Adaptive comfort theory applied to office buildings

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ABSTRACT
There has been much debate over the use of steady-state and adaptive thermal comfort models. Many researchers have suggested that the former model is better suited to buildings with full HVAC systems whilst the latter is better suited to naturally ventilated buildings. This paper suggests that the most appropriate form of thermal comfort model is dependent on the adaptive opportunity available to building occupants, regardless of climate control strategy. Some results from a series of field studies carried out in the UK as part of a doctoral thesis are presented. Adaptive Opportunity is discussed and a method of quantifying it introduced.

INDEX TERMS
Thermal comfort; Adaptation; Office buildings; Energy efficiency; Temperature

INTRODUCTION
In recent years, there has been much debate over the use of steady-state and adaptive models of thermal comfort in office buildings. The former type of model is the one adopted by the main building standards relating to indoor climate, e.g. BS EN ISO 7730 (ISO, 1994) and ASHRAE 55-92 (ASHRAE, 1992) and has been universally applied to all building types in all climates (Parsons, 1994). Steady-state thermal comfort models are based on the premise that a subject's response to environmental stimuli will be purely physiological. The models are thus developed from analysis of heat balance equations and studies conducted under laboratory conditions. However, this type of data does not reflect real working situations with inherent environmental and social complexities. Also, the above standards recommend narrow limits of environmental conditions to maintain optimum levels of thermal comfort and this has led to an increased reliance on mechanical climate control strategies with obvious implications for energy use.

The principle behind adaptive thermal comfort models is that 'if a change occurs that produces discomfort, people react in ways that tend to restore their comfort' (Humphreys and Nicol, 1998). Laboratory studies are inappropriate for assessing this kind of behaviour and so adaptive thermal comfort models are based on data collected from field studies. Whilst the data collected are more prone to error and widely variable, they come from real working environments and will include adaptive effects. Analysis of adaptive thermal comfort models has shown that building occupants are comfortable at a far wider range of environmental criteria than the steady-state models would suggest. By increasing the range of indoor environmental conditions, the need for high-energy mechanical climate control strategies is reduced or eliminated. There is also evidence that adopting an adaptive solution to climate control improves thermal comfort conditions (Humphreys, 1978).

It would be misleading, however, to suggest that an adaptive thermal comfort model can be universally applied. This issue is discussed by de Dear and Brager (2002) who argue that the design and control of some building types, particularly buildings with full HVAC systems, lowers the occupants' tolerance of environmental criteria such that a steady-state solution with the associated close control of indoor climate will result in optimum thermal comfort levels and indeed may provide a better environment than if an adaptive model were used.

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The ASHRAE RP-884 study (de Dear *et al.*, 1997) was conducted in the late 1990s and collated field study data from some 160 office buildings around the world. The results suggested that steady-state thermal comfort models were appropriate for air-conditioned (HVAC) buildings but not for naturally ventilated buildings. For naturally ventilated buildings, there was a distinct relationship between desired comfort temperature and outdoor temperature, indicative of an adaptive thermal comfort model.

But is the presence/absence of air-conditioning the sole governing issue as to the most appropriate form of thermal comfort model? A recent project, which forms the backbone of the author's doctoral thesis, carried out at the Oxford Centre for Sustainable Development, Oxford Brookes University, UK, sought to answer this question. This paper presents some key findings from this project.

PROJECT DESCRIPTION

The EnRei Project was undertaken between 1996 and 1998. This project involved the collection of thermal comfort field study data from 15 office buildings in the UK with the buildings representing a mixture of sizes, usages and climate control strategies. In each building, both environmental and subjective measurements were recorded, the latter via a series of tranverse (monthly) and longitudinal (daily) questionnaires. A total of 4849 transverse and 34 786 longitudinal datasets were collected over the course of the project. Additionally, the subjects were asked to complete background questionnaires to ascertain general information about their demographics and their working environment (453 completed questionnaires). A summary of the surveyed buildings is shown in Table 1.

Table 1 Summary of surveyed buildings

Number	AC/NV	Public/private	Sample size	Number	AC/NV	Public/private	Sample size
1	NV	Public	66	9	NV	Public	99
2	NV	Public	33	10	AC	Private	85
3	AC	Private	16	11	NV	Public	83
4	NV	Private	53	12	AC	Private	100
5	AC	Private	34	13	NV	Public	75
6	NV	Private	17	14	NV	Public	75
7	NV	Private	34	15	AC	Public	42
8	NV	Private	22				

RESULTS

Application of Steady-State Thermal Comfort Model

For each dataset, the Predicted Mean Vote (PMV) was calculated (Fanger, 1970) as an example of a steady-state thermal comfort model. The calculations were made using WinComf®, software developed by University of California Berkeley under ASHRAE RP-781. The PMV was compared to the Actual Mean Vote (AMV) taken from the subjects. Correlation between the two variables was carried out and the results are shown in Table 2 (data from the transverse (monthly) results has been used as the environmental measurements were more accurate).

Table 2 Correlation coefficients—PMV versus AMV (transverse database)

Dataset	Correlation coefficient (PMV vs AMV)	Significance
All buildings	0.188	$p < 0.001$
Air-conditioned buildings (all year)	0.156	$p < 0.001$
Air-conditioned buildings (summer)	0.235	$p < 0.001$
Naturally ventilated buildings (all year)	0.258	$p < 0.001$
Naturally ventilated buildings (summer)	0.342	$p < 0.001$

The results are surprising as they show a better correlation coefficient for PMV versus AMV for the naturally ventilated buildings. It should be remembered that 'naturally ventilated' includes buildings with mechnical heating in place. However, as the above table shows, even during periods when the naturally ventilated buildings are free-running (summer), the correlation between PMV and AMV is still better.

Application of Adaptive Model

One criticism of adaptive thermal comfort models has been their inherent complexity. In an attempt to overcome this criticism, the Adaptive Control Algorithm (ACA) was developed, based on the work of Humphreys (1978). Humphreys showed that the comfort temperature desired by building occupants was directly related to the outdoor temperature via a linear relationship of the form:

$$T_{\mathrm{C}} = a + b \cdot T_{\mathrm{OUT}} \qquad (1)$$

where T_{C} and T_{OUT} are the comfort temperature and outdoor temperature index, respectively, and a and b are constants. Figure 2 shows the comfort temperature (calculated using the Griffiths method; Griffiths, 1990) against the mean outdoor temperture. The graph shows that whilst the relationship between desired comfort temperature and outdoor temperature is better in naturally ventilated buildings than in air-condtioned buildings, is it not strong and should not be considered significant.

The results do not mirror those of the ASHRAE RP-884 study and suggest that the choice of thermal comfort model may not be solely governed by climate control strategy. Indeed, the definition of what consistutes 'air-conditioned' and 'naturally ventilated' buildings is open to question; some air-conditioned buildings have openable windows, some naturally ventilated buildings have mechanical fans. A better method of building classification is required.

ADAPTIVE OPPORTUNITY

Adaptive thermal comfort theories assume that building occupants are able to carry out various adaptive actions in order to maintain thermal comfort. But in many cases, there are constraints that will hinder an adaptation action. Consider the adaptive action of 'opening a window'. If full adaptation is available, then the window could be opened fully at any time with no conflicts arising from external noise/pollution or complaints from other building occupants. If the window cannot be opened, e.g. in a sealed air-conditioned building, then this adaptive action is unavailable. Between these two extremes, there will be varying degrees of adaptation, e.g. the window can be opened, but only to a limited extent; the window can be fully opened, but there are problems with external noise; the window can be fully opened, but management dictate that they must only be used at certain times. This variation is termed the Adaptive Opportunity, a concept developed by Baker and Standheven (1995). Baker and Standheven suggested that a building occupant's tolerance of environmental criteria would be increased with more Adaptive Opportunity. This argument makes sense, but how does one quantify Adaptive Opportunity?

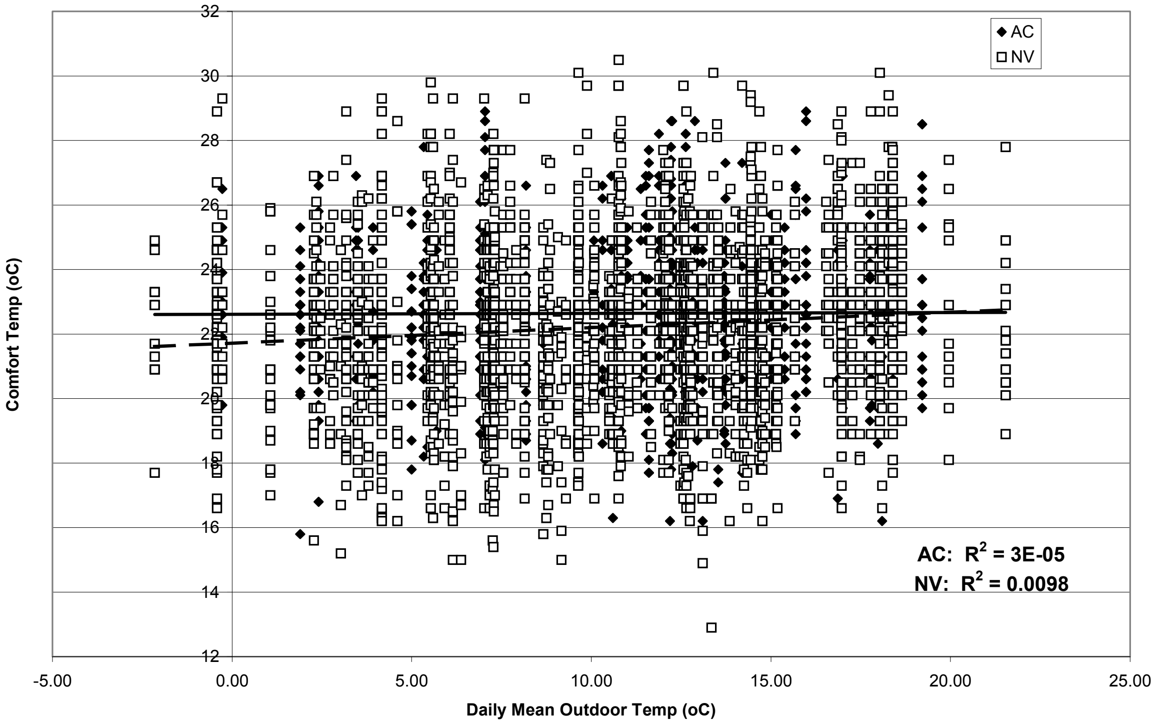

Figure 2 Comfort temperature versus mean outdoor temperature (solid trendline—air-conditioned buildings; dashed trendline—naturally ventilated buildings).

Adaptive Control Index

An index was developed in an attempt to quantify adaptive opportunity. Brager and de Dear (1998) identified three main forms of adaptation: behavioural, physiological and psychological. For the purposes of this index, forms of behavioural adaptation were assessed, specifically technological adaptive actions, i.e. use of controls. As part of a background questionnaire, each building occupant was asked to rate seven control options in terms of the availability of the control, how often the control was used, the perceived effectiveness of the control and the speed of response. All responses were rated 0–4, with '0' meaning no control/minimum effectiveness and '4' meaning full control/maximum effectiveness. The Adaptive Control Index (ACI) was then expressed as a percentage of the total possible score (112). The control options assessed were: windows, blinds/curtains, heating, lighting, air-conditioning (comfort cooling), additional fans and internal doors (Nicol and McCartney, 1999). Table 3 shows the final ACI for each building.

Table 3 Adaptive control indices (air-conditioned buildings in italics)

Building	ACI	Building	ACI	Building	ACI
1	49.5	6	41.7	11	51.9
2	51.5	7	41.7	*12*	*34.5*
3	*26.6*	8	47.5	13	37.4
4	39.0	9	46.0	14	50.0
5	*43.2*	*10*	*22.6*	*15*	*4.9*

The regression coefficients for the comfort temperature (calculated from AMV) versus the mean outdoor temperature were calculated for each building, the same methodology as applied in Figure 2. The regression coefficients were then plotted against the ACIs for each building and the results are shown in Figure 3. The results show that the relationship between comfort temperature and mean outdoor temperature improve as the ACI increases. This suggests that an adaptive thermal comfort model is more appropriate in buildings with increased adaptive opportunity, regardless of whether or not the building is air-conditioned or naturally ventilated (although in most cases, air-conditioned buildings show a lower ACI).

DISCUSSION

The relationship between comfort temperature and outdoor temperature is not strong, even in buildings with a high ACI. McCartney and Nicol (2002) suggest that the strength of this relationship, and hence the appropriateness of an adaptive thermal comfort model, is improved at higher outdoor temperatures with a cut-off point of approximately 10°C. When outdoor temperatures are below this level, a steady-state thermal comfort model (fixed setpoint control) is more appropriate. At temperatures greater than 10°C, the effectiveness of an adaptive thermal comfort model will be dependent on a building's Adaptive Opportunity. For buildings with a low Adaptive Opportunity, a steady-state thermal comfort model may be more appropriate at all outdoor temperatures.

It should be noted that only technological adaptation has been considered in calculating the above ACI. In steady-state models, e.g. PMV, some adaptation is taken into account within the index, i.e. clothing insulation level (behavioural adaptation) and metabolic rate (physiological adaptation). So, PMV could be described as a 'partially adaptive' thermal comfort model (de Dear *et al.*, 1997). de Dear *et al.* go on to suggest that psychological adaptation must be taken into account in order to understand the application of the different types of thermal comfort model.

The next step with the above work is to refine Adaptive Opportunity and develop a more comprehensive index that includes all aspects of adaptation. This work is ongoing and results are expected in April/May 2003. The models must also be applied to buildings in other climates.

CONCLUSIONS

The results presented here, whilst limited, are interesting and go a step further towards definitive guidelines for applying the most appropriate form of thermal comfort model to office buildings. The results show that no one model can be applied universally and suggest that adaptive opportunity is the key to defining the most appropriate model. This, in combination with external climatic issues, will determine the best form of thermal comfort model for use in office buildings.

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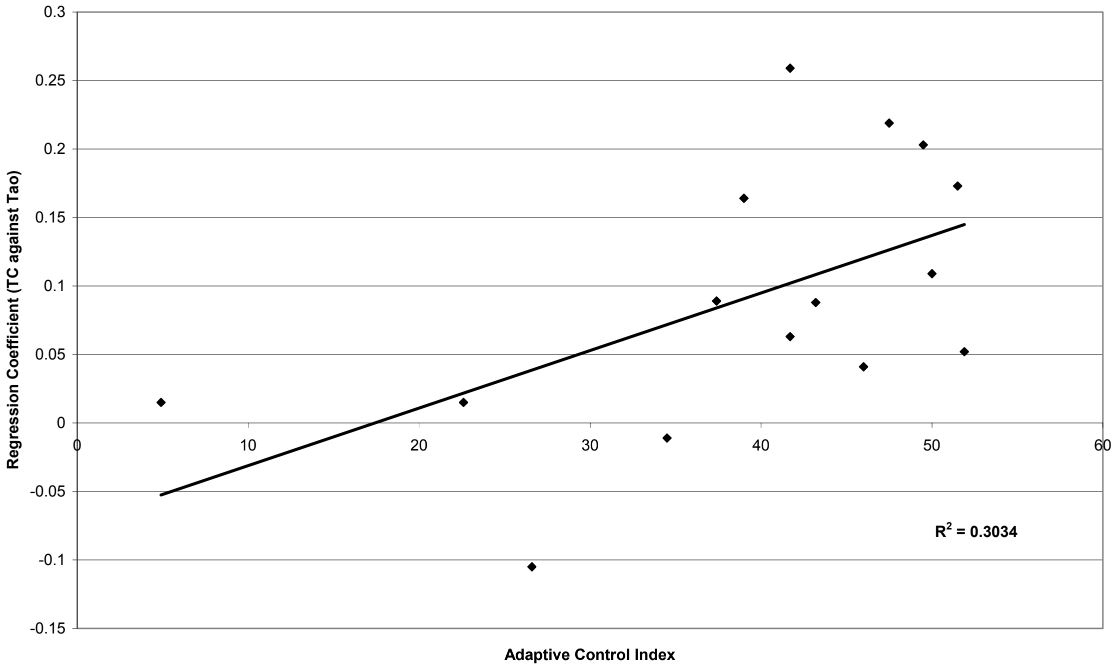

Figure 3 ACI against regression coefficient for T_C versus T_{ao}.

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