position, and it is not possible to describe a draught by speed and temperature alone. Pedersen (1976) found a greatly increased sensitivity on the part of his subjects when the air speed varied regularly; a frequency of 0.3 Hz gave the greatest effect. At this frequency a draught of temperature 22^{o}C and mean speed 0.05 m/s was found uncomfortable by 20% of subjects. It seems unlikely that people would respond unfavourably to a free jet of this magnitude.

4.7 Non-specific Symptoms

In each of the above sections, the effect on comfort of a single physical factor has been discussed. The effects have been studied in the laboratory by varying the magnitude of the physical factor, and asking about symptoms in the subjects. In the field, the position is reversed. The symptoms are there, and the researcher has to try and identify the cause. We have often heard complaints of 'stuffiness' or 'lack of oxygen' from the occupants of air conditioned offices, in situations where measurements of air quality showed nothing wrong. Other symptoms, such as headaches, tiredness or drowsiness, may be blamed on the environmental system. The problem is widespread, and various cures have been proposed, such as negative ionisation or electric fields; these systems have not been generally accepted. Research is needed to investigate these non-specific discomforts, and find if they can be related to environmental factors.

5. DISCUSSION

Most of the recommendations given in this paper imply that if the strength of a potentially uncomfortable stimulus is increased, there comes a point when the person experiencing it finds it no longer acceptable. However, in reality, a person's decision as to whether the stimulus is unacceptable depends on more factors than its strength. Clothing and physical activity have an important effect; in general they act to reduce a persons's sensitivity to a stimulus, but study of this topic is only beginning (McIntyre and Gonzalez, 1976). There are other, less quantifiable factors. Mental activity will determine how much attention will be paid to a thermal stimulus; a minor discomfort will go unnoticed if there are more important matters to be attended to. Judgements of acceptability are greatly affected by context. A gentle stroll across the office produces a self-inflicted draught well in excess of any comfort recommendation, and a coal fire flouts every guideline on discomfort from thermal radiation.

Poulton (1977) warns strongly of the dangers of quantitative subjective assessments, pointing out that subjective ratings of a stimulus depend on the range of stimuli experienced. He gives examples of judgements of 'noisiness', and concludes that whatever the range of noise a person is exposed to, he will rate the loudest noises as 'too loud'. This may provide some crumb of comfort to air conditioning engineers who find that standards of expectation seem to rise just as fast as the standard of air conditioning.

Thermal sensation judgements behave more reliably than evaluative judgements, and it is possible to display information on the spread of sensation of a group as in Figure 5. The PPD curve makes the assumption that anyone voting outside the central three categories is dissatisfied. This may not be so, and where it has been tested (Berglund and Gonzalez, 1978) the ratings of 'unacceptability' did not coincide with the PPD criterion. When asking subjects to give ratings of discomfort or unacceptability, the precise wording of the question and the manner of asking it may have an important effect on the answer. There is the danger that techniques producing consistent results may unwittingly introduce bias. In an experiment on ceiling heating (McIntyre, 1977a) the subjects produced quite different answers to the two questions 'How uncomfortable are you?' and 'Is the heat from the ceiling causing you any discomfort?'. The subjects were ready to ascribe discomfort to the heated ceiling whether or not its temperature was raised.

The comfort criteria in this paper have been collected from a wide range of published papers, and so inevitably include different assumptions of what constitutes 'unacceptable' discomfort. In the future, attention must be paid to this problem, so that criteria of unacceptability may be set in the context of the experience of the group to which they apply.

APPENDIX

ENVIRONMENTAL VARIABLES

The main body of this paper has described comfort criteria in terms of the various variables describing the environment. Further notes on their definition, and tables of typical values are given in this appendix.

Metabolic rate

The activity level of a person is described quantitatively as his metabolic free energy production $M(W/m^2)$; note that it is conventionally expressed in terms of unit body surface area. Some of this energy may be used to perform external work, but most is lost as heat from the body. The metabolic rate of a person may be estimated by measuring his rate of oxygen consumption. A great deal of information is available in the literature on the metabolic rate associated with different activities. A list of activities is shown in Table 3.

Clothing insulation

The thermal insulation of clothing acts as a barrier between skin and air, and so allows man to be comfortable in cool air temperatures. The insulation is expressed quantitatively in clo units, where one clo corresponds to a thermal resistance of 0.155 m^2K/W. The resistance is measured from the inner to the outer surface of the clothing, and does not include the thermal resistance of the external air film. The clo unit was introduced towards the beginning of the last war (Gagge et al., 1941) to provide an easily understood descriptive unit: 1 clo unit was the insulation value of the contemporary European business suit. Clothing has become lighter since, and Table 4 gives a list of the clo values of some typical ensembles. The values are obtained from measurements made on a heated mannikin (Seppanen et al., 1972), or on a person in vivo (Nishi et al., 1975). Sprague and Munsen (1974) give details of a method by which the insulation value of an ensemble may be estimated from a description of the individual garments.

Air temperature and speed

The description and measurement of air temperature presents few problems, though it is necessary to use an aspirated thermometer to avoid errors in the presence of thermal radiation. The description of air speed is more difficult, since air movement is notoriously variable in both space and time. An anemometer of the heated sphere type is the most useful, since it gives a non-directional measure of the general cooling effect of the air motion.

Mean Radiant Temperature

The mean radiant temperature (m.r.t.) is defined as the temperature of a uniform enclosure with which a small sphere at the test point would have the same radiation exchange as it would have in the real environment. In a non-uniform enclosure, the m.r.t. varies with position, and the term <u>test point</u> is used to describe the position of interest. When the surroundings consist of i surfaces, each of temperature T_i, the m.r.t. is given by

$$T_r = \Sigma F_{si} T_i$$

so long as the T_i do not differ by more than about 20 K from ambient; if they do, the weighted average of the fourth powers of the absolute temperatures should be used. F_{si} is the form factor from the small sphere to the ith surface, i.e. the fraction of radiation leaving the sphere which reaches the surface.

The effect of small high temperature sources on the m.r.t. is more easily dealt with by a different method, since a source such as a bar fire or infra red lamp presents neither a simple shape nor uniform temperature, making both F and T difficult to evaluate. If the source contributes an irradiance E W/m^2 at the test point, this increases the mean radiant temperature at that point by

$$\Delta T_r = E/(16 \sigma T_r^3)$$

At normal temperatures it is sufficient to use the approximation

$$\Delta T_r = 0.043 E \quad (K)$$

This is accurate for small ΔT_r; the error increases to about 5% for $\Delta T_r = 20$ K. The value of the irradiance may be obtained from the manufacturer's data, or measured with a radiation thermopile.

Plane Radiant Temperature

The plane radiant temperature is the surface temperature of the inside of a uniform hemisphere which produces the same irradiance on a small plane element at the test point as exists in the real environment. The element lies in the basal plane of the hemisphere. Plane radiant temperature is a function of direction as well as position; the direction is specified by the outward normal to the test element. The irradiance E (W/m^2) is the total radiant energy falling on a surface per unit area; it is not the radiant exchange, and is independent of the temperature of the surface.

When the surroundings consist of i surfaces of temperature T_i,

$$T_{pr} = \Sigma F_{pi} T_i$$

As before, the fourth power law must be used if the temperatures differ by more than about 20 K from ambient. F_{pi} is the form factor from a small plane element to the ith surface.

The plane radiant temperature is simply related to the irradiance E by

$$E = \sigma T_{pr}^4$$

The irradiance and hence the plane radiant temperature, is readily measured using a net radiometer fitted with a reference cavity.

Vector Radiant Temperature

At other times it is necessary to describe the asymmetry of the radiation environment. Consider a small plane element at the test point. The plane radiant temperature seen by the front surface is denoted by T_{pr1}, and that by the rear surface by T_{pr2}. If the element is now pointed in different directions it is found that $(T_{pr1} - T_{pr2})$ has a maximum value in a unique direction. The normal to the element is now pointing along the direction of flow of radiant energy, and the value of $(T_{pr1} - T_{pr2})$ is the vector radiant temperature T_v. This quantity has both magnitude and direction, and is a vector quantity, obeying the laws of vector addition. The vector radiant temperature is the difference between plane radiant temperatures in opposite directions and is therefore easily visualised as the average surface temperature of one half of a room minus the average of the other half. The equivalent of the vector radiant temperature in units of power is the radiation vector, alternatively known as the differential radiant flux. The radiation vector $R(W/m^2)$ is the difference in irradiance on opposite sides of a plane element.

$$T_v = R/(4\sigma \ T_r^3)$$
$$= 0.17R \text{ at room temperature}$$

The radiation vector is easily measured with a net radiometer. The above concepts are discussed in detail by McIntyre (1974).

ANDERSEN, I., LUNDQVIST, G. R. AND PROCTOR, D. F.
Human perception of humidity under four controlled conditions. Arch. Environ. Health, 26: 22-27, 1973.

ANDERSEN, I., LUNDQVIST, G. R., JENSEN, P. L. AND PROCTOR, D. F.
Human response to 78 hr exposure to dry air. Arch. Environ. Health, 29: 319-324, 1974.

ANQUEZ, J AND CROISET, M.
Thermal comfort requirements adjacent to cold walls - application to glazed opening. NBS-TN-710-4. May 1972. US Dept. of Commerce, Washington DC.

AZER, N. Z. AND HSU, S.
The prediction of thermal sensation from a simple model of human physiological regulatory response. ASHRAE Trans. 83: (2) 88-102, 1977.

BANHAM, R.
Architecture of the well-tempered environment. Architectural Press, London 1969.

BENNETT, C. A.
What's so hot about red? Human factors 14: 149-154, 1972

BERGLUND, L. G. AND GONZALEZ, R. R.
Application of acceptable temperature drifts to built environments as a mode of energy conservation. ASHRAE Trans. 84 (1): 110-121, 1978.

BILLINGTON, N. S.
The warmth of floors - a physical study. J. Hyg. (Camb.) 46: 445-450, 1948.

BRUNDRETT, G. W.
A review of the factors influencing electrostatic shocks in offices. J. Electrostatics 2: 295-315, 1976.

BURTON, A. C.
The pattern of response to cold in animals and the evolution of homeothermy in temperature: Its Measurement and Control in Science and Industry, Vol. 3 Part 3 Biology and Medicine, ed. J. D. Hardy, Reinhold, New York 1963.

CARLETON, W. M. AND WELCH, B. E.
Fluid balance in artificial environments. USAF School of Aerospace Medicine. NASA Report CR-114977, 1971.

DICKSON, D. J.
Air movement in offices. ECRC/N1012, Electricity Council Research Centre, 1977.

EWERT, G.
On the mucus flow rate in the human nose. Acta Otolaryng. (Stockholm) 200: Supp. 21, 1965.

FANGER, P. O.
Thermal Comfort. McGraw-Hill, New York, 1972.

FANGER, P. O.
The influence of age, sex, adaptation, season and Circadian rhythm on thermal comfort criteria for men. Annexe 1973-2 au Bulletin de L'Institut International du Froid, pp. 91-97. Proceedings of meeting of Institut International du Froid (Commission E1) in Vienna 1973.

FANGER, P. O., BREUM, N. O. AND JERKING, E.
Can colour and noise influence man's thermal comfort? Ergonomics 20: 11-18, 19

FANGER, P. O., HØJBJERRE, J. AND THOMSON, J. O. B.
Can winter swimming cause people to prefer lower room temperatures? Int. J. Biometeorol. 21: 44-50, 1977.

FANGER, P. O. AND LANGKILDE, G.
Inter-individual differences in ambient temperature preferred by seated persons. ASHRAE Trans. 81 (2): 140-147, 1975.

FANGER, P. O., OSTBERG, O., NICHOLL, A. G. McK., BREUM, N. O. AND JERKING, E.
Thermal comfort conditions during day and night. Europ. J. Appl. Physiol. 33: 255-263, 1974.

GAGGE, A. P., BURTON, A. C. AND BAZETT, H. C.
A practical system of units for the description of the heat exchange of man with his thermal environment. Science N.Y. 94: 428-30, 1941.

GAGGE, A. P. AND NEVINS, R. G.
Effect of energy conservation guidelines on comfort, acceptability and health. Thermal analysis - Human Comfort - Indoor environments. National Bureau of Standards Special Publication 491. US Dept. of Commerce, Washington, 1977.

GAGGE, A. P., NISHI, Y. AND GONZALEZ, R. R.
Standard effective temperature. Conseil International du Batiment, Commission W. Symposium: Thermal Comfort and Moderate Heat Stress, Watford, Sept. 1972. Published HMSO, London, 1973.

GAGGE, A. P., STOLWIJK, J. A. J. AND HARDY, J. D.
Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environmental Research, 1: 1-20, 1967.

GAGGE, A. P., STOLWIJK, J. A. J. AND NISHI, Y.
An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Trans. 77 (1): 247-262, 1971.

GERLACH, K. A.
Environmental design to counter thermal boredom. J. Arch. Res. 3: 15-19, 1974.

GREEN, G. H.
The effect of indoor relative humidity on absenteeism and colds in schools. ASHRAE Trans. 80 (2): 131-141, 1974.

GRIFFITHS, I. D. AND McINTYRE, D. A.
The balance of radiant and air temperatures for warmth in older women. Environmental Research, 6: 382-388, 1973.

GRIFFITHS, I. D. AND McINTYRE, D. A.
Sensitivity to temporal variations in thermal conditions.
Ergonomics, 17: 499-507, 1974.

GRIFFITHS, I. D. AND McINTYRE, D. A.
The effect of mental effort on subjective assessments of warmth. Ergonomics 18: 29-33 1975.

HABER, R. N.
Discrepancy from adaptation level as a source of affect. J. Exp. Psychol. 56: 370-375, 1958.

HOUGHTEN, F. C., GUTBERLET, C. AND WITKOWSKI, E.
Draft temperatures and velocities in relation to skin temperature and feeling of warmth. Trans. ASHVE, 44: 289-308, 1938.

HUMPHREYS, M. A.
Field studies of thermal comfort compared and applied. Building Services Engineer, 44 (April) 5-23 & 27, 1976.

HUMPHREYS, M. A.
A study of the thermal comfort of primary school children in summer.
Building and Environment, 12: 231-239, 1977.

LEWIS, H. E., FOSTER, A. R., MULLEN, B. J., COX, R. N. AND CLARK, R. P.
Aerodynamics of the human micro-environment. Lancet, i: 1273-1277, 1969.

McINTYRE, D. A.
The thermal radiation field. Building Science, 9: 247-262, 1974.

McINTYRE, D. A.
Radiation draughts. Building Services Engineer, 43: 136-139, 1975(a).

McINTYRE, D. A.
Determination of individual preferred temperatures. ASHRAE Trans. 81 (2): 131-139, 1975(b).

McINTYRE, D. A.
Radiant heat from lights. Lighting Research & Technology, 8: 121-128, 1976(a).

McINTYRE, D. A.
Subjective temperature. A simple index of warmth. ECRC/M916, Electricity Council Research Centre, 1976(b).

McINTYRE, D. A.
Sensitivity and discomfort associated with overhead thermal radiation.
Ergonomics, 20: 287-296, 1977(a).

McINTYRE, D. A.
Overhead radiation and comfort. Building Services Engineer, 44: 226-234, 1977(b).

McINTYRE, D. A.
Draughts on the face. ECRC/M1119, Electricity Council Research Centre, 1978(a).

McINTYRE, D. A.
Seven point scales of warmth. Building Services Engineer, 45: 215-226, 1978(b).

McINTYRE, D. A.
Three approaches to thermal comfort. ASHRAE Trans. 84 (1): 101-109, 1978(c).

McINTYRE, D. A.
Response to atmospheric humidity at comfortable air temperatures: a comparison of three experiments. Ann. Occ. Hyg. (in press) 1978(d).

McINTYRE, D. A.
Preferred air speeds for comfort in warm conditions. ASHRAE Trans 84 (2) to be published, 1978(e)

McINTYRE, D. A. AND GONZALEZ, R. R.
Man's thermal sensitivity during temperature changes at two levels of clothing insulation and activity. ASHRAE Trans. 82 (2): 219-233, 1976.

McINTYRE, D. A. AND GRIFFITHS, I. D.
The effect of dummy and real controls on thermal comfort and perceived warmth, ECRC/N761, Electricity Council Research Centre, 1974.

McINTYRE, D. A. AND GRIFFITHS, I. D.
Subjective responses to atmospheric humidity. Environmental Research, 9: 66-75, 1975(a).

McINTYRE, D. A. AND GRIFFITHS, I. D.
The effect of uniform and asymmetric radiation on comfort. Clima 2000. III-03, 1-22. 6th International Congress of Climatistics, Milan 1975(b).

MACKEY, C. O.
Radiant heating and cooling, Pt. II. Cornell University Engineering Expt. Station Bulletin No. 33, 1944.

McNALL, P. E. AND BIDDISON, R. E.
Thermal and comfort sensations of sedentary persons exposed to asymmetric radiant fields. ASHRAE Trans. 76(1): 123-176, 1970.

McNALL, P. E., RYAN, P. W. AND JAAX, J.
Seasonal variation in comfort conditions for college-age persons in the Middle West. ASHRAE Trans. 74 (1): IV. 2. 1-9, 1968.

NEVINS, R. G. AND FEYERHERM, A. M.
Effects of floor surface temperature on comfort. Part IV Cold floors. ASHRAE Trans. 73 (2): III.2.1-8, 1967.

NEVINS, R. G., GONZALEZ, R. R., NISHI, Y. AND GAGGE, A. P.
Effects of changes in ambient temperature and level of humidity on comfort and thermal sensations. ASHRAE Trans. 81 (2): 169-182, 1975..

NEVINS, R. G., MICHAELS, K. E. AND FEYERHEM, A. M.
The effect of floor surface temperature on comfort. Parts I and II. ASHRAE Trans. 70: 29-43, 1964.

NEVINS, R. G., ROHLES, F. H., SPRINGER, W. AND FEYERHEM, A. M.
A temperature-humidity chart for thermal comfort of seated persons. ASHRAE Trans. 72 (1): 283-291, 1966.

NISHI, Y., GONZALEZ, R. R. AND GAGGE, A. P.
Direct measurement of clothing heat transfer properties during sensible and insensible heat exchange with the thermal environment.
ASHRAE Trans. 81 (2): 183-199, 1975.

OLESEN, B. W.
Thermal comfort requirements for floors. Proceedings of Conference of Institut International du Froid, Commissions B1, B2 and E1, Belgrade, Yugoslavia, pp. 337-343, 1977.

OLESEN, S., FANGER, P. O., JENSEN, P. B. AND NIELSEN, O. J.
Comfort limits for men exposed to asymmetric thermal radiation.
Conseil International du Batiment, Commission W45.
Symposium: Thermal Comfort and Moderate Heat Stress, Watford, Sept. 1972.
Published HMSO, London, 1973.

PARCEWSKI, K. I. AND BEVANS, R. S.
A new method of rating the quality of the environment in heated spaces.
ASHRAE J. 7. (June): 80-86, 1965.

PEDERSEN, C. J. K.
Komfortkrav til luftbevaegelser i rum. Thesis, Danmarks Tekniske Højskole, 1977

POULTON, E. C.
Quantitative subjective assessments are almost always biased, sometimes completely misleading. Br. J. Psychol. 68: 409-425, 1977.

ROHLES, F. H. AND JOHNSON, M. A.
Thermal comfort in the elderly. ASHRAE Trans. 78 (1): 131-137, 1972.

ROHLES, F. H. AND NEVINS, R. G.
The nature of thermal comfort for sedentary man. ASHRAE Trans. 77 (1): 239-246, 1971.

ROHLES, F. H. AND WELLS, W. W.
The role of environmental antecedents on subsequent thermal comfort.
ASHRAE Trans. 83 (2): 21-29, 1977.

SEPANNEN, O., MCNALL, P. E., MUNSON, D. M., AND SPRAGUE, C. H.
Thermal insulating values for typical indoor clothing ensembles.
ASHRAE Trans. 78 (1): 120-123, 1972.

SPRAGUE, C. H. AND MUNSON, D. M.
A composite ensemble method for estimating thermal insulating values of clothing. ASHRAE Trans. 80 (1): 120-129, 1974.

WYON, D. P., ASGEIRSDOTTER, T. L., KJERULF-JENSEN, P. AND FANGER, P. O.
The effects of ambient temperature swings on comfort, performance and behaviour.
Archives des Sciences Physiologiques, 27: A441-A458, 1973.

TABLE 1

REGRESSION COEFFICIENTS OF WARMTH VOTE ON TEMPERATURE

Sampling	Regression coefficient (scale units/K)
Climate chamber studies (standard clothing)	0.33
Field studies, extending over weeks	0.23
Field study, over year	0.16
Between studies regression	0.05

(After Humphreys, 1976)

TABLE 2

COMFORTABLE FLOOR TEMPERATURES

Floor material	Acceptable temperature range	
	Bare feet	Shod feet
Carpet	20-28	20-28
Wood	23-28	
Concrete	26-29	

Figures are from Olesen (1977), and are based on 10 min exposure. For long exposures, the upper temperature acceptable to people wearing shoes should be reduced to 25°C (Chrenko, 1957).

TABLE 3

METABOLIC RATES FOR DIFFERENT ACTIVITY LEVELS

Activity	Metabolic Rate (M) (W/m^2)	
Basal metabolic rate	45	
Seated at rest	60	
Standing at rest	65	
General office work	75	
Light industrial work	150	(η = 0.1)
Heavy manual work	250	(η = 0.1)
Walking on level ground, at 4 km/h	140	
Walking on level ground at 6 km/h	200	
Walking up 5% slope, at 4 km/h	200	(η = 0.1)
Walking up 15% slope at 4 km/h	340	(η = 0.2)

Approximate mechanical efficiency (η) shown in brackets.

TABLE 4

INSULATION VALUES OF SOME CLOTHING OUTFITS

Clothing	Insulation (clo units)
Nude	0
Light sleeveless dress, cotton underwear	0.2
Light trousers, short sleeve shirt	0.5
Warm, long sleeve dress, full length slip	0.7
Light trousers, vest, long sleeve shirt	0.7
Light trousers, vest, long sleeve shirt, jacket	0.9
Heavy three piece suit, long underwear	1.5

BEDFORD SCALE	ASHRAE SCALE	NUMERICAL CATEGORY	UNDERLYING CONTINUUM	
MUCH TOO WARM	HOT	7	7	
TOO WARM	WARM	6	6	
COMFORTABLY WARM	SLIGHTLY WARM	5	5	
COMFORTABLE	NEUTRAL	4	4	COMFORT RANGE
COMFORTABLY COOL	SLIGHTLY COOL	3	3	
TOO COOL	COOL	2	2	
MUCH TOO COOL	COLD	1	1	

Figure 1. The two seven point scales of warmth in current use. The central three categories are conventionally regarded as the comfort range.

ECRC/M 1185

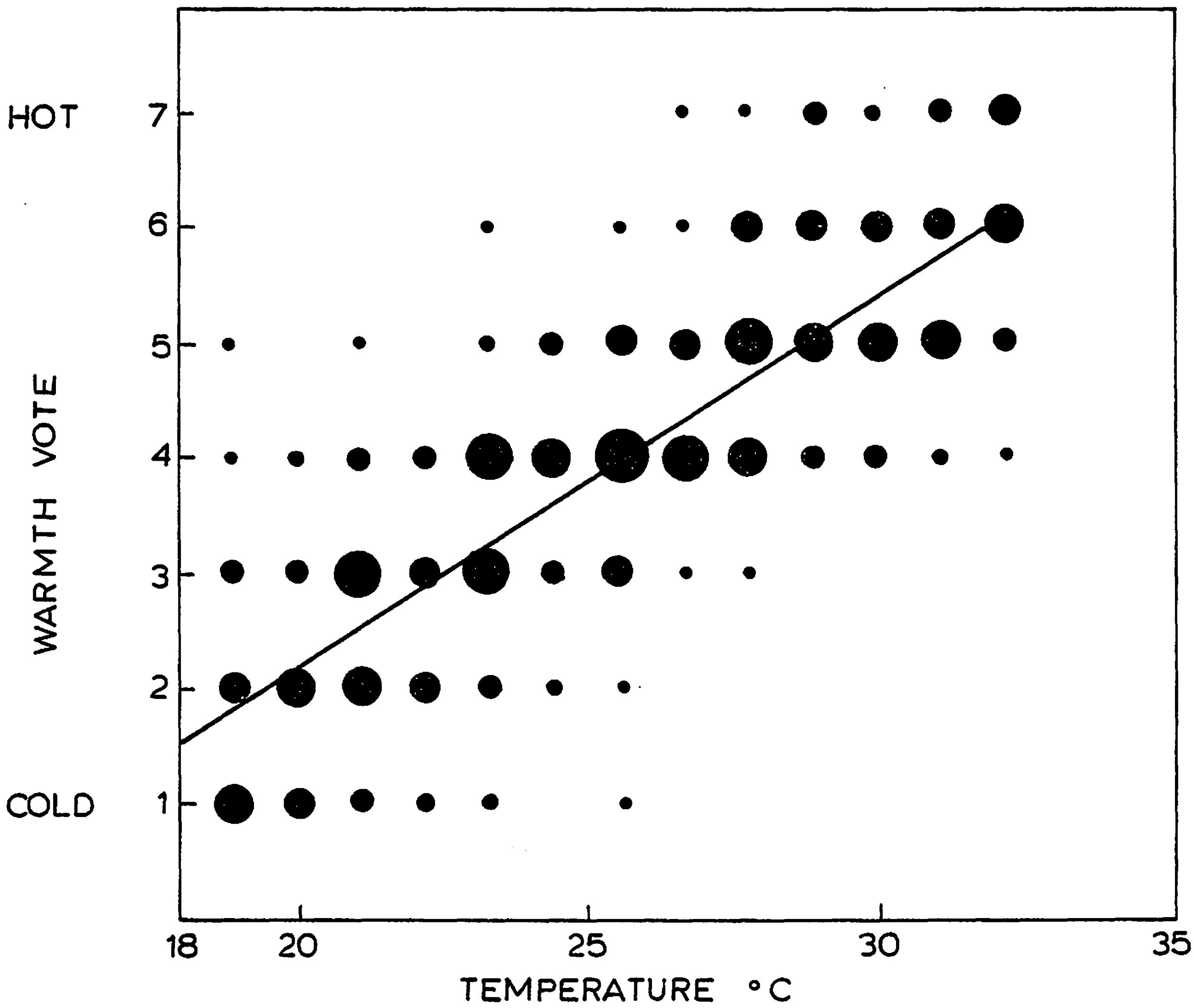

Figure 2. The warmth vote of 1296 subjects as a function of ambient temperature. The area of each circle is proportional to the number of respondents. Data from Nevins et al. (1966) and Fanger (1972). The best fitting regression line is shown.

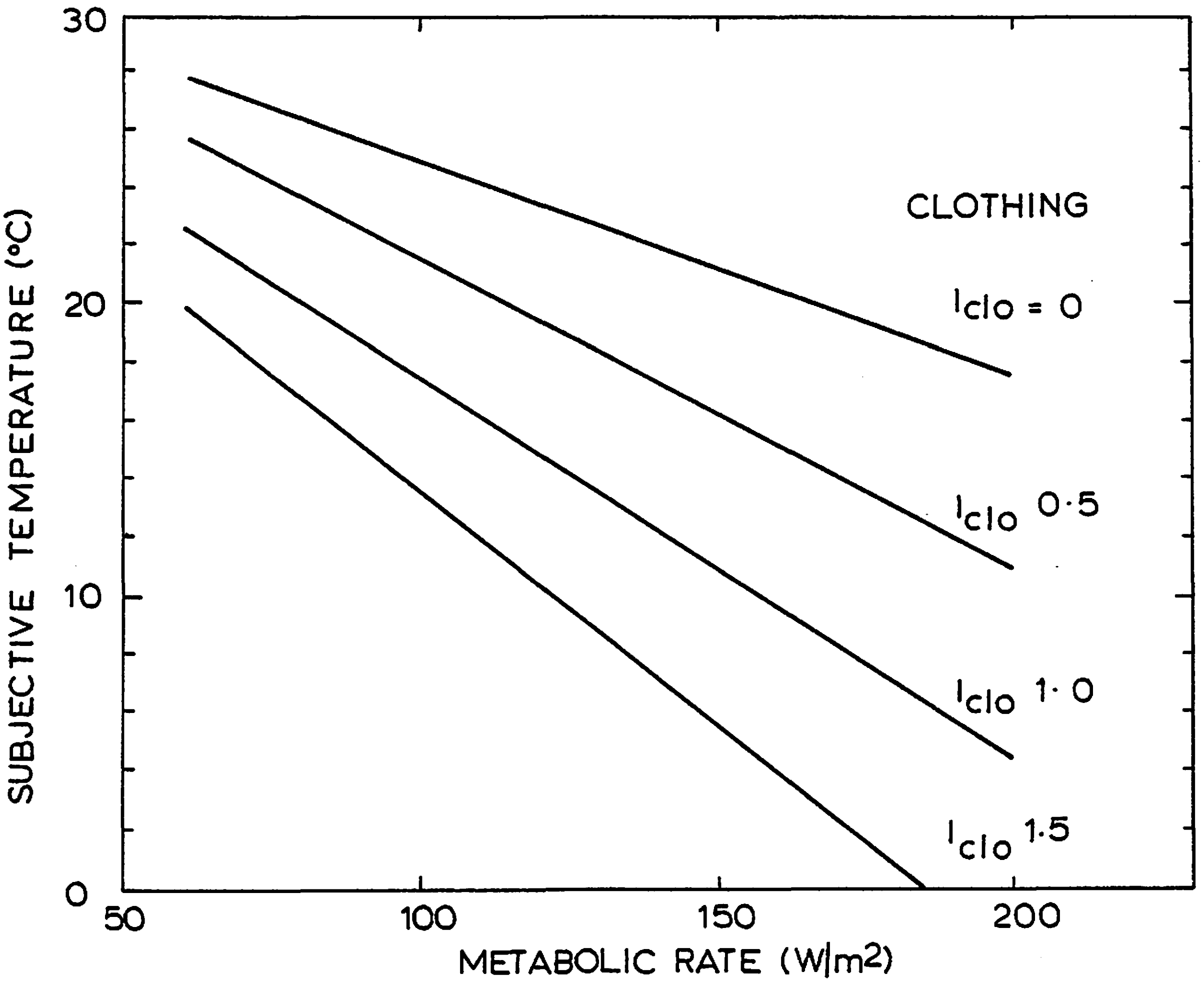

Figure 3. The subjective temperature required for comfort as a function of activity and clothing insulation.

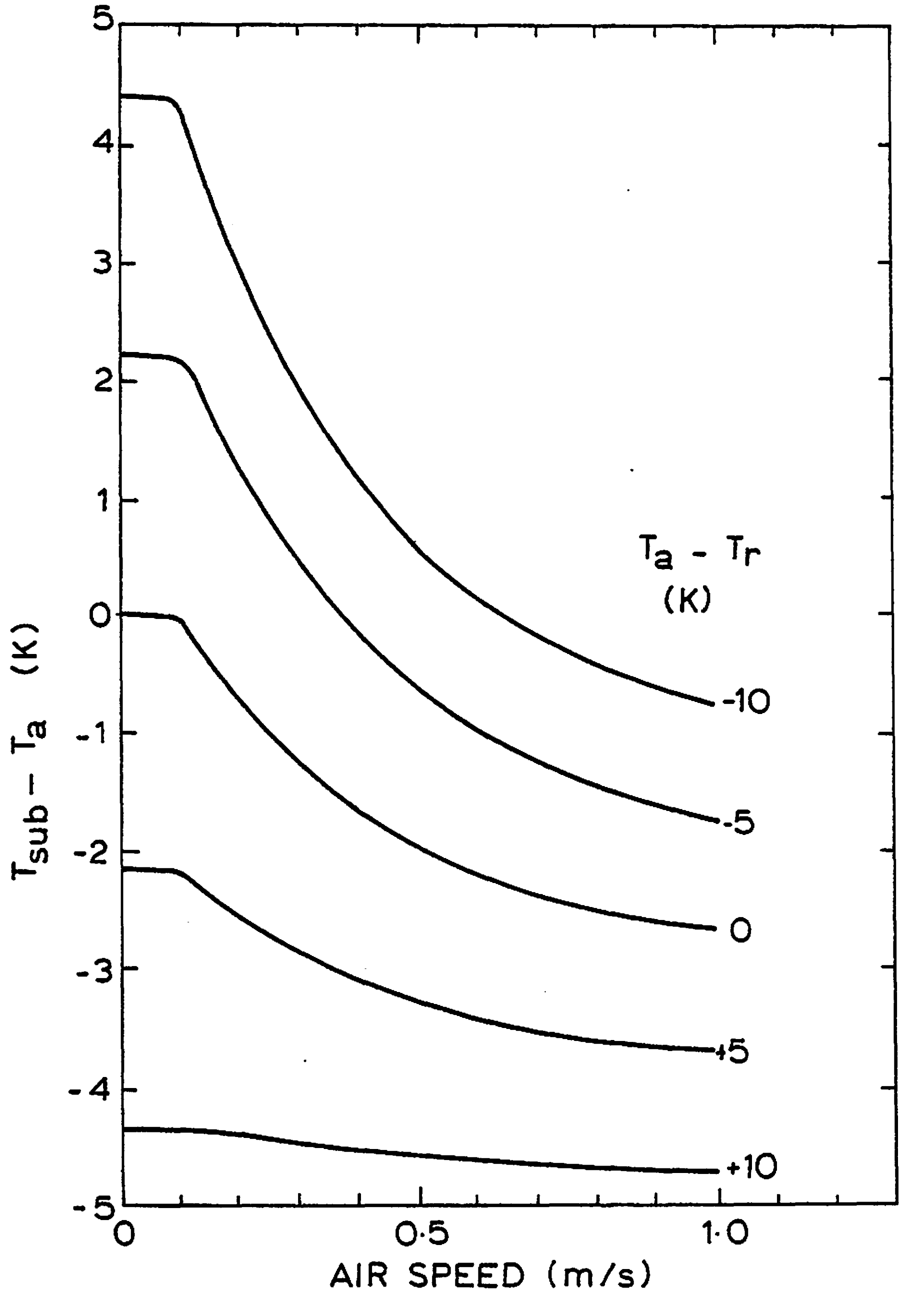

Figure 4. The relation between subjective temperature, T_{sub}, and the physical variables of air temperature T_a, mean radiant temperature, T_r, and air speed v. The differential (T_a-T_r) is determined by the heating system and building structure.

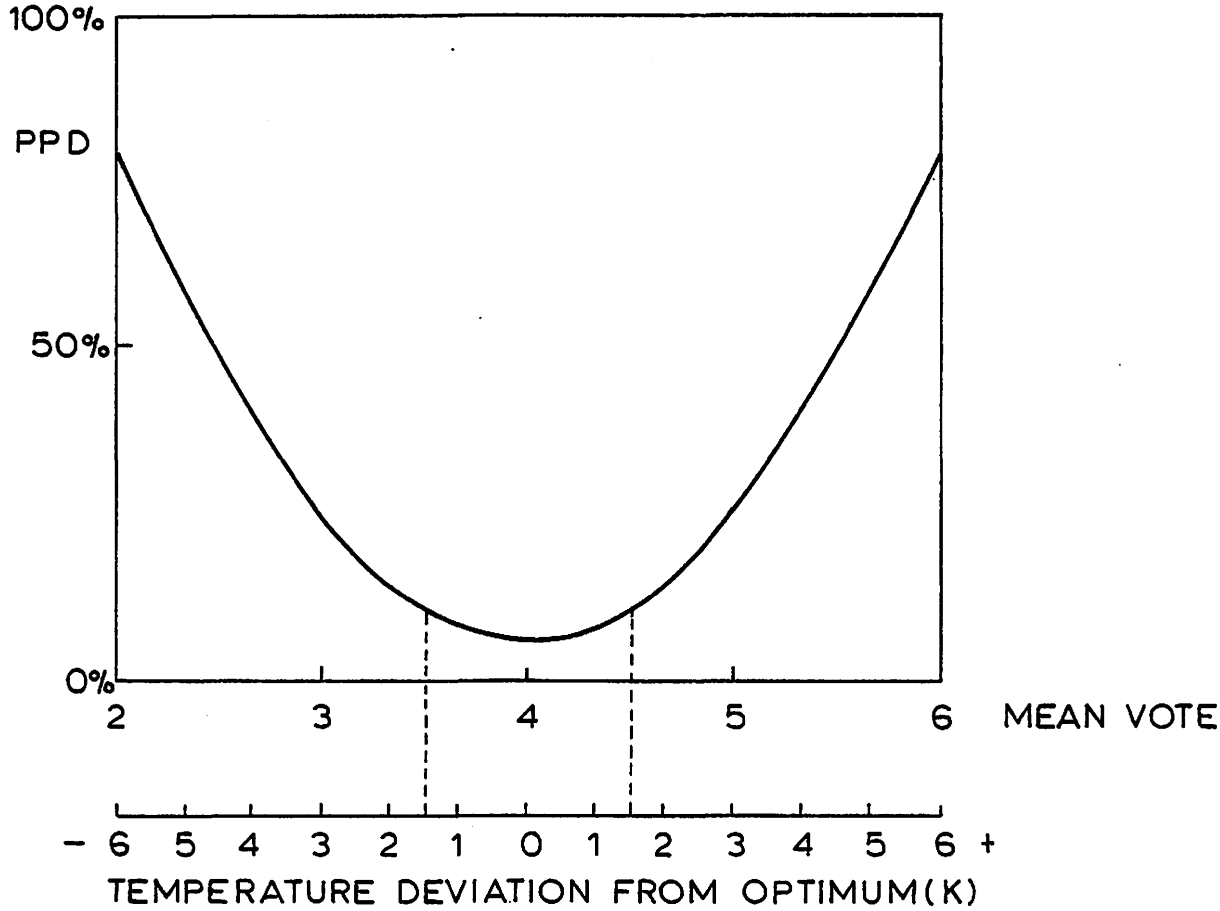

Figure 5. The predicted percentage dissatisfied (PPD) of a group of people as a function of the mean warmth vote of the group. The PPD is also shown as a function of the deviation of the temperature from the optimum value. A temperature range of ± 1½ K about the optimum ensures a PPD of less than 10%. After Fanger (1972).

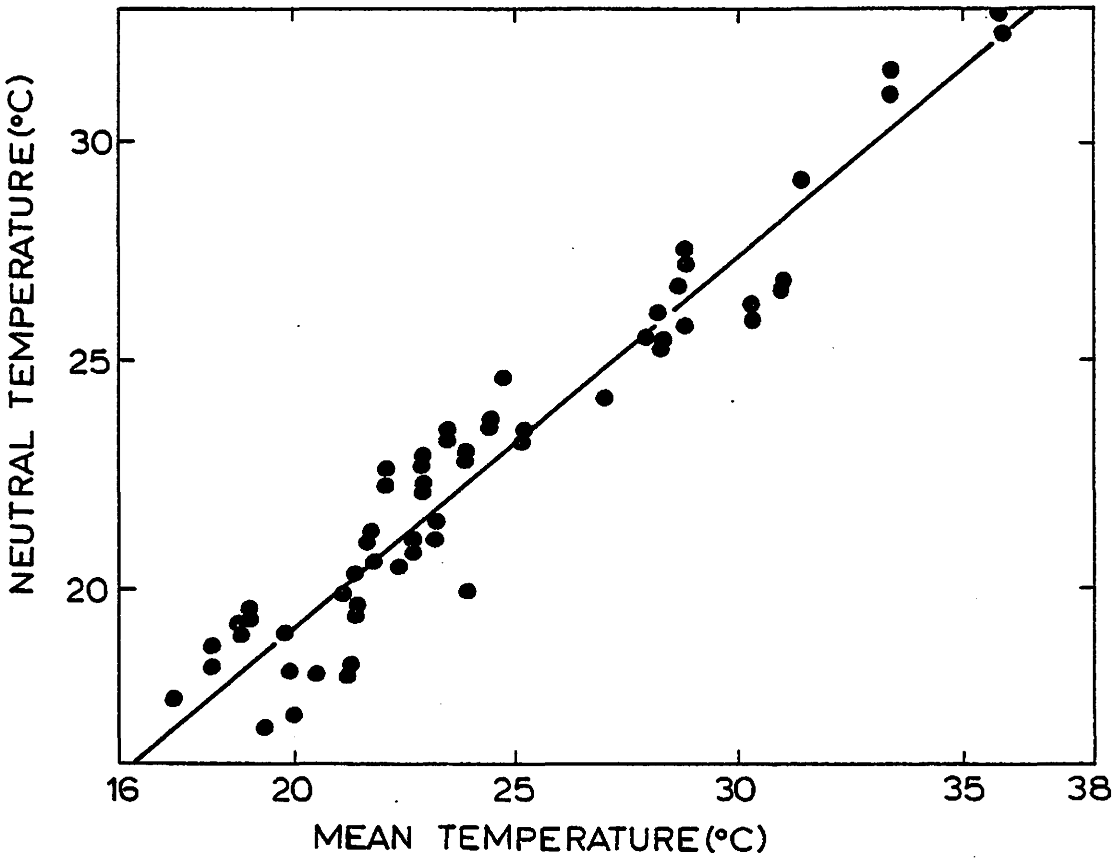

Figure 6. The neutral temperature of a group of people as a function of their thermal experience. Each point represents the result of an entire field survey. The abscissa is the average temperature recorded during the survey. After Humphreys (1976).

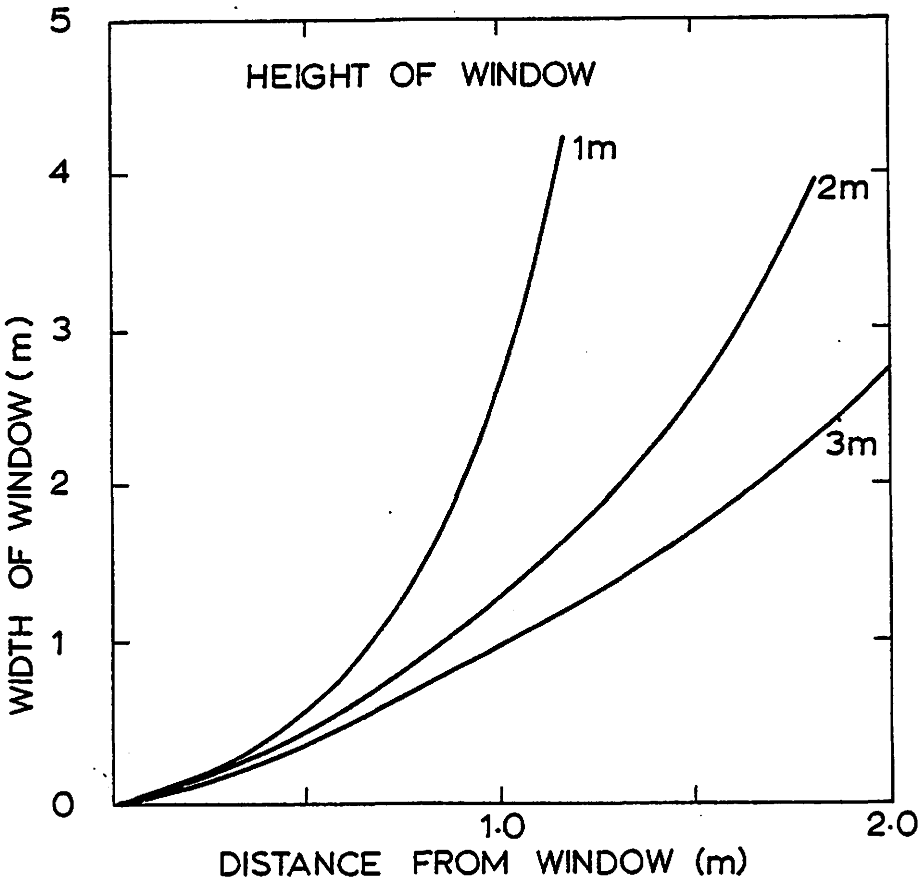

Figure 7. The minimum comfortable distance from the centre of a rectangular window, calculated for single glazing with an outside temperature of $-1^{\circ}C$.

ECRC/M1185

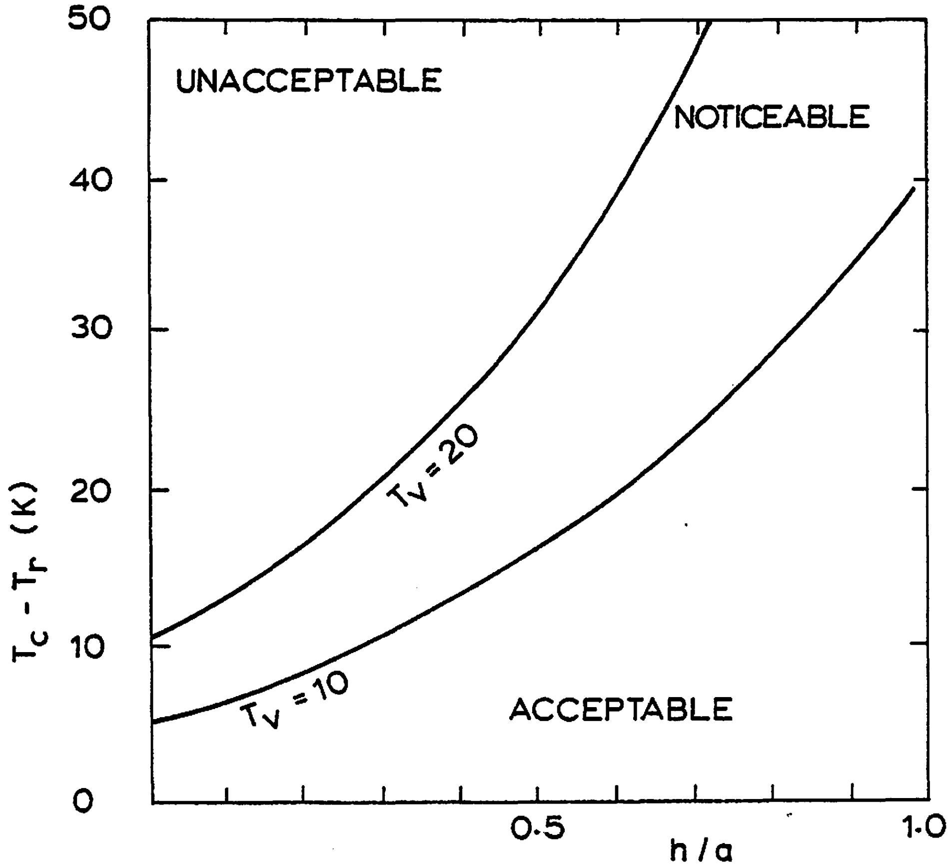

Figure 8. The permitted elevation of the temperature T_c (^oC) of an overhead square panel above the mean radiant temperature T_r (^oC) in a room, as a function of the size of the panel. The heated panel has dimensions a x a, and is at a height h above head level.