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Thermal comfort in indoor and outdoor transitional spaces of buildings in Bangkok

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Abstract

Thermal comfort in transitional spaces of buildings is established from a field study conducted in the cool season of Bangkok, Thailand. It involved 302 indoor subjects occupying either air-conditioned or naturally-ventilated environments and 291 outdoor subjects who were leaving the indoors. The data were analysed by using a calculating method, "Griffiths" values, giving neutral temperatures, and a quadratic regression for thermal acceptability. The results show that, firstly, while neutral temperatures of A/C-indoor and N/V-indoor are quite similar at 27.4°C and 27.7°C, respectively, the A/C-outdoor result is slightly lower at 26.4°C and N/V-outdoor, slightly higher at 28.6°C. Secondly, thermal acceptability of outdoor subjects are at higher temperatures than those of indoors. The range of N/V-indoor acceptability is 26.6°C-30.4°C and N/V-outdoor, 29.2°C-31.6°C. The upper boundaries of A/C-indoor and A/C-outdoor are at 26.0°C and 27.3°C, respectively, but their lower limits are very low and undefined. These findings suggest a wider range of comfort conditions than the standards and the tolerance of the subjects when they are out of doors. If these attitudes of expectation and tolerance could be applied for the internal conditions, the comfort zone would be extended and would result in using less energy to cool buildings.

INTRODUCTION

Background

It is believed that the use of an "adaptive" approach will be able to achieve comfort, and at the same time, to consume less energy for heating or cooling built environments [1]. The adaptive opportunity is also suggested to be able to extend the neutral zone for human comfort [2]. The current standards, ISO 7730 [3], give the summer comfort condition as 23.0°C to 26.0°C operative temperature (T_o), which was challenged by several researchers, eg: Busch [4], Karyono [5], and Sharples and Malama [6].

This paper presents another application of the adaptive model to thermal comfort in transitional spaces, i.e. the relationship between mean air temperature and neutrality of subjects, emphasising the relationship of outdoor conditions to indoor comfort. Its aim is to establish comfort conditions of individual subject groups who were in and around the transition zones inside or outside buildings. Several methods of analyses such as simple linear regression, probit regression, "calculating model" and estimating thermal acceptability have been used.

This is a further study following up the initial research by Jitkhajornwanich et al [7], which reported the comfort condition of all subjects. The findings from this study could eventually depict the Thai thermal comfort in transitional spaces and help minimising energy consumption by reducing use of building services system.

Geography and climate

Bangkok is the capital city of Thailand. It is situated at 13°45' north latitude and 100°28' east longitude, which is categorised as a hot and humid tropical climate. During November to January is the cool season, when it is the north-east monsoon: air is relatively dry and wind is blowing overland from China or Indo-China. Generally, mean air temperature at this time is around 26°C and mean relative humidity is 75% [8].

THE FIELD SURVEY

Procedure of the survey

The "transverse" field survey [9] was carried out within a six-day period in the cool season (December 1996/January 1997) in Bangkok. The areas surveyed were in and around transitional spaces of the selected buildings: three air-conditioned and two naturally-ventilated.

The procedure was based upon the Field Study methodology [10]. While the physical quantities namely air temperature, relative humidity and air velocity were measured, the questionnaires were at the same time handed out to the subjects to rate their thermal responses. The survey forms were translated into the Thai language, based on Busch's [4]. Additionally, this field study included an extra question of thermal expectation as the first question, in order to form the sequence of thermal responses: *expectation, sensation and preference.* The questionnaires had two types: one for subjects entering the buildings and the other for those leaving the buildings.

Data from the survey

The total 593 subjects were categorised into four groups: "A/C-indoor" refers to those in air-conditioned buildings; "N/V-indoor" to those in naturally-ventilated buildings; "A/C-outdoor" to those who were leaving indoor air-conditioned to outdoors; and "N/V-outdoor" to those leaving indoor naturally-ventilated to outdoors.

All subjects were aged between 8 and 68, with a mean of 25. There were 262 males and 331 females. The bodies of the subjects averaged 55 kilograms in weight and 164 centimetres in height. The data of environmental and individual parameters are summarised in Table 1.

Table 1. Mean values of environmental and individual parameters of each subject group.

	A/C-indoor	N/V-indoor	A/C-outdoor	N/V-outdoor
T_a (°C)	25.0	28.5	27.6	30.1
• min	23.1	26.3	25.0	28.0
• max	26.3	30.0	29.7	31.8
RH (%)	49	56	45	52
• min	38	50	38	42
• max	59	63	57	62
V (m/s)	0.21	0.17	0.63	0.44
• min	0.1	0.0	0.2	0.1
• max	0.5	0.8	1.9	1.4
clo-value	0.65	0.59	0.61	0.57
met-value	1.3	1.5	1.7	1.6

Air temperatures of A/C buildings were lower than those of N/V buildings. Mean air temperature varied from 25.0°C in A/C-indoor to 30.1°C in N/V-outdoor. Relative humidities of 38% to 63% were within the recommended range of summer comfort standards: between 30% and 70% [3]. Air velocities of indoors and outdoors were different; in indoor environments, air velocity was about 0.0-0.8 m/s, but it could be up to 1.9 m/s in outdoors.

Mean clothing insulation values of A/C-indoor and A/C-outdoor were higher than those of N/V-indoor and N/V-outdoor. Greater mean clo-values of the A/C groups resulted from an additional shirt or a casual suit worn in air-conditioned environments. Mean metabolic rate of A/C-indoor was the lowest value, close to "sedentary" of 1.2 met [3], whereas the other groups had mean met-value of or near "standing" of 1.6 met [3]. However, from the observations in the field, the activities the subjects performed were not influenced by the environmental conditions, but were the normal/usual activities in transitional spaces themselves.

Results of thermal responses

The subjects voted their thermal expectation and sensation on the seven-point ASHRAE Scale: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (1), warm (2) and hot (3); and their preference on the three-point McIntyre Scale: "would like to be...cooler (-1), no change (0), warmer (1)" in their questionnaires. The majority of the votes in the thermal expectation and sensation were "neutral" and in the preference were "cooler". Mean thermal responses are shown in Table 2.

Table 2. Mean thermal responses of each subject group.

	A/C-indoor	N/V-indoor	A/C-outdoor	N/V-outdoor
Expectation	-0.76	0.17	0.81	0.41
Sensation	-0.80	0.27	0.41	0.50
Preference	-0.23	-0.67	-0.47	-0.72

Only A/C-indoor had all mean thermal responses in the cool side, i.e. mean expectation at -0.76 and mean sensation at -0.80, nevertheless, its mean preference was for yet "cooler" (-0.23). The other groups had their mean thermal expectation and sensation in the warm side and mean preference logically for "cooler". Mean expectation at 0.81 of A/C-outdoor shifting to mean sensation at 0.41, indicated a substantial disagreement about its thermal experiences, i.e. the subjects expected warmer than they felt. In N/V groups, the transformations of mean expectation to mean sensation in indoors from 0.17 to 0.27 and in outdoors from 0.41 to 0.50, showed the subjects' sensation of slightly warmer than their expectation.

ESTABLISHING NEUTRAL TEMPERATURES

Simple linear regression analysis

Simple linear regression analysis is performed on thermal responses as a function of air temperatures, to give the information of regression coefficient (slope), intercept, goodness of fit (R^2) and predicted neutral temperature (T_n). In this study, the simple regression was used on thermal expectation, sensation and preference of each subject group, but it failed to establish T_n. This was due to two reasons: some results were not statistically significant and some slopes were less steep, giving unreliable T_n. However, it succeeded when using the data of all subjects, as reported in Jitkhajornwanich et al [7]. These results are recapped in Table 3.

Table 3. Simple linear regression analysis of all subjects.

	Slope	Intercept	R^2	T_n (°C)
Expectation	0.16	-4.39	0.53	26.7
Sensation	0.21	-5.60	0.75	27.1
Preference	-0.09	1.87	0.83	21.6

Of all subjects, the expected temperature of 26.7°C was slightly lower than the neutral temperature of 27.1°C and moreover, the preferred temperature was very low at 21.6°C. However, the slopes of both expectation and preference were relatively low, compared with that of 0.22 found by Humphreys [9] from field studies world-wide and 0.33 by Fanger [11] in climate chamber studies.

Probit regression analysis

Probit analysis [12] is a technique, which has been widely used to evaluate subjective thermal responses in field studies ([9]; [13]; [14] and [15]). Its principle is to analyse those responses into proportions over the range of "binned" temperatures. Any cumulative relative frequency distribution, i.e. the transition line, represents a binary set of a selected category to the higher or lower adjacent [14]. The advantage of the probit regression analysis is that it can be successfully used even though the distribution of data is not a normal bell-shaped curve [9].

In this study, all categories of every thermal response were calculated into percentages within each binned temperature, and were used to give the cumulative relative frequency distributions. Each curve depicted the transition from one thermal response to the next, i.e. the transition temperature [14]. An example of the probit analysis of thermal sensation of all subjects is graphically demonstrated in Figure 1. Considering at the 50% line crossing the cumulative distribution curves, two transition temperatures can be determined: transition -1 to 0 (from slightly cool to neutral) at approximately 24.5°C, and transition 0 to 1 (from neutral to slightly warm) at 29.5°C. These transition temperatures imply the width of the "neutral" category of 5°C. The neutral temperature can also be predicted from the mean of these two transition lines ([13] and [15]). Accordingly, the neutral temperature of all subjects from the probit analysis is 27.0°C.

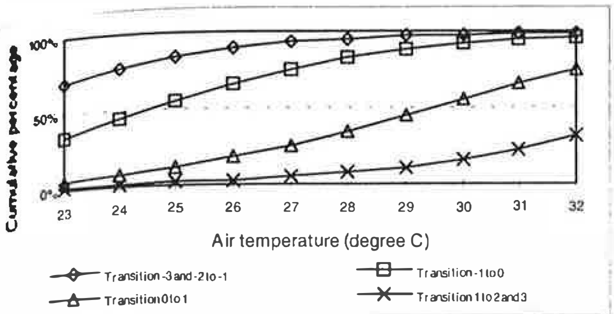

Figure 1. Probit analysis of thermal sensation of all subjects.

The same method was applied to thermal expectation and preference of all subjects and the results are shown, in comparison with those from simple regression, in Table 4.

Table 4. Comparison of T_n (°C) of all subjects from probit analysis and simple regression.

	Probit analysis	Simple regression
Expectation	26.9	26.7
Sensation	27.0	27.1
Preference	22.2	21.6

The results from probit analysis showed that the expected temperature of 26.9°C was almost identical to the neutral temperature of 27.0°C, but the preferred temperature was very low at 22.2°C. These results were quite similar to those from simple regression analysis. The probit technique was also performed on thermal responses of each subject group and the results are shown in Table 5.

Table 5. T_n (°C) of each subject group from probit analysis.

	A/C-indoor	N/V-indoor	A/C-outdoor	N/V-outdoor
Expectation	28.6	n/a	24.2	n/a
Sensation	27.3	29.9	26.0	n/a
Preference	22.3	n/a	23.5	n/a

The results of T_n in A/C buildings were contradictory. The expected and neutral temperatures of A/C-indoor at 28.6°C and 27.3°C, respectively, were higher than those of A/C-outdoor at 24.2°C and 26.0°C, respectively, although mean air temperatures of both groups were vice versa. The preferred temperatures of both A/C-indoor and A/C-outdoor were very low at 22.3°C and 23.5°C, respectively. Many results from N/V buildings were not available because of the unreliability of regression coefficients. Only neutral temperature of N/V-indoor was predicted and it was 29.9°C.

Calculating method: "Griffiths" value

Since both simple linear regression and probit analysis failed to predict T_n of every subject group, the alternative method using a calculating model, "Griffiths" value [16], was introduced. Nicol et al [15] suggested this method if the data had a small number of samples or the regression coefficient was unreliable. The model applies an assumed value of the regression coefficient of 0.33, which was derived from Fanger's chamber studies [11], to estimate the neutral temperature. The equation is:

$$T_n \quad = \quad T_a + (0 - C_m) / a^*$$

Where T_n is neutral temperature, T_a is mean air temperature, 0 is neutral category, C_m is mean comfort vote, and a^* is regression coefficient of 0.33.

The expected and neutral temperatures of each subject group were calculated using the "Griffiths" value, and are shown in Table 6.

Table 6. T_n (°C) of each subject group from "Griffiths" value.

	A/C-indoor	N/V-indoor	A/C-outdoor	N/V-outdoor
Expectation	27.3	28.0	25.1	28.9
Sensation	27.4	27.7	26.4	28.6

It is clear that the "Griffiths" value analysis is apparently a useful method to establish T_n of individual subject group. The range of the expected temperature of every group was from 25.1°C to 28.9°C, and that of the neutral temperatures, from 26.4°C to 28.6°C. The disparity between expectation and sensation of each group was not more than 0.3°C, except that of A/C-outdoor, was 1.3°C.

The results of T_n in A/C groups were lower than those in N/V groups. In A/C buildings, it should be noted that the neutral temperature of A/C-outdoor was 1°C lower than that of A/C-indoor and this phenomenon was identical to that in probit analysis. In N/V buildings, the neutral temperature of N/V-outdoor was about 1°C higher than that of N/V-indoor.

Thermal acceptability

Thermal acceptability is performed to estimate a range of temperatures the subjects voted "-1 to 1" (slightly cool, neutral and slightly warm) in thermal sensation response. It could be thought as a comfort zone, rather than a single predicted neutral temperature. Usually, it is determined by using 80% of the subjects' votes, binned against each temperature and weighted by the number of the subjects ([7] and [14]).

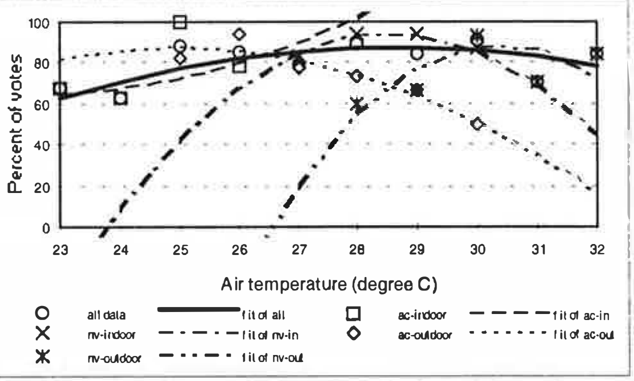

Figure 2. Thermal acceptability at the 80% line of thermal sensation votes on "-1 to 1".

In Figure 2, the technique of quadratic regression was used to analyse and to draw the curve estimated lines of all subjects and each subject group. Thermal acceptability of all subjects was between 25.5°C and 31.7°C, and this range covered the N/V groups' acceptability, but did not include the lower levels of the A/C groups. The acceptable temperatures of the subjects when out of doors of both A/C and N/V buildings were higher than those of indoors: the range of N/V-outdoor was 29.2°C to 31.6°C, while that of N/V-indoor was 26.6°C to 30.4°C; and the upper boundary of A/C-outdoor was 27.3°C, while that of A/C-indoor was 26.0°C. The lower boundaries of both A/C groups were very low and undefined because the results were in the extrapolated areas beyond the surveyed data.

DISCUSSION

Several methods of analyses were used to establish the neutral temperatures, but only "Griffiths" equation could give the results for every subject group. The probit analysis could predict the neutrality for only A/C groups, and the quadratic regression for the whole range of thermal acceptability in N/V groups.

The neutral temperature of A/C-indoor found in this study was higher than that of A/C-outdoor, although mean air temperatures of both groups were opposite. The reasons could be explained by the expectation, preference and other related parameters namely clothing insulation and air speed of the outdoors. The subjects, who were leaving indoor air-conditioned to outdoors, would expect a warmer outside air and would prefer a cooler environment, thereby reducing their clothing insulation. Furthermore, when they were exposed to a higher mean air velocity up to 0.63m/s in the cool season from the north-east, which brings a comfortably cool and dry air to the subjects in a tropical city, their neutral temperatures could probably be comparatively low. However, the difference of both neutrality temperatures was not very great, compared to what happened in the temperate or cold climates? [17].

Both neutral temperatures of N/V-indoor and N/V-outdoor were higher than that of A/C-indoor, being equivalent to 0.3°C and 1.2°C, respectively. They were not greatly different. As a consequence, the common neutrality could be estimated as 27.5°C ± 1.1°C, an average of every subject group, which was quite at the same level of the neutral temperature of all subjects. It should be noted that the variables in "Griffiths" value express the relationship of air temperature and thermal responses to the neutral temperature. This model therefore supports the concept of the adaptive approach to thermal comfort.

With the analysis in thermal acceptability, the range of acceptable temperatures of outdoors was higher than that of indoors. These extended temperatures in the outdoors could be presented as the adaptive opportunity. It can be achieved by the relationship between the extent of the comfort zone linked to the ambient temperature fluctuations, i.e. "cognitive tolerance", and the irritability of humans [2]. These will bring a new thermal comfort theory established for hot and humid climates and then the step change between indoors and outdoors, in terms of thermal environments, could be removed. The advantage of outdoor environments was supported by Evans [18]: in warm climates, outdoor spaces or semi-enclosed spaces could be used for normal daily activities if designed in relation to climate.

CONCLUSION

This paper presents a further study from the initial research [7] reported the neutrality of all subjects in transitional spaces in the cool season of Bangkok. The conclusions in this study can be drawn as follows:

Simple regression and probit analysis give the expected temperature of 26.7°C-26.9°C, the neutral temperature of 27.0°C-27.1°C, and the preferred temperature of 21.6°C-22.2°C for all subjects, but they fail to predict the neutrality for each subject group.

1. "Griffiths" value is the only method to establish the neutral temperature of each subject group: 27.4°C of A/C-indoor, 27.7°C of N/V-indoor, 26.4°C of A/C-outdoor and 28.6°C of N/V-outdoor. Quadratic regression gives the range of thermal acceptability: 26.6°C-30.4°C of N/V-indoor and 29.2°C-31.6°C of N/V-outdoor; the upper limit: 26.0°C of A/C-indoor and 27.3°C of A/C-outdoor; but the lower limits of both groups are very low and undefined. All results are beyond the current summer comfort standards of 23.0°C-26.0°C.
2. The neutrality of A/C-indoor is higher than that of A/C-outdoor, although their mean air temperatures are opposite; this phenomenon can be explained by the expectation, preference and clothing insulation of the subjects, as well as by air velocity in outdoors.
3. The "adaptive" opportunity is proposed to extended the comfort zone, applying outdoor conditions to internal transitional spaces for two advantages: human comfort and energy savings. Outdoor spaces are supported to be used as a function for daily life in the warm climates.

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