An adaptive thermal comfort approach in air-conditioned buildings in the tropical hot-and-humid climates

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ABSTRACT
The air-conditioned office building design in the tropical hot-and-humid climates has seldom taken into account adaptation principle to thermal comfort. This induces the occupants to find comfort at the pre-determined comfort criterion in air-conditioned enclosure and they soon develop a higher expectation of homogeneity that in turn leads to demand of cooler temperatures. Though the research knowledge is large, practical implementation has aptly ignored the variability of individuals' comfort criteria. Such complexity and difficulty has often resulted in static low temperatures and in turn leading to cooling energy wastage. As recourse, the idea of dynamic adaptive thermal comfort approach is used to solve what may prove to be novel and complex problems in indoor cooling in the hot-and-humid climates. The proposed adaptive approach is deemed desirable for it could help to study the adaptive pattern of subjects with respect to their physiological needs in thermal comfort through passage of time.

INDEX TERMS
Hot-and-humid climates; Adaptive comfort opportunities; Productivity

INTRODUCTION
The novel development of an adaptive approach to thermal comfort is to meet the varying comfort requirement of occupants in the air-conditioned office buildings for tropical hot-and-humid climates. The grounds for the theoretical underpinning are accepted claims and evidence from past thermal comfort research (Busch, 1990, 1995; de Dear and Fountain, 1994; Baker and Standeven, 1995; de Dear and Brager, 1998). The adaptive thermal comfort approach has been suggested for outdoors and free-running buildings, but has not seen its application in air-conditioned buildings. Time is a central consideration in the adaptive approach. There are a few time relations, namely,

1. Instantaneous—transition from hot-and-humid outdoor to air-conditioned indoor space, and vice versa, may cause sudden discomfort.
2. Within a day—the change that occurs within a day, such as putting on extra garments to keep comfortably warm in the air-conditioned environment.
3. Day to day—daily change in weather or indoor temperature prompting a change in clothing.
4. Long term—change in fashion or customs that may occur over many months or years. This can be weather variation, for example, over a period of hottest months or a period of wet months.

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The physiological adaptation can be classified into genetic adaptation and acclimatization (within the subject's lifetime). The behavioural patterns will determine the subject's thermal response. This paper presents evidences to demonstrate the possible adaptive thermal comfort opportunities during the office hours in air-conditioned office buildings and also uses the finding to assess the adaptive opportunity in managing the mechanism of productivity.

METHODS

Interactive monitoring is carried out with an experimental population. A questionnaire survey is carried out with them prior to the start of the experiment and at the end of each experiment. Time is a central consideration in the adaptive approach. This finding, based on a particular group of people with intervention (Nicol, 1993), is compared to the finding of another population in air-conditioned offices in the same building where no interference in clothing, activity and thermal environment is made. The subjects in this experiment where no interference is made are classified as the control population.

The subjects cast their thermal sensation vote using the Fanger's seven-point PMV thermal sensation scale (Fanger, 1970); and this is correlated with empirical measurement in comfort indices such as air temperature, relative humidity, air velocity and clothing level. The interactive experiments 1–3 were carried out with general office workers in open-plan office space, and selected staff in enclosed rooms. Sample sizes of 162 and 100 subjects were achieved in the control and experimental populations, respectively. A total of 292 sets of responses for the experimental population over three field experiments were collected. The two populations belong to different offices in the same building. The chosen workers are located in the deep open-plan office spaces and are long-term occupants, for over 1 year. They are untrained, because the aim is to get accurate returns of their true thermal comfort experience in the experiments. Initially, the occupants were allowed a period of time (days) to adjust to the new thermal experience. The experiments were carried out over a 3-day period, sufficiently lengthy to observe any change in the thermal behaviour of subjects. The operation strategy, making use of dynamic control principle for the interactive monitoring (Figure 1), allows the temperature to vary gradually throughout the day depending on the thermal loading. This information on the thermal variation was not disseminated to the occupants and control was via the BAS, where the changes in outdoor climate and indoor microclimate are monitored over time. As the AHU system starts early in the morning, the purpose is to remove the temperature built-up over the night. When workers enter their office, the room temperature is around 23°C. Gradually, the temperature is allowed to increase very slightly to 23.5°C at 1100 h and by start of lunch time, it is around 24°C.

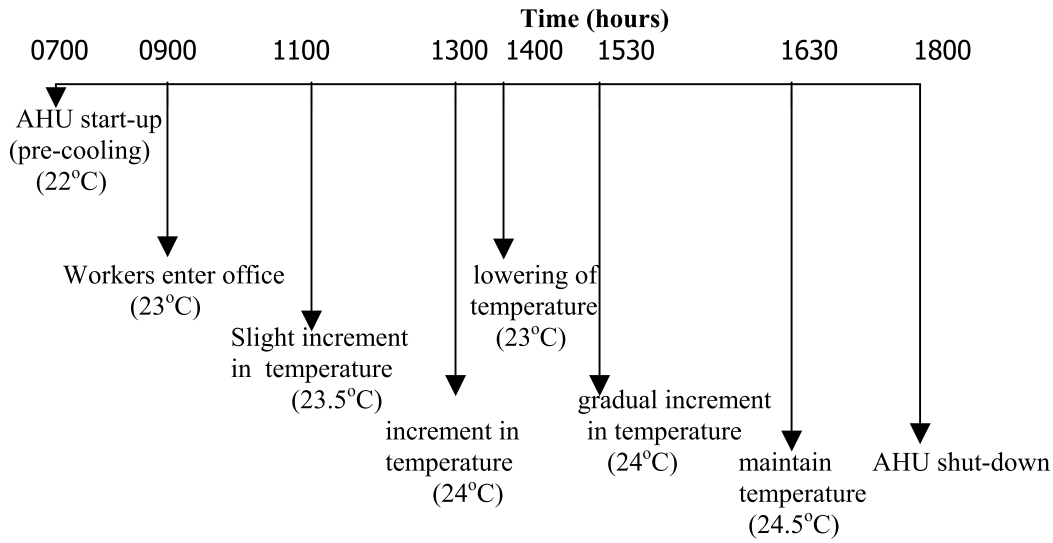

Figure 1 Dynamic room air temperature control during experiment.

Prior to the re-commencement of office activities in the afternoon at 1400 h, the temperature is reduced to 23°C to prepare for the return of workers. The temperature is increased to 24°C by 1530 h and subsequently to 24.5°C at 1600 h. This remains till the AHU shutdown at 1800 h. The relative humidity is kept between 55 and 60% at still air (0.1 m/s) condition. Experiment 2 is similar except there is a 1°C increase in room temperature at each stage of the procedure. The added dimension is the improved air motion (up to 0.25 m/s) to offset the appreciable effect of higher temperature. This seeks to understand the psychological influence of air movement on the perceived thermal comfort. The relative humidity ranges from 60 to 65%. The temperature starts at 24°C in the morning and gradually increases to 25.5°C in the afternoon. Experiment 3 is identical to Experiment 2, except that the air temperature is allowed to increase to beyond 25.5°C in the afternoon, which amounts to 0.5°C higher in the afternoon. For the control experiment, the temperature setting is not varied. It represents the usual and similar thermal comfort experience with a temperature setting between 22 and 23°C, still air condition and relative humidity ranged from 55 to 60%. Adaptive opportunity, such as improved airflow, changing the clothing value, relaxed posture and intake of cold drinks, is deemed to assist comfort and this claim is supported in the research field (Baker and Standeven, 1995).

In the statistical analysis, regression analyses are used to establish the relationship between actual vote and temperatures for both experimental and control populations. For the experimental population, the average comfort temperature data in the adaptive increment experiments is used in the analysis (Figure 2). The various temperature bins are divided into three categories, namely, 23, 24 and 25°C. This is the range of comfort temperature envisaged by the participants in experiments. The subjective votes that responded at each temperature interval (bin) are computed into the calculation to yield the combined observed mean vote of occupants for each temperature bin in the experimental population. Thermal acceptability is a parameter that is a closer indication of actual thermal comfort requirements and the curve in Figure 3 shows the relationship of the percentage of the experimental population which is likely to return a 'thermal acceptability' vote at the corresponding adaptive temperature. Thermal acceptability accommodates the comfortable sensation range from neutral (0), slightly cool (–1) to slightly warm (+1) sensations in the ASHRAE Thermal Sensation Scale. Beginning with a temperature of 24.5°C for the experimental population at the perceived slightly cool thermal sensation (the actual mean vote value is –0.6), the adapted temperatures are calculated and plotted at the higher levels of thermal acceptability that in turn corresponds to a higher range of adapted temperatures from 25 to 26.2°C.

RESULTS

This study presents three important results. (i) The statistical relationships between temperature (*Temp*) and mean vote (*Vote*) for both the control and experimental populations. (ii) Evidence of adaptation in experimental population. (iii) The adaptive temperatures at various level of thermal acceptability in the experimental population. Figure 3 presents the evidence of adaptation in the experimental population, where the relationship between the combined observed mean vote of occupants and the increase in indoor temperatures has demonstrated the correction of thermal sensation votes vis-à-vis temperature change.

The regression relationship for the experimental population is found to be the following:

$$\text{Temp } (^{o}\text{C}) = 0.20(\text{Vote}) + 24.78 \quad (1)$$

On the other hand, the regression relationship in the control population is

$$\text{Temp } (^{\circ}\text{C}) = 0.28(\text{Vote}) + 22.92 \quad (2)$$

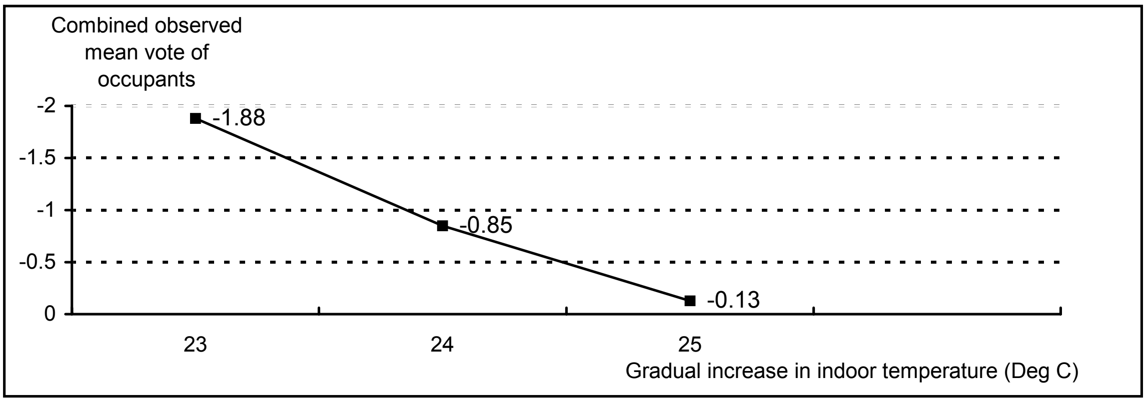

Figure 2 Actual mean vote of occupants as a function of indoor temperature in experimental population.

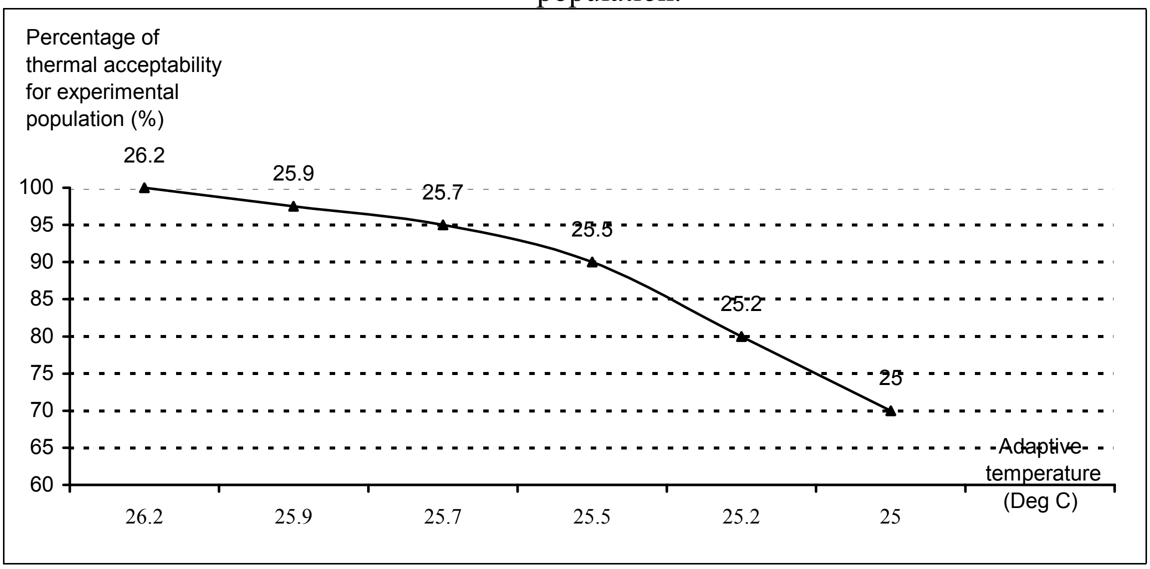

Figure 3 Thermal acceptability at various temperature levels in experimental population.

DISCUSSION

The R^2 value is 0.69 at 95% confidence level for the control population (Eqn 2) and this is close to the correlation (R^2 value) of 0.7 suggested by Nicol (1993) for a closely controlled environment. The low R^2 value of 0.43 at 95% confidence level for the experimental population (equation 1) is not surprising because adaptation has taken place, though is not fully completed, and this suggests that the subjects in this population may have assessed their thermal sensation against some kind of background expectation. In this case, the subjects have shown to be objective in their thermal assessment of their immediate environment and not prejudicially influenced by the single attribute of temperature. The evidence of a lower regression coefficient (0.20) for the variable, Vote, supports the fundamental principle of adaptive approach to thermal comfort that postulates the subject plays an active role to secure comfort. In this case, the thermal sensation vote has shown less effect on the comfort temperature. Hence, it is appropriate to conclude that if adaptation were fully completed, the comfort vote would depend even less upon the temperature. The neutral temperature of the control population is approximately 22.9°C whereas the neutral temperature of the experimental population is about 24.8°C. Adaptation process has resulted in an adaptive increment of 1.9°C in neutral temperature. Though thermal neutrality is a limited concept, it offers, by mean of comparison, an understanding of the potential benefits of adaptation.

When the temperature is increased gradually (Figure 2), the mean thermal sensation vote moves from slightly cool sensation (–0.85) to approaching neutral sensation (–0.13). As the temperature experience is on the low side (23°C), the subjects have voted on the cool side of the thermal sensation scale. This has showed that hot-and-humid climate subjects are increasingly sensitive to temperature when it is gradually increased over time. The adaptation here can be concluded to be a form of shifting expectations and the residual variation is attributed to the subjective comfort set points. Figure 3 shows the percentage of the experiment population which is likely to return a 'thermal acceptability' vote at the corresponding adaptive temperature. If adaptation is fully completed in air-conditioned office spaces, the adaptive temperature is likely to be 26.2°C. The gradient of the curve is lower when the adaptive temperature is lower. This means that the subjects have to make full use of behavioural adjustment in order to achieve a small improvement in the percentage of satisfaction. On the other hand, from the comfort point of view, a 1°C increment beyond the temperature of 25°C can be secured much more easily with certain outdoor weather conditions such as cool and wet days. Based on 90% thermal acceptability, 25.5°C (Figure 3) appears to be a good upper temperature limit for background cooling. This is not perceived to be a rigid maximum limit as the intent is to encourage long-term adaptation to a higher comfort temperature.

CONCLUSIONS

The adaptive approach to thermal comfort is suitable for use in a tropical hot-and-humid climate and it provides the means to determine the likely thermal comfort requirement of occupants that in turn can be used as meaningful guidelines to design the building and ventilation systems. The upper comfort limit is not rigid but flexible, taking into account the climate. The comfortable temperature can be 25.5°C at a thermal acceptability limit of 90%. Adaptation, if fully complete, can help to achieve 26.2°C.

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