



Guest editors:
J. Fergus Nicol and S. Roaf

Volume 45: Number 7 October 2017
ISSN 0961-3218 (Print) 1466-4321 (Online)
DOI: 10.1080/09613218.2017.1301698



ISSN: 0961-3218 (Print) 1466-4321 (Online) Journal homepage: <https://www.tandfonline.com/loi/rbri20>

Rethinking thermal comfort

J. Fergus Nicol & Susan Roaf

To cite this article: J. Fergus Nicol & Susan Roaf (2017) Rethinking thermal comfort, Building Research & Information, 45:7, 711-716, DOI: [10.1080/09613218.2017.1301698](https://doi.org/10.1080/09613218.2017.1301698)

To link to this article: <https://doi.org/10.1080/09613218.2017.1301698>



Published online: 30 Mar 2017.



Submit your article to this journal [↗](#)



Article views: 9995



View related articles [↗](#)



View Crossmark data [↗](#)



Citing articles: 26 View citing articles [↗](#)

Rethinking thermal comfort

J. Fergus Nicol ^a and Susan Roaf ^b

^aSchool of Architecture, Oxford Brookes University, Oxford, UK; ^bHeriot-Watt University, Edinburgh, UK

‘Thermal comfort’ is the term used to describe a satisfactory, stress-free thermal environment in buildings and, therefore, is a socially determined notion defined by norms and expectations. The idea of what is comfortable has certainly changed from one time, place and season to another (Chappells & Shove, 2005). For instance, it is estimated that the Houses of Parliament in London were found comfortable at 15°C by the original inhabitants (Schoenefeldt, 2016), who wore heavier clothing than is common today. Schoenefeldt (2016, p. 165) remarks that attendants reported difficulty getting MPs, who all sat in different areas, to agree on a set temperature. ‘There was scarcely a meeting of the house at which there are not some members who would like the temperature to be at 55°F (13°C), and others at 70°F or 72°F’ (21–22°C).

Large variation exists in indoor thermal comfort according to different climates, times of year and culture. These responses and the actions and the lifestyles and beliefs they engendered ensured that the human race could survive in almost all the wide variety of conditions to be found across the planet. In ‘Temperature and adaptive comfort in heated, cooled and free-running dwellings’ (in this issue), Nicol finds that in their everyday life 90% of Japanese subjects are comfortable in their own homes with a temperature range between 18 and 28°C. A similar analysis among Pakistani office workers gives a range of 21–30°C (Nicol, Raja, Allaudin, & Jamy, 1999). At the extremes people can be comfortable in indoor temperatures as low as 10°C and as high as 35°C or more.

Nonetheless, in any one given situation the comfort range will tend to be much narrower. The ability to find different temperatures acceptable depends on the access to opportunities to modify conditions such as the ability to change clothing or activity level which will enable individuals to be more comfortable (Cole, Robinson, Brown, & O’Shea, 2008). The most powerful of these intervention opportunities is the provision of

controllable mechanical heating or cooling. This is a perk of living in the modern world that is dependent on there being a local supply of reliable and appropriate energy. However, the phenomenon of global warming has made mechanical solutions doubly problematic: not only does it make the weather conditions increasingly difficult to predict and therefore to deal with, but the very use of fossil fuels to generate the necessary energy is increasingly part of its cause in the first place.

This seeming contradiction makes the understanding of the nature of the human interaction with the thermal environment increasingly important. This special issue addresses some of the ways in which scientific research is addressing the issue.

The science of comfort developed in the 20th century around the needs of the heating, ventilation and air-conditioning (HVAC) industry. Engineers needed to feed target conditions into their HVAC sizing calculations to ensure a *comfortable* or *neutral* environment for a group of building occupants. *Comfort* was repositioned and redefined as a *product* sold by the HVAC industry (Fanger, 1970, preface). The HVAC industry therefore needed to define ‘comfort’ in terms of the physical variables that could be controlled using the HVAC system. In such calculations, it is assumed that a thermal balance is needed between the environment and an ‘average person’, and this thermal environment is assumed to be constant. The terminology used by comfort researchers is that of engineering and physics – temperature, humidity and air speed, clothing insulation and watts of metabolic heat/m². It therefore answers the needs of the engineering community in a way that allows them to size their plant. In doing so, it also dissuades them from addressing the shortcomings of the approach.

The most common definition of a ‘comfort zone’ or range of environments which are experienced as comfortable is based on the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) seven-point scale of comfort (Table 1). The

Table 1. ASHRAE and Bedford scales of thermal comfort.

ASHRAE descriptor	Numerical	Bedford descriptor	Numerical
Hot	3	Much too warm	7
Warm	2	Too warm	6
Slightly warm	1	Comfortably warm	5
Neutral	0	Comfortable neither warm nor cool	4
Slightly cool	-1	Comfortably cool	3
Cool	-2	Too cool	2
Cold	-3	Much too cool	1

alternative Bedford scale (Table 1) behaves in much the same way, but the scale itself implies a notion of comfort that is wider than the narrow definition represented by the ASHRAE scale. The structured interview method Bedford used to ask subjects about their responses is well described by Humphreys, Nicol, and Roaf (2016, pp. 10–11). Notice that both scales are essentially one-dimensional, though they may be used to create a ‘comfort index’ which includes several environmental measures. The predicted mean vote (PMV) is the best-known of such thermal indices. Based on a simple steady-state physiological model, it predicts the mean comfort vote on the ASHRAE scale of a group of building occupants from a value derived from the four physical variables of radiant temperature, air temperature, humidity and air movement, along with the insulation of their assumed clothing level and their metabolic rate (Nicol, Humphreys, & Roaf, 2012). This type of thermal index does have the merit of giving a multidimensional description of the comfort ‘product’ which the HVAC industry is selling. A comfortable environment is deemed to be one in which PMV is -1, 0 or 1 on the ASHRAE scale.

Having been developed from data collected in climate chambers, PMV does not, however, reflect the recognition that comfort has a psychological or a social dimension (despite being described as a ‘state of mind’ in the classic definition). The conditions in this system for comfort are derived from the mean skin temperature and the mean evaporative heat loss from sweating for subjects who consider themselves to be comfortable. Nor did the developers of the PMV index consider that it was part of their remit to concern themselves too much with the energy implications of controlling the indoor environment on the basis of their theory.

There has been an increasing acceptance of the behavioural, or adaptive approach to comfort based on surveys in the field (Cole, Brown, & McKay, 2010). This has opened the way for a more holistic and dynamic understanding of thermal comfort where change and

development of new ideas are welcomed. As can be seen in Figure 1, the adaptive approach was based on the assumption that building occupants will take conscious actions (shown on the right-hand side of the diagram) in addition to the involuntary physiological responses of the body (indicated on the left-hand side) to achieve the ‘goal’ of being thermally comfortable. The details of how such environmental controls work and can be accounted for has been the subject of much subsequent and ongoing work (e.g. Boerstra, Loomans, & Hensen, 2016).

Both types of action are initiated by the central nervous system (CNS) in response to signals from the skin and the body, which suggest that there is a danger to the homeostasis (constancy of the deep body temperature) of the body which could become dangerous. The thermoregulatory system is in fact a complex and continually active feedback system. Such systems are known to have not a single optimal state but many states which are optimal depending on their time-related physical and psychological contexts. Comfort in reality is a much more multidimensional system than is assumed in the steady-state PMV-type indices.

The difference between the two approaches lies in more than just the very different experimental approaches; they embody a real difference of underlying philosophy. The ‘index’ approach sees the role of thermal comfort as defining comfortable environments, but the adaptive approach suggests what range of conditions building occupants are likely to want. The scientific reductionism of the PMV approach and the associated problems with it have already been noted. So whilst it can measure (relatively accurately in the climate chamber) a range of four physical variables and two ‘personal’ generally rather approximate variables – clothing insulation and metabolic rate – there are other key variables (including culture, climate, season and even differences of age or gender) that can be recorded and whose effects are closely connected with the way in which individuals will experience, interpret and interact with the world (Raw & Oseland, 1994).

The fact that both approaches use a simple one-dimensional scale to measure thermal comfort has advantages for the simplicity of the model, and allows the results of both experimental approaches to be compared. However, the danger exists that the comparison does not allow for like to be compared with like. Thermal comfort is famously defined as ‘That state of *mind* which expresses satisfaction with the thermal environment’ (ASHRAE, 2009, emphasis added). Yet no psychologist would imagine that so complex a construct as a state of mind could be measured by a single linear scale. Nor is the normal linear regression model really

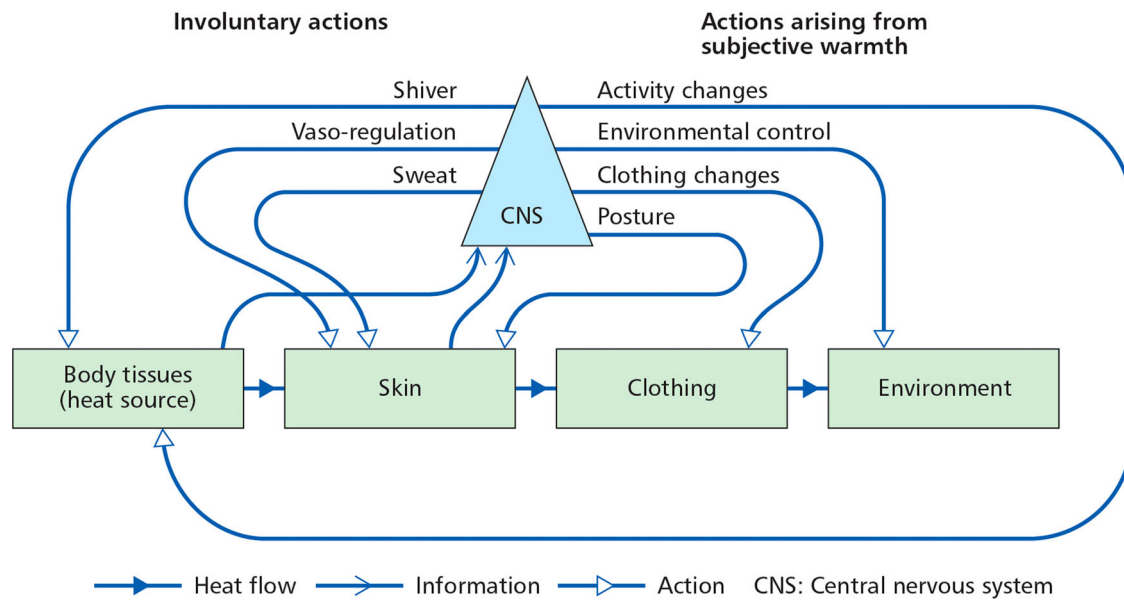


Figure 1. Thermal regulatory system.

Source: Nicol and Humphreys (1973) and subsequently used in CIBSE (2013).

satisfactory for such a complex system (even the use of multiple linear regression, *e.g.* Sharma & Ali, 1986, still assumes the linearity of the interactions).

The developments of comfort theory therefore lie in three directions. One is to understand better the mechanisms on the left-hand side of the Nicol and Humphreys (1973) diagram in Figure 1: the involuntary response of the physiological system that underlies our interaction with the outside thermal environment and how it keys into the relationship. For instance, emerging research by van Marken Lichtenbelt, Hanssen, Pallubinsky, Kingma and Schellen (in this issue) suggests that mild thermal discomfort can actually be good for

your health. This conclusion would not be predicted by the standard approaches. The second is to understand in a more rounded way the conscious (or semi-conscious) actions, and forms of engagement taken by building inhabitants to handle the environment and to modify it to their thermal comfort. The third direction that needs attention is the question of how to design and build buildings to address the first two challenges. This would shift thermal comfort away from being a product produced by machines and delivered through ducts. Instead, it provides an opportunity to mould the building form and its accoutrements to influence the behaviours and habits of its inhabitants and to provide them with

Table 2. Articles in this special issue 'Rethinking Thermal Comfort', *Building Research & Information* (2017), vol. 45(7); guest editors: J. Fergus Nicol and Susan Roaf.

Authors	Title	doi
J. F. Nicol and S. Roaf	Editorial: Rethinking thermal comfort	10.1080/09613218.2017.1301698
H. B. Rijal, M. A. Humphreys and J. F. Nicol	Towards an adaptive model for thermal comfort in Japanese offices	10.1080/09613218.2017.1288450
J. F. Nicol	Temperature and adaptive comfort in heated, cooled and free-running dwellings	10.1080/09613218.2017.1283922
M. Schweiker and A. Wagner	Influences on the predictive performance of thermal sensation indices	10.1080/09613218.2017.1256673
G. Vargas, R. Lawrence and F. Stevenson	The role of lobbies: short-term thermal transitions	10.1080/09613218.2017.1304095
C. Farnham, L. Zhang, J. Yuan, K. Emura, A. M. Alam and T. Mizuno	Measurement of the evaporative cooling effect: oscillating misting fan	10.1080/09613218.2017.1278651
H. Pallubinsky, B. R. M. Kingma, L. Schellen, B. Dautzenberg, M. A. van Baak and W. D. van Marken Lichtenbelt	The effect of warmth acclimation on behaviour, thermophysiology and perception	10.1080/09613218.2017.1278652
B. Kingma, M. Schweiker, A. Wagner and W. D. van Marken Lichtenbelt	Exploring internal body heat balance to understand thermal sensation	10.1080/09613218.2017.1299996
W. D. van Marken Lichtenbelt, M. Hanssen, H. Pallubinsky, B. R. M. Kingma and L. Schellen	Healthy excursions outside the thermal comfort zone	10.1080/09613218.2017.1307647

the capabilities and affordances to make themselves comfortable over time.

There are additional important concerns involving engagement. For the research community, there is a set of challenges involving how to improve the accessibility and utility of thermal comfort research results to designers, regulators, decision-makers and inhabitants. How can our research help architects and engineers design better, more comfortable buildings? Thermal comfort studies already inform the writing of specifications for international standards or help to size an HVAC system. But more strategic and practical advice is needed for designers, *e.g.* to decide what type of building is best in a humid tropical climate or how much diurnal variability is desirable in a north European home. Where to build using massive stonework or where from wood and cane? When to use shading or shutters and when to welcome in the sun? New tools are needed to answer such questions and then convert this understanding into advice – using terminology that is accessible to architects and builders. Finally, how will researchers and teachers inform and inspire architectural students to place thermal comfort as a central, exciting responsibility? The future of good building design in the warming decades ahead will be determined by the cost and quality of the comfort provided in them.

This special issue draws on papers first presented at the Windsor Conference in April 2016,¹ which then underwent rewriting and independent peer review (Table 2). In their paper ‘Towards an adaptive model for thermal comfort in Japanese offices’, authors Hom Rijal, Michael Humphreys and Fergus Nicol report on an example of the empirical approach. Based on measurements of comfort votes and the indoor environment in 11 Japanese office buildings, statistical estimates are derived for the temperatures that office workers will find comfortable. This range of temperatures can be used to set the heating or cooling in the building. The social position of the survey subjects is also contrasted in this estimate with that found among subjects in their homes. The differences between Japanese and European office workers are also explored in these respects.

In ‘Temperature and adaptive comfort in heated, cooled and free-running dwellings’, Fergus Nicol explores the relationship between indoor and outdoor temperatures in dwellings using reports and datasets from surveys in different parts of the world. Dwellings that are heated or cooled (at the time of the survey) show a greater range of indoor temperature at any given outdoor temperature than do dwellings which are free running (naturally ventilated). This suggests that occupants use the powerful adaptive opportunity of the mechanical heating or cooling system to fit the temperature to their varying

needs or possibilities. In free-running buildings where the mechanical option is not in use, the relationship between indoor and outdoor temperature is largely decided by the form and materials of the building, leaving the occupants to fit themselves to the building.

However, despite being valued for its ability to deal with variable conditions, the field study approach has continued to concentrate on finding a *comfort temperature* for a particular group of occupants or their environment. It has also been criticized for appearing to take little account of aspects of the thermal environment other than temperature. There have been attempts to marry the two approaches: the ‘rational’ typified by indices such as PMV, and the ‘empirical’ typified by the adaptive approach. In their paper ‘Influences on the predictive performance of thermal sensation indices’, Marcel Schweiker and Andreas Wagner present such a ‘hybrid’ approach. The input ‘personal’ variables are modified to take account of the adaptive changes – including the psychological – which might be taken to give a better prediction of the actual comfort vote measured in comfort surveys.

In a world of rapid cultural and architectural changes, increasing pressures exacerbate the challenge of providing comfort. The rising cost of energy, the need to reduce energy use and cope with extreme weather and power outages while making indoor environments more delightful fuel a growing need for research into the dynamic nature of comfort and different means of affordably and safely providing it. Increasingly the insights of psychology and thermal physiology will inform research in the field.

Two papers, ‘The role of lobbies: short term thermal transitions’, by Gloria Vargas, Randal Lawrence and Fionn Stevenson, and ‘Measurement of the evaporative cooling effect: oscillating mist fan’, by Craig Farnham, Lili Zhang, Jihui Yuan, Kazuo Emura, Ashraful Alam and Takeo Mizuno, illustrate the ways in which transient conditions can be investigated using field surveys.

Results from ‘The role of lobbies’ suggest that patterns in thermal perception can be identified in fieldwork, and that the judicious use of lobby spaces could possibly alter people’s thermal perception in a positive direction. In the long-term, this may help to reverse the effect of air-conditioning in people’s memories of their own thermal history and support the theory of temporal thermal alliesthesia (de Dear, 2011), rewarding and programming people to enjoy thermal sensations in non-uniform environments.

Farnham et al. test the use of an oscillating mist fan system during summer in an indoor factory space in Japan. The system was first used and reported in an outdoor context (Farnham, Emura, & Mizuno, 2015). The

results are positive and encouraging: temperature decrease and humidity increase ranged at about 0.2–1.9 K and 5–10% respectively inside the misted area. Although the ISO 7243 index based on wet bulb globe temperature (WBGT) would suggest that mist has almost no effect, a modification of the ASHRAE 55 model to include the added cooling of the mist could quantify the mist effect in a similar manner as the cooling effect of increased local air speed. If the mist effect causes a 20 W/m² increase in heat flux, the cooling effect could be about double that of the fan alone.

Thermophysiological models were often developed to answer questions such as will soldiers survive in the desert, sailors in the North Sea, explorers in the Antarctic or miners in a deep mine? The answers were sought in climate chamber experiments. Heat stress indices such as the predicted four-hour sweat rate (P4SR) helped to define the strain on the human body of an unusual set of circumstances.

Physiology has also played a considerable part in the development of thermal comfort theory. Such circumstances were referred to as those of ‘moderate heat stress’ (Langdon, Humphreys, & Nicol, 1973). Thermal comfort used thermophysiological models to characterize the conditions for human heat balance, and by implication comfort, and to calibrate the relationship between metabolic heat production and heat loss at the body surface. There has lately been a return to these roots by physiologists following the realization that physiology has important things to say about not only comfort but also the thermal environment, and in turn about people’s health, energy use and ultimately even the survival of the planet.

This special issue includes three papers addressing this new direction in understanding physiological responses to thermal conditions. In ‘Exploring internal body heat balance to understand thermal sensation’, authors Boris Kingma, Marcel Schweiker, Andreas Wagner and Wouter van Marken Lichtenbelt explore the idea of the thermoneutral zone (TNZ), which is defined as the range of operative temperatures where the body can maintain body core temperature without any regulatory changes to the metabolic rate or sweating. The paper explores the thesis that the thermal sensation is related to the thermal distance of the individual from the centre of the TNZ.

The second paper, ‘The effect of warmth acclimation on behaviour, thermophysiology and perception’, by Hannah Pallubinsky, Boris Kingma, Lisje Schellen, Bas Dautzenberg, Marleen Van Baak and Wouter van Marken Lichtenbelt, deals with the passive acclimation of subjects to high temperatures. Research participants who made nine daily visits to a heated room were tested.

Their thermoregulatory behaviour and thermal physiology were shown to be changed by this experience, as was their perception of the thermal environment and their use of adaptive behaviour.

‘Healthy excursions outside the thermal comfort zone’, by Wouter van Marken Lichtenbelt, Mark Hansen, Hannah Pallubinsky, Boris Kingma and Lisje Schellen, advocates studying the effect of dynamic thermal conditions. This work links to the adaptive comfort model, monitoring these conditions in actual living conditions. New evidence is presented that relatively small deviations from the neutral state can have a beneficial effect on persons suffering from a range of conditions associated with too high or low an energy intake. This emerging research can change how thermal comfort is conceptualized – as some stress may have positive health benefits. Using this information can help to design healthy, comfortable and energy-friendly indoor environments.

The papers in this special issue cover a spectrum of thinking behind advances in our understanding of the thermal relationship between people and buildings, the physiology (Kingma et al., Pallubinsky et al., van Marken Lichtenbelt et al.) which underlies the related health effects and the ways to interpret the body’s response to the environment (Schweiker and Wagner) either as comfort or discomfort. Ways that can be used to produce a desired affect either straight away (Farnham et al.) or through manipulation of the environment or environments we use (Vargas et al.). Finally, the overall estimation of the effect of the environment on our comfort either in a single context (Rijal et al.) or learning what we can from the relationship between a wide variety of environments with a common thread (Nicol).

Over the last 20 years the study and understanding of thermal comfort has moved from being a peripheral consideration where ‘good enough’ decisions were acceptable. The low cost of energy meant it was not a concern if a comfort was achieved at a very high energy cost. All this has changed in the past two decades due to changes in global economies, and reduced buying power for many households making the affordability of comfort into an issue. In addition, an increase in extreme weather events challenges the security of supply and the environmental impacts challenge our excessive energy use. These issues have risen on the agenda for both governments and civil society. The increased recognition that excessive energy demand needs to be curtailed demonstrates the range and vitality of the thermal comfort research being undertaken around the world and the growing importance of the subject to the design of more resilient buildings in the future.

Note

1. The biennial Windsor Conferences are organized by the Network for Comfort and Energy Use in Buildings. The conferences bring together researchers, practitioners, policy-makers and students to present their work for considered discussion and feedback (see <http://windsorconference.com/>).

ORCID

J. Fergus Nicol  <http://orcid.org/0000-0003-0035-7918>

Susan Roaf  <http://orcid.org/0000-0001-7238-8460>

References

- ASHRAE. (2009). *ASHRAE handbook of fundamentals*. Atlanta Georgia: American Society of Heating Refrigeration and Air Conditioning Engineers.
- Boerstra, A., Loomans, M., & Hensen, J. (2016). Effectiveness of operable windows in office environments, *Proceedings of 9th Windsor Conference: Making Comfort Relevant*. London: Network for Comfort and Energy Use in Buildings. <http://nceub.org.uk>.
- Chappells, H., & Shove, E. (2005). Debating the future of comfort: Environmental sustainability, energy consumption and the indoor environment. *Building Research & Information*, 33(1), 32–40. doi:10.1080/0961321042000322762
- CIBSE. (2013). *The limits of thermal comfort: Overheating in European buildings*. Technical Memorandum 52 (TM52). London: Chartered Institution of Building Services Engineers.
- Cole, R. J., Brown, Z., & McKay, S. (2010). Building human agency: A timely manifesto. *Building Research & Information*, 38(3), 339–350. doi:10.1080/09613211003747071
- Cole, R. J., Robinson, J., Brown, Z., & O'Shea, M. (2008). Re-contextualizing the notion of comfort. *Building Research & Information*, 36(4), 323–336. doi:10.1080/09613210802076328
- de Dear, R. (2011). Revisiting an old hypothesis of human thermal perception: Alliesthesia. *Building Research and Information*, 39(2), 108–117. doi:10.1080/09613218.2011.552269
- Fanger, P. O. (1970). *Thermal comfort*. Copenhagen: Danish Technical Press.
- Farnham, C., Emura, K., & Mizuno, T. (2015). Evaluation of cooling effects: Outdoor mist fan. *Building Research & Information*, 43(3), 334–345. doi:10.1080/09613218.2015.1004844
- Humphreys, M., Nicol, F., & Roaf, S. (2016). *Adaptive thermal comfort, foundations and analysis*. London: Earthscan/Routledge. ISBN 978-0-415-69161-1.
- Langdon, F. J., Humphreys, M. A., & Nicol, J. F. (Eds.). (1973). *Thermal comfort and moderate heat stress*. Proceedings of CIB commission W45 (Human Requirements). London: Her Majesty's Stationary Office.
- Nicol, J. F., & Humphreys, M. A. (1973). Thermal comfort as part of a self-regulating system. *Building Research and Practice*, 6(3), 174–179. doi:10.1080/09613217308550237
- Nicol, J. F., Humphreys, M. A., & Roaf, S. C. (2012). *Adaptive thermal comfort: Principles and practice*. London: Earthscan/Routledge. ISBN 978-0-415-69159-8.
- Nicol, J. F., Raja, I. A., Allaudin, A., & Jamy, G. N. (1999). Climatic variations in comfort temperatures: The Pakistan projects. *Energy and Buildings*, 30(3), 261–279. (ISSN 0378-7788). doi:10.1016/S0378-7788(99)00011-0
- Raw, G. J., & Oseland, N. A. (1994). *Why another thermal comfort conference? Thermal Comfort: Past present and future*, BRE report BR264. ISBN 0-85125-633-3.
- Schoenefeldt, H. (2016). The lost (First) chamber of the house of commons. *AA Files*, 72, 161–173. ISSN 0261-6823.
- Sharma, M. A., & Ali, S. (1986). Tropical summer index – a study of thermal comfort in Indian subjects. *Building and Environment*, 21(1), 11–24. doi:10.1016/0360-1323(86)90004-1