

Temperature and sleep

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Abstract. Expert guidance in the UK suggests a limit the temperatures in bedrooms to of 26°C or less to avoid overheating. This short paper looks at the temperatures in bedrooms and uses data from comfort surveys combined with models which link comfort to the thermal environment. Evidence is given that people sleep comfortably where temperatures are 29 - 31°C in their personal space within the bed and they use bedclothes to allow them to attain these temperatures. The effect of the use of a mattress and the adaptive opportunities afforded by the bedclothes and sleepwear are briefly explored as are methods used in hot climates to offset high bedroom temperatures.

Keywords temperature; sleep quality; comfort; bedclothes and sleepwear; energy.

1. Introduction

Acceptable bedroom temperature

The environmental temperature in the bedroom is known to have an effect on the quality of the sleep which the occupant can expect. One investigation of this is presented in the first chapter of CIBSE Guide A (2015). The researcher (Humphreys 1979) plotted the temperature against the number of blankets (and eiderdown) the subject used (Figure 1). The subjects were living in England and almost all wore pyjamas or a nightdress. Also shown is the quality of sleep the subject experienced (on a five-point scale from good to bad).

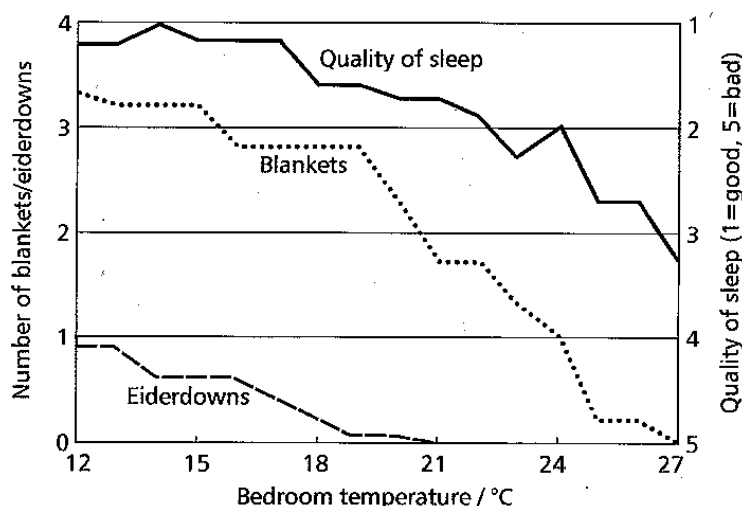


Figure 1. The effect of bedroom temperature upon bedding and quality of sleep (Humphreys 1979)

In the CIBSE (2017) Technical Memorandum TM59, Humphreys' study has been cited amongst others to justify a recommendation to limit temperatures in dwelling bedrooms to less than 26°C, because it gives some evidence that, in the UK, bedroom temperatures over 26°C may be experienced as "bad" for sleep quality, (particularly for those in double beds).

But in view of the likelihood that building designers will resort to financially and environmentally expensive mechanical cooling if they expect the room to be overheated, there is a need to revisit existing literature to ensure that the recommendation will not lead to unnecessarily increased energy use and impacts on occupant's quality of life and the

environment. Recent advice from the Department of communities and Local Government (DCLG) may further influence designers into following the advice of TM59, so potentially increasing uptake of air-conditioning in UK homes.

Part of the reason for this reconsideration is the changes which have taken place in bedding since much of the historic experimental work was undertaken. Firstly, the accepted bed clothing nowadays is the quilt or duvet, providing different seasonal grades of insulation and/or sheets. Bedclothes now seldom include blankets or eiderdowns¹. As well as changing the range of insulation available to the sleeper to adapt to bedroom temperature, this change in bedding may have also led to a change in their sleepwear.

Bedrooms are often found in the upper part of the house, and their windows may be kept closed during the day when they are unoccupied, so they could be particularly likely to be hot in summer. But adaptive opportunities such as external shading or shuttering, or improved window opening and security opportunities do not appear in the palette of proposals supplied by CIBSE in their advice to designers. The only solution in their cooling repertoire is a straight move to a mechanical solution, with obvious cost consequences for building owners and users. Getting the correct upper limit for the bedroom temperature is therefore particularly important, as it may also encourage more passive solutions to problems of sleep heat-disturbance with less cost to the owners and the environment

2. Measurements and modelling of temperature for comfort in bed

2.1 Temperature and sleep

The metabolic rate of a sleeping person is low and as the body prepares for sleep vasodilation occurs which facilitates heat loss and signals a drop in body temperature and a simultaneous increase in the temperature of distal parts such as hands and feet (Krauchi, 2007). In line with this Zhang et al (2018) found that the wrist temperature of sleeping people is 33.8°C – some 1.6 degrees higher than during waking hours. As a result changes the temperature regime in the bed becomes an important part of the quality of sleep and the maintenance of body temperature is a part of this.

R K Macpherson (1973) considered the basic requirements of the sleeping person. He quotes an experiment in which the mean temperature close to the body of sleeping subjects was measured and found to be about 28°C. This is similar to that reported by McIntyre (1937) (27-29°C) and Haskell (1981) (29°C). Kingma (Kingma et al 2012 and 2017) and his colleagues of Maastricht University report that the ‘thermoneutral zone’ of the human body (the band of temperature within which neither sweating nor shivering is necessary) lies between 28 and 32°C. A temperature of 28-30°C under the bedclothes and close to the body suggests the comfortable operative temperature in the room would be one which allows the sleeping person to achieve a temperature of about 29°C close to the body. This estimate is in the absence of air movement, as it was taken under the bedclothes close to the subject.

Djongyang (2012) and his co-workers, using a mixture of theory and climate chamber studies, have suggested thermo-neutral operative temperatures in the region of 29-32°C for nude subjects in desert climates. They quote a number of papers which have come to the same or a similar sleep temperature for nude subjects. The argument could be advanced that the temperature which people require for comfortable sleep is in the region of 30°C. The

¹ The **duvet** is a soft quilt filled with down, feathers or synthetic fibre used instead of blankets, an **eiderdown** is like the duvet but smaller, used as an addition to the blankets in cold weather

function of the bedclothes and sleepwear is to provide a microclimate at that temperature in the vicinity of the skin surface when they are asleep.

Lan et al (2014) measured sleep quality for subjects in a climate chamber and wearing light sleepwear and a blanket, at three temperatures: 23°C, 26°C and 30°C and found that proportion of subjects reporting 'sufficient sleep' at 26°C, was greater than at either 23°C or 30°C. In addition 26°C was less likely to cause thermal discomfort either before or during the sleep period.

Obradocich et al (2017) showed that human sleep loss is also affected by the weather, in that greater sleep loss is indicated when the outdoor temperature is hotter than normal for the time of year.

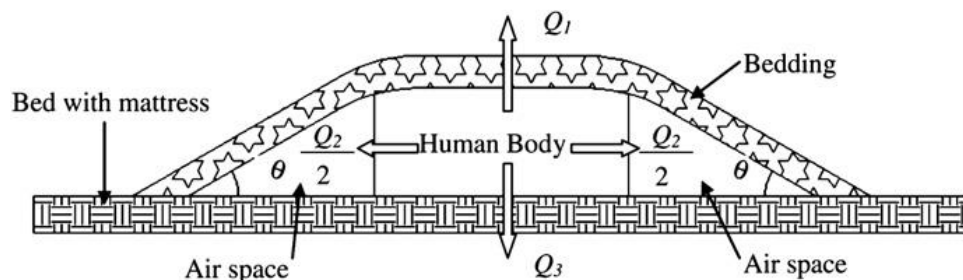


Figure 2. Schematic of heat transfer pathways in a bedding system including a sleeping occupant (from Pan et al 2010)

2.2. Heat balance for sleeping people

There is some complexity in the thermal pathways to the room environment from the body beneath the bedclothes and the sleepwear. Heat is lost in many directions and through different combinations of coverings: downwards through the sleepwear, sheet and mattress; upwards through the sleepwear sheet and blankets or duvet, and sideways into the air around the body, and maybe movements of the body allow air to escape or enter the 'capsule' of air surrounding the sleeper. In addition there is the heat loss directly from the uncovered parts of the body such as the face and limbs exposed during sleep. In addition heat is also lost through respiration and sweating. A useful model of the heat loss pathways is given by Pan et al (2010) (Figure 2)

There is an additional complication when the subject is in a bed with the highly insulated sprung mattress as used in many countries. In summer, when the clothing above is light, the body is losing heat almost entirely through that part which is not in contact with the mattress. This is physically equivalent to increasing the metabolic rate by about 20% because the proportion which is in contact with the mattress is about 20% of the area of the whole body (Pan et al 2010, Raja and Nicol 1997).

3. Room temperature for comfort in physiological models

3.1. Physiological models

Humphreys' simple 1970 model of the thermal relationship between clothing, metabolic rate and operative temperature is illustrated in Figure 3a. The ASHRAE standard 55 suggests that the metabolic rate for a sleeping person is about 41Wm^{-2} . This (approximate) model suggests that the temperature comfort zone in still air is 30-32°C and with the increase in the effective metabolic rate to about 50Wm^{-2} to allow for a mattress it is 29-31°C. The maximum comfort temperature for the sleeping unclothed body (above which an increase is required in sweat rate to maintain the thermal equilibrium) is therefore about 32°C - or 31°C with allowance for a mattress (from Humphreys et al (2016) chapter 20). A development of Humphreys' diagram

(Figure 3b) suggests these maximum temperatures can be increased to 34°C (33°C with mattress) if the air speed is increased to 1m/s.

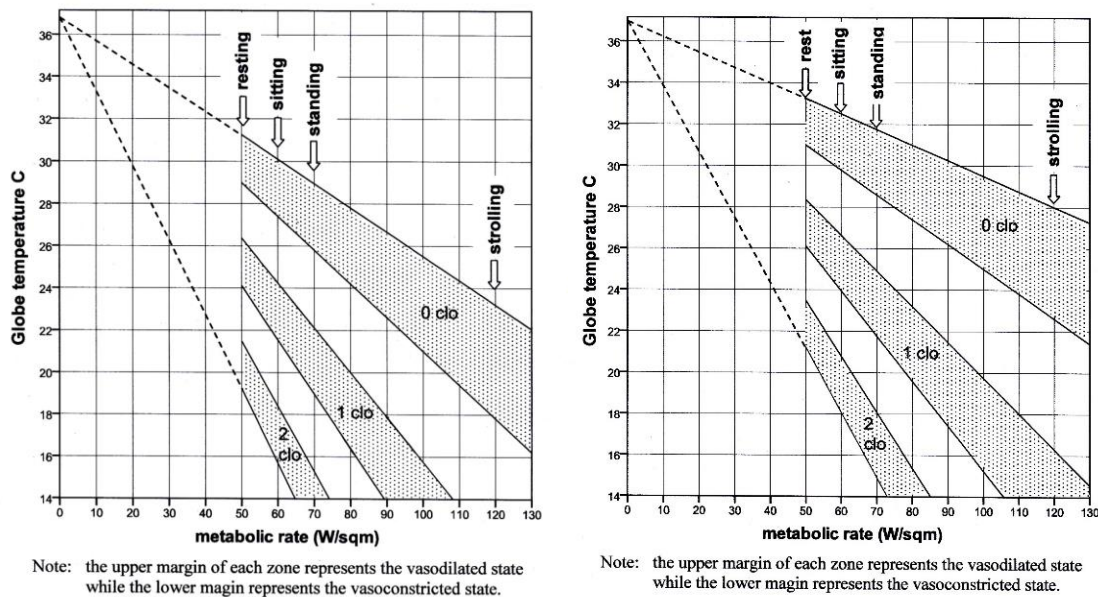


Figure 3, Humphreys 1979 schematic diagram of comfort zones various levels of clothing. The diagram on the left (a) is for still air and on the right (b) for air speed of 1m/s (from Humphreys et al 2016 chapter 20)

The optimum ($PMV = 0$) sleeping temperature is predicted by Fanger's (1972) PMV index for nude people at minimal metabolic rate and no bedclothes or sleepwear covering is 31°C. Fanger also gives a comfort temperature of 34°C for air speed of 1 m/s. To allow for a mattress we can increase the metabolic rate by 20% from 0.7 met to 0,85 met; then the temperature at which there is a balance between heat production and heat loss is reduced to 30°C. The upper temperature limit to avoid heat discomfort (i.e. $PMV=0.5$) is 31.5°C or 30.5°C with mattress. These temperatures can again be increased by about 2-3K by an increase in air speed to 1m/s².

This analysis suggests that the maximum comfort temperature for nude sleeping people is about 4-6K above the 26°C suggested by TM59. The low values of temperature suggested by Humphreys in 1979 may be explained by the sleeping habits of the UK subjects. It is not recorded what night clothes the subjects were wearing but some sort of light sleepwear was the norm at the time of the surveys, added to which a light cotton sheet would have been normal, bringing the equivalent clothing insulation up to approximately 0.4 -0.6Clo. Using Fanger's PMV this set-up would give a sleeping comfort temperature of about 30.5°C, and the temperature-limit for ($PMV= +0.5$) would have been 31.5°C. Using the Humphreys diagram would suggest a comfort temperature of 29°C and an upper limit of 31°C

There is a popular conception that humidity plays an important role in the thermal comfort of people. In terms of the thermal sensation of the subjects the thermal comfort of the individuals as measured in comfort surveys (Humphreys et al 2016 pp179,180) is small if a direct measurement such as the water vapour in the atmosphere is used. If humidity is measured as relative humidity it may appear important but that is because RH incorporates temperature in its definition, and this is reflected in the statistics. At the temperatures we are

² All estimates in these PMV calculations use the Berkeley 'CBE Thermal Comfort Tool' which is available on the internet at <http://comfort.cbe.berkeley.edu>

assuming within a bed (say 30°C) the difference between 0kPa (zero humidity) and 4kPa (about the maximum for air at this temperature) the difference in PMV is about 1. In reality the inside of an occupied bed is unlikely to have anything like this range of humidity.

3.2. Bedclothes

Bedclothes such as sheets and blankets and duvets have an important function in making the bed occupants comfortable and safe.

The thermal insulation of bedclothes is measured in Togs which roughly translate to the more familiar clo units according to the ratio $1 \text{ clo} \approx 1.55 \text{ tog}$. Commonly a summer duvet is about 3 Tog (about 2 clo) and a winter duvet about 9 Tog (about 6 clo). The Humphreys model suggests that, in the resting metabolic rate, each clo of insulation reduces the comfort temperature by about 5K ignoring the mattress or 6K including the mattress. This suggests that the summer duvet is appropriate at bedroom temperatures of around 21.5°C without a mattress or 18°C with a mattress. The winter duvet should provide comfort down to just above 0°C, or even lower in combination with a highly insulating mattress and/or under-blanket.

3.3. Adaptive actions

The way in which a duvet is used can be very adaptive. They are not normally 'tucked in' under the mattress as were blankets and this allows the users to move themselves around and adjust the bedclothes to their personal needs (Figure 4) During cold conditions this could be a problem if cold air from the room infiltrates or the exposed parts of the body get too cold, so the above calculated values of the comfort temperature with a winter duvet may be too low. However, in a cold room many will tend to sleep curled up, with the limbs and even the head under the cover of the duvet. Air movement is another adaptive opportunity as suggested by Lan et al (2013) in a study of personal ventilation.

The success of the adaptive use of bedclothes is indirectly illustrated by the finding by Imagawa et al (2015a) following a survey in 25 houses in Japan. From an analysis of over 3000 assessments of the effect of temperature on sleep in bedrooms with indoor air temperatures between 21 -34°C Imagawa and Rijal (2015b) that "there was no distinctive relationship between the depth of sleep reported by the subjective vote and indoor air temperature".

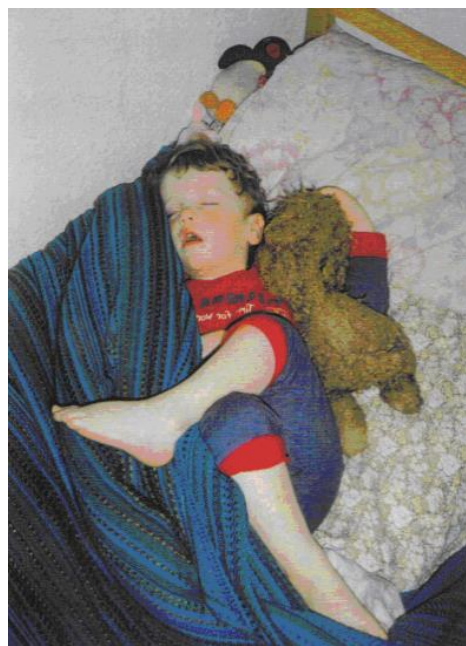


Figure 4 illustrating the ability of a young duvet user to adjust his posture and bedclothes to suit his needs
(from Nicol et al 2012, photograph by R. H. Roberts)

3.4 Posture in bed

Another common response to discomfort in bed is to adjust posture. Most of the experimental evidence for comfort in bed (e.g. Zhang et al) measures bedding insulation using mannikins in a prone position. Many people sleep in what can be characterised as a Foetal position (curled up like a baby). In a standing person a change of posture can reduce the effective surface area of the body by as much as 30% (Raja and Nicol, 1997). In bed the heat flow paths are less defined and the warming effect of curling up less clear. A smaller area will be warmed by the bed occupant as the legs are drawn up in the bed and this will result in a smaller heat loss if the inner temperature of the bed is almost constant, at the same time within the bed many body parts are not in contact with the bedclothes (which are the heat sink) but in effect with each other, reducing heat loss. Over all the effect of postural changes of this sort will be to reduce heat loss, potentially improving comfort for those who are cold.

4. Sleeping in hot climates

In hot climates there are several ways in which people avoid the problem of being too hot in bed without the use of mechanical cooling. Some are listed below:

- using a bed without the insulated mattress (for example using a string mattress)
- using a fan to provide air movement
- wrapping themselves in a 'sleeping cloth' which in hot conditions will become wet and thereby reducing its insulation and at the same time spreading the sweat and so increasing evaporation, and preventing disturbance from sweat running down the skin
- moving to another place (for instance on to the roof to take advantage of radiant cooling to the sky) or into a cool basement

Sekhar and Goh (2011) suggest that in a hot-humid climate a mechanically ventilated bedroom has a wider and hotter range of acceptable temperatures (27-30.5°C) than one with air conditioning (22.5-25.5°C) and ascribe the difference, at least in part, to the greater level of personal control which they have over the indoor conditions. Lin and Deng (2006) found that 80% of their respondents in air conditioned apartments preferred a room temperature below 24°C and Yang and Olofsson (2017) got a similar result in Singapore.

5. Discussion

This short paper suggests that a model of the dependence of comfort and sleep quality on bedroom temperature could start with the observation suggested by a number of researchers that the temperature of the immediate microclimate around the sleeper should be around 29-32°C. This finding is strengthened by the use of two thermal models of the human body (Humphreys and PMV) which suggest a similar comfort temperature for nude sleeping subjects in the absence of air movement. The role of sleepwear and bedclothes is to allow the sleeping person to adapt to the temperature in the bedroom. This is primarily a behavioural adaption of the person to the conditions in the bedroom. Other adaptive responses would be to modify the temperature in the room using heating or cooling devices or passive means as

are suggested (for hot conditions) in the bullet points in section 2.1 above. The desirability of further research of the microclimate in the bed and its relationship to bedroom temperature is indicated.

6. Conclusions

There have been a number of attempts to gauge the thermal comfort of sleeping people but this is a difficult endeavour. In the first place the normal field survey relies on the ability of the researcher to ask a subjective question, and the ability of the subject to give an answer. In addition there are problems with the measurement of such important facts as clothing resistance and posture of the subject, which may vary in an unpredictable way.

This paper seeks use a mixture of physiological modelling and adaptive theory to look at the acceptable temperature within bedrooms as the product of the provision of comfort within the bed. Accepting that the sleeping occupants will have a constant body temperature and a fixed metabolic rate it is possible to calculate the level of insulation which will be required. The findings are:

- The temperature of the immediate space around a sleeping person should be about 30°C to ensure access to comfort and adequate sleep.
- The purpose of the bedding is to allow the sleeping person to achieve this temperature in their immediate personal space within the bed.
- The maximum temperature in bedrooms to avoid discomfort and sleep loss is therefore a function of the bedroom environment (temperature and air movement) and the available adaptive opportunities including passive or mechanical heating or cooling, sleepwear and bedding.
- The use of a well-insulated mattress will lower the room temperature the occupant will find comfortable.
- Bedroom occupants will use bedding as an adaptive opportunity at temperatures which would otherwise make sleep difficult

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