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Full Length Research Paper

Investigation of the effect of climatic adaptation on users' thermal comfort requirement in outdoor space

Ming-Jen Cheng[1]*, Jen-Hao Lo[2] and Shang-Yuan Chen[1]

[1]Department of Architecture, Feng-Chia University, Taichung, Taiwan.
[2]Ph.D. Program in Civil and Hydraulic Engineering, Feng Chia University, Taiwan.

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With the increasing demand for leisure outdoor spaces, understanding the occupants' thermal comfort requirement outdoors is an essential and forward-looking matter for designers to design more new attractive spaces. This paper presents the results of a long-term field comfort survey in shaded outdoor spaces, which primarily concerned with the comfort conditions of open spaces in cities. The database consists of 3,837 questionnaire guided interviews from field surveys in different study sites in a campus, in Taichung, throughout a whole year. The findings confirm a strong relationship between people's thermal sensation votes and the operative temperature or ET* of microclimate. There is also convincing evidence for adaptive behaviors happening, with the monthly variation in thermal neutral temperature, as well as the boundaries of comfort zone. In determining a range of temperatures around the thermal neutral temperature corresponding with 90 and 80% thermal acceptability, in this study, we apply the relationship between mean thermal sensation and percentage of dissatisfied, as illustrated in the classic PPD versus PMV curve. The relationship indicates that a large group of subjects expressing mean thermal sensation vote in the interval between -0.42 and +0.42 (or -0.76 and +0.76) could expect to have 10% (or 20%) of its members expressing dissatisfaction. Applying the criteria to each monthly regression model of thermal sensation as a function of ET* produced a mean yearly comfort band of 5°C ET* for 90% acceptability and 7°C ET* for 80% acceptability, both center on the thermal neutral temperature.

Key words: Outdoor spaces, thermal comfort, long-term field survey, thermal neutral temperature, thermal comfort band.

INTRODUCTION

The improvement of life quality has increased the demand for recreational outdoor spaces. Human beings are in favor of staying in thermally comfortable outdoor spaces for sports, leisure and social inter-activities. There are concrete evidences for the correlation between the conditions of outdoor thermal environment and usage rate of outdoor spaces (Nikolopoulou and Lykoudis, 2007; Lin, 2009; Lin et al., 2010; Hwang et al., 2011; Lin et al., 2011). In addition, global warming has rapidly aggravated the environmental conditions of outdoor space in recent years. In this context, the planning and design of outdoor spaces, which meet people's thermal comfort expectation, has become a vital issue for densely populated urban in modern cities (Nikolopoulou and Steemers, 2003; Walton, et al., 2007; Gaitani, et al., 2007).

Generally, the aspects of people's thermal comfort requirements on outdoors differ from indoors (Nikolopoulou et al., 2001; Höppe, 2002). The differences resulted from different adaptations, both in behavioral and psychological context, adopted by people to achieve thermal comfort in the two kinds of space.

The findings from many studies (Ahmed, 2003; Spagnolo and de Dear, 2003; Stathopoulos et al., 2004; Nikolopoulou and Lykoudis, 2006; Hwang and Lin, 2007; Oliveira and Andrade, 2007; Lin et al., 2010; Hwang et al., 2011) also indicated that the optimal comfort temperature (thermal neutral temperature) is subjected to the influence of local long-term climate conditions. For example, Nikolopoulou and Lykoudis conducted field

*Corresponding author. E-mail: mjcheng@fcu.edu.tw. Tel: +886-4-24517250; ext 3307; Fax: +886-4-24525397.

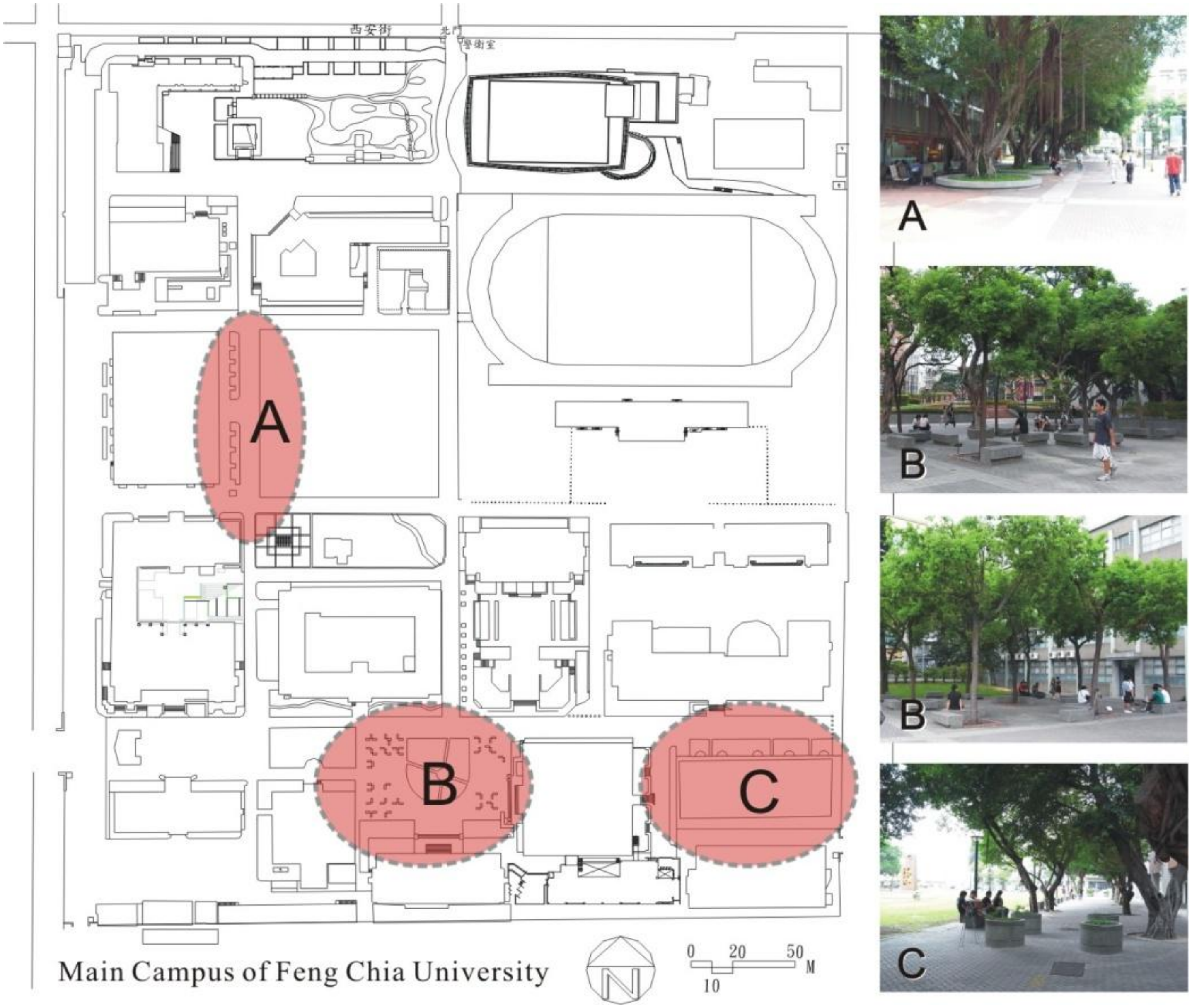

Figure 1. The situation of investigation sites in the campus and their photos.

surveys in 10 different climate zones across the Europe and reported a difference of 10°C in thermal neutral temperature (optimal comfort temperature). However, most of them carried out the thermal comfort surveys in a certain selected period in different seasons, rather than conducted successive surveys throughout a whole year, to investigate the profile of occupants' thermal responses varying with the season. Generally speaking, a longer-term survey conducted every month in a year would be helpful to understand people's thermal responses which are expected to vary with seasonal or monthly climate.

Therefore, a long term field survey throughout a whole year was performed in outdoor spaces, in central Taiwan and its findings were presented in this study.

METHODOLOGY

The field surveys were conducted from April 2007 to March 2008 in a Taichung city's campus, Taiwan. Sites surveyed in this study, as shown in Figure 1, were chosen on the principle where there are purpose-built recreational facilities and plant shaded spaces. Over 300 subjects were interviewed every month. A total of 3,837 data sets were collected, of which 2,110 were from male subjects and 1,727 from female ones. The subjects aged between 16 and 69 and are in good physical condition. The interview was done in a one-on-one way between 8 a.m and 5 p.m in sunny days and measurement of environmental parameters was done simultaneously at the time of interview. The environmental parameters monitored were those factors relating to human thermal comfort, including air temperature and humidity, mean radiant temperature and wind speed.

The questionnaire consisted of three questions to collect the information on: 1) demographical data, such as gender, age, height

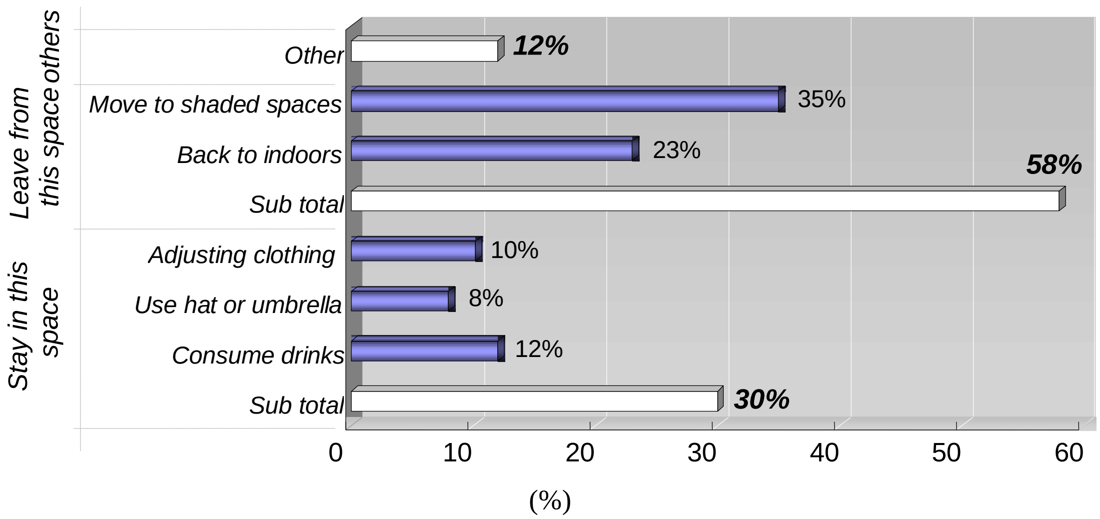

Figure 2. Summary of the behaviors that the interviewees adopted in outdoor spaces when they felt uncomfortable.

and weight of the subjects; 2) the individual adaptation and expectation to improve the thermal comfort level; 3) subjects' thermal sensation votes and wind sensation votes on the outdoor condition at the time of interview. The ASHRAE's seven-point thermal sensation scale (that is, -3 for cold, -2 for cool, -1 for slightly cool, 0 for neutral, +1 for slightly warm, +2 for warm, and +3 for hot) and three-point scale (that is, -1 for strong, 0 for neutral and -1 for weak). They were used in the questionnaire to measure the interviewee's thermal sensation and wind sensation on the outdoor thermal conditions when the interview are performed, respectively.

RESULTS

Individual adaptive behaviors

People may seek to adapt to thermal conditions and subsequently to achieve better thermal comfort through active behavioral changes when such mechanisms are available. In this study, the questionnaire on the adaptive behaviors commonly adopted by the subjects was evaluated by asking:

> "What method do you use when you feel the environment is uncomfortable (too hot or cold)? To leave from this space and move to indoors and give up your activity; shaded outdoors and continue your activity, or stay in this space and adjust clothing; use a hat or umbrella; consume cool or hot drinks or others"

Figure 2 summarizes the behaviors that the interviewees usually adopted if they feel thermal discomfort in the outdoor spaces. As shown in Figure 2, the interviewees would choose to stay in and use an adaptive strategy only in 30%, much less than to leave from the spaces in 58%. The use of a cool or hot drink (12%) was the most favored mean of adaption when they stay in, clothing adjustment (10%) and the use of a hat or umbrella (8%) were also favored means of adaptation. It is worth to note that an uncomfortable outdoor space would drive 23% of the interviewees to terminate their outdoor activities due to uncomfortable conditions. In addition, 35% of the interviewees moved to shaded outdoor spaces. In light of this, it is reasonable to suggest that proper implantation of large landscape trees to create shaded spaces can have direct and positive influence on utilization outdoor spaces.

Physical measurements

Table 1 summarized the statistic results of physical measurements. The environmental characteristic of outdoors we surveyed: air temperature and humidity are in the range of 14.2 to 37.5°C and 40 to 86%, respectively, wind speed has a maximum of 5.6 m/s, and the temperature difference between air temperature and mean radiant temperature never exceeded 5°C. According to the range of climatic conditions measured, the range of physical measurements is sufficient to cover the majority of comfort conditions of people in outdoor spaces.

Subjects' thermal sensation votes

It should be noted that people in daily life are not passive in relation to their environment but tend to make themselves comfortable. People do this by making adjustments (adaptations) to their clothing, activity and posture. For the long-term study subjects were in the recreational activities with a metabolism rate between 1.0 to 1.5 met, and had a similar activity during a year. In such a scene, the distribution of the sensation votes is interesting. If the thermal adaption, both in behaviors and psychology, had done the influence on subjects' thermal sensations, then the thermal sensation votes on same climatic condition may be different in different month. The long-term study results did show a similar outcome Figure 3. Since thermal sensation votes differ among people, even when they stay in the same environment, de Dear (1998) suggested that the bins' mean thermal sensation votes (TSV), rather than the individual actual votes, should be used in the analysis.

Based on the rounded value of ET* at the time of interview, the subjects' votes on thermal sensation were grouped into an appreciated temperature bin at increments of 1°C. Figure 4 shows the overall picture of mean sensation votes at each bin of effective temperature (ET*) very month from the long-term study. The ET* is an integrated index which takes the impact of air temperature and humidity, wind velocity and mean radiant temperature on the thermal comfort of the human body into consideration. The remaining part of this paper is discussing on the comfort (neutral) temperature and the acceptable range of temperature, were based on the information gathered from Figure 4.

DISCUSSION

Monthly neutral temperature

Neutral temperature is a temperature at which people have a neutral thermal sensation to their environment that is, they do not feel warm or cool. One recognized method for predicting the neutral temperature is the simple linear regression analysis (de Dear, 1998). Figure 4 presented the use of simple linear regression to calculate the neutral temperature (t_n). The size of bubbles in Figure 4 stands for the number of corresponding samples. Table 2 shows the estimated monthly neural temperature, which was obtained by substituting TSV = 0 into the best-fitted lines shown in Figure 4. Table 2 shows that the neutral temperature from this study ranges between 22.6 ~ 28.5°CET* during a year, with the lowest one of 22.6°CET* in January and the highest one of 28.5°CET* in August. The neutral temperatures for the hot, mild and cold seasons are 23.9, 25.7 and 27.7°CET* respectively.

The three temperatures were obtained from by pooling data sets in June, July, August and September into hot season, January, February, November and December into cool season and the remained months into mild season. An interesting point indicated by adaptive comfort model is a strong relationship between the mean monthly outdoor temperature and neutral temperature. Figure 5 establishes the correlations between the neutral temperature and mean monthly outdoor temperature (t_{om}) from the long-term study and gives:

$$t_n = 15.2 + 0.40 \times t_{om} \qquad R^2 = 0.90 \tag{1}$$

The operative temperature (t_{op}), which takes the impact of air temperature (t_a), mean radiant temperature (t_r) and wind speed on the thermal comfort of the human body into consideration, is also often regarded as another index in thermal comfort study. The monthly neutral temperatures in operative temperature from Hwang et al. (2010) were also shown in Table 2, and the correlation between neutral operative temperature and mean monthly outdoor temperature was given as:

$$t_n = 16.8 + 0.38 \times t_{om} \qquad R^2 = 0.88 \tag{2}$$

A correlation between percentages of dissatisfied and mean sensation votes for outdoors

The solid curve in Figure 6 represent the correlation, named TSV-PPD_{out}, between the thermal sensation votes (TSV) and the predicted percentages of dissatisfied (PPD_{out}) from the long-term study, as illustrated in classic PMV-PPD in ISO 7730 (2005). The approach to derive the TSV-PPD_{out} was described as follows:

In most studies on thermal comfort, it is usual to determinate the percentage of subjects reporting thermal discomfort from heat or cold at a certain temperature from calculating the proportion of subjects voting 'warm' and 'hot' or "cool" and "cold" on ASHRAE scale, respectively. By calculating the percentage of hot or cold dissatisfied and the mean thermal sensation votes of each temperature bin in each month provides the percentage of hot or cold unsatisfied as a function of the TSV (the dots in Figure 6). As shown in Figure 6, it revealed that a cumulative normal distribution exists between the percentages of unsatisfied and the TSV. Therefore, the Probit regression model of logistic analysis can be applied on the collected data to obtain the relationship between PPD and TSV. The best-fitting Probit models for the percentages of dissatisfaction due to warmness and coolness were given in Equations 3 and 4, respectively and plotted in Figure 6 (the dash lines).

$$\text{For warmness}: \text{probit}(PPD_{warm}) = 1.079 \times TSV - 1.702 \qquad R^2 = 0.89 \tag{3}$$

$$\text{For coolness}: \text{probit}(PPD_{cold}) = -1.014 \times TSV - 1.596 \qquad R^2 = 0.81 \tag{4}$$

Now we should move on to discuss the method used to determine the percentage of dissatisfied corresponding to a certain TSV. The TSV value is applied into Equations 3 and 4 to obtain the probability for warmness and coolness,

Table 1. Statistic summaries the physical measurements in each month.

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Ta (°C)	Ave.	19.7	22.9	22.9	26.1	30.3	30.5	32.0	32.9	30.2	28.2	25.0	21.9
	Min.	14.2	17.3	17.2	20.1	26.1	26.3	27.5	27.3	26.0	23.1	17.4	15.3
	Max.	25.2	28.9	30.3	32.9	33.7	36.3	35.9	37.5	33.2	33.8	31.2	26.5
RH (%)	Ave.	58.9	64.7	64.1	64.4	59.0	71.9	61.5	58.4	69.8	63.7	62.1	60.2
	Min.	39.9	38.8	38.8	50.3	40.3	49.1	46.0	45.5	58.8	50.4	51.2	39.7
	Max.	85.4	76.4	76.4	76.3	70.9	92.3	78.1	86.4	86.4	80.6	80.1	83.4
V (m/s)	Ave.	1.5	0.9	0.9	1.3	1.2	1.0	1.4	1.4	0.9	1.3	1.1	1.3
	Min.	0.1	0.1	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.3	0.3	0.2
	Max.	4.6	4.0	4.4	3.8	3.0	3.6	4.4	4.6	3.2	3.6	3.6	3.6
MRT (°C)	Ave.	22.6	24.0	24.7	28.3	32.7	32.8	33.6	35.5	33.3	30.3	27.3	24.1
	Min.	15.0	17.8	17.8	20.9	28.4	27.1	28.8	27.9	26.4	24.0	18.7	16.0
	Max.	29.4	31.5	34.6	36.0	39.0	42.7	42.1	42.1	40.7	38.4	37.8	30.5

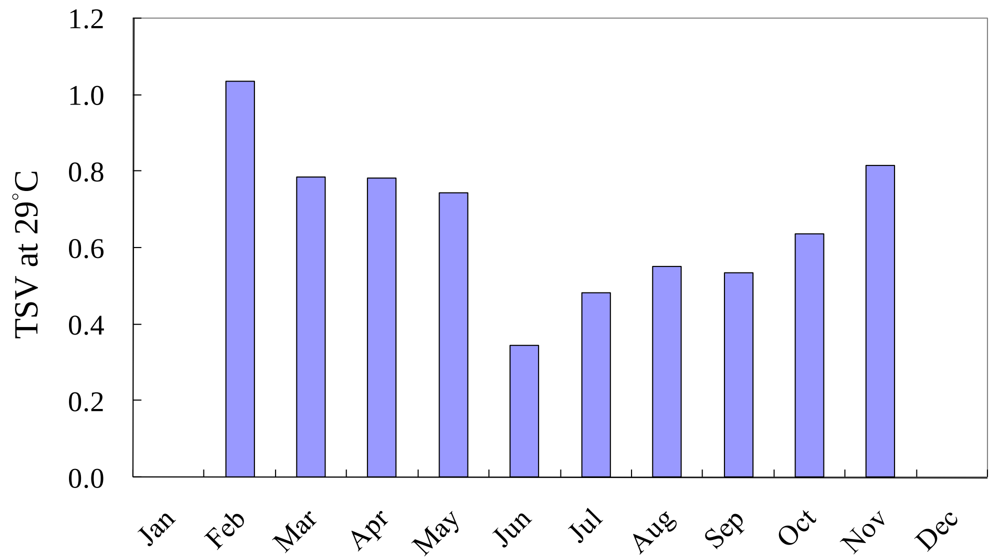

Figure 3. Monthly variation of mean TSV at same temperature of 29°C.

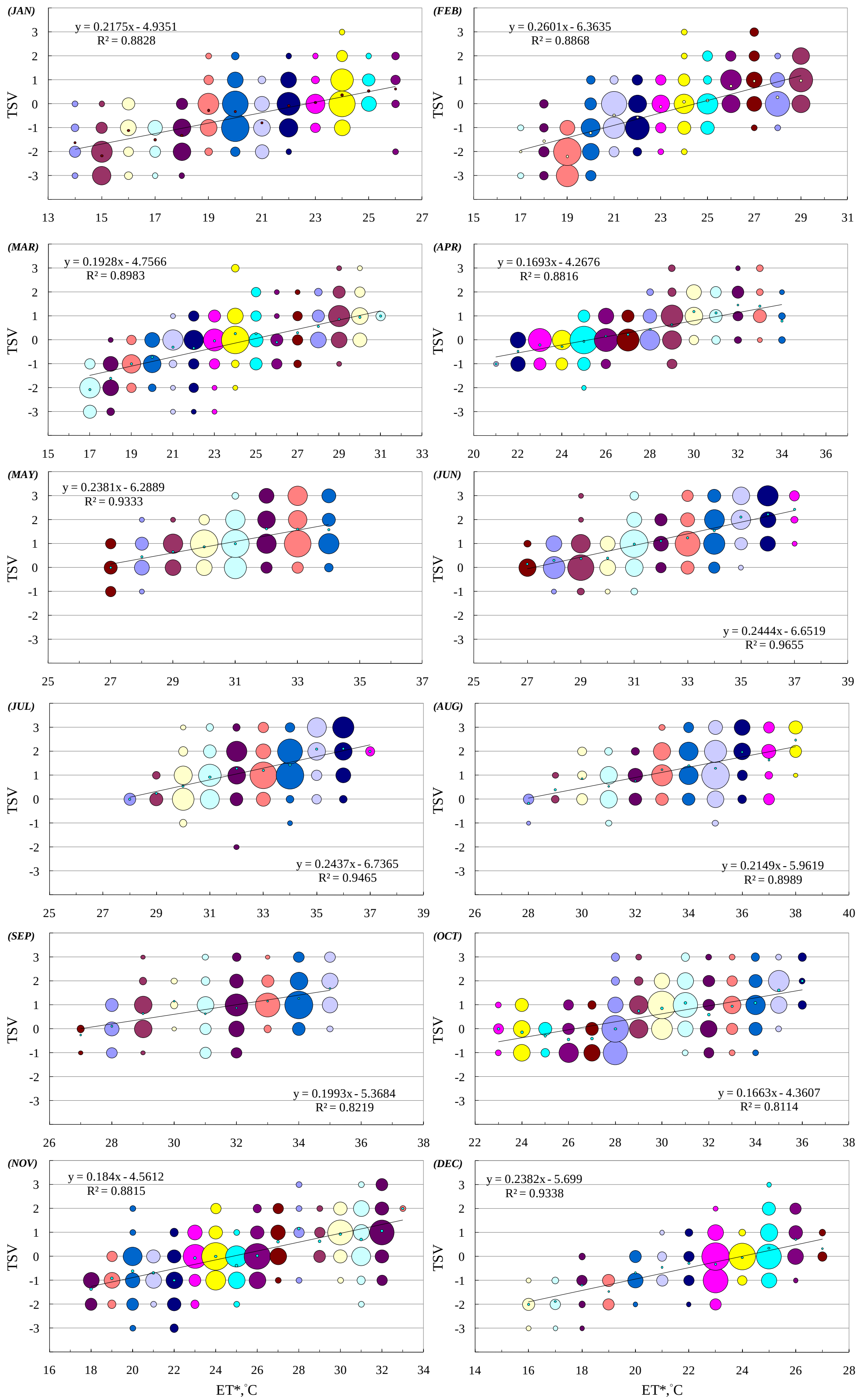

Figure 4. Distribution of mean thermal sensation votes at each ET* bin in each month.

Table 2. The estimated neutral temperature during a year.

Month	Jan.	Feb.	Mar.	Apr.	May.	Jun.
ET*	22.6	24.5	24.6	25.3	26.4	27.3
Month	Jul	Aug	Sep	Oct	Nov	Dec
ET*	28.1	28.5	27.0	26.1	24.8	23.9

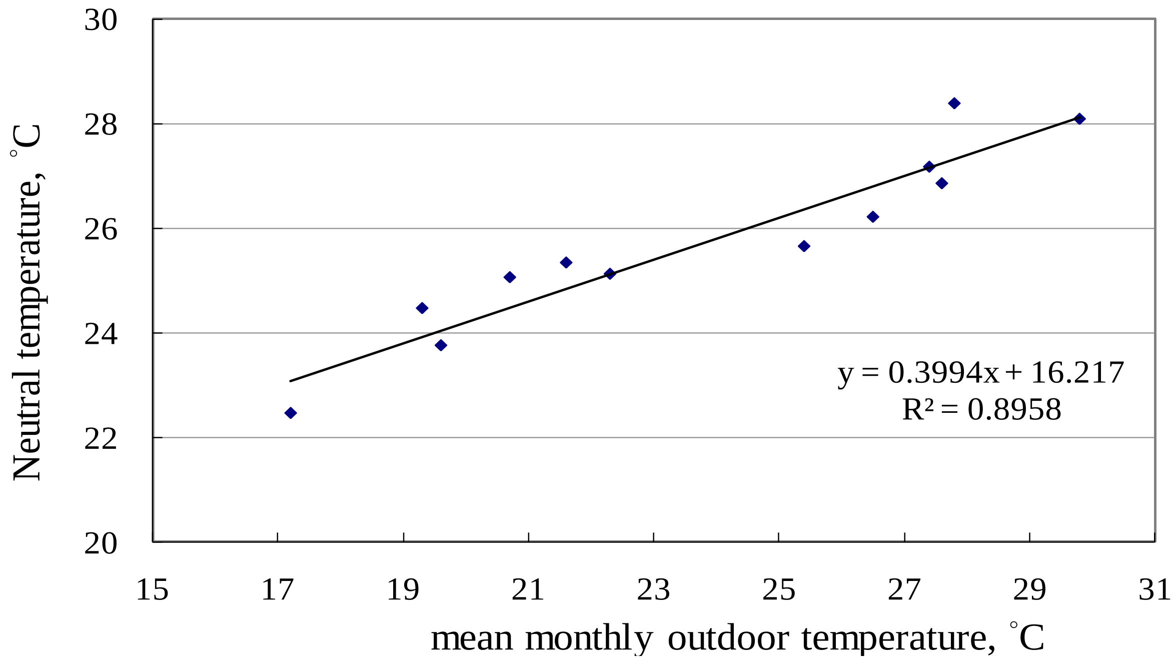

Figure 5. Correlations between the neutral temperature in ET* and mean monthly outdoor temperature.

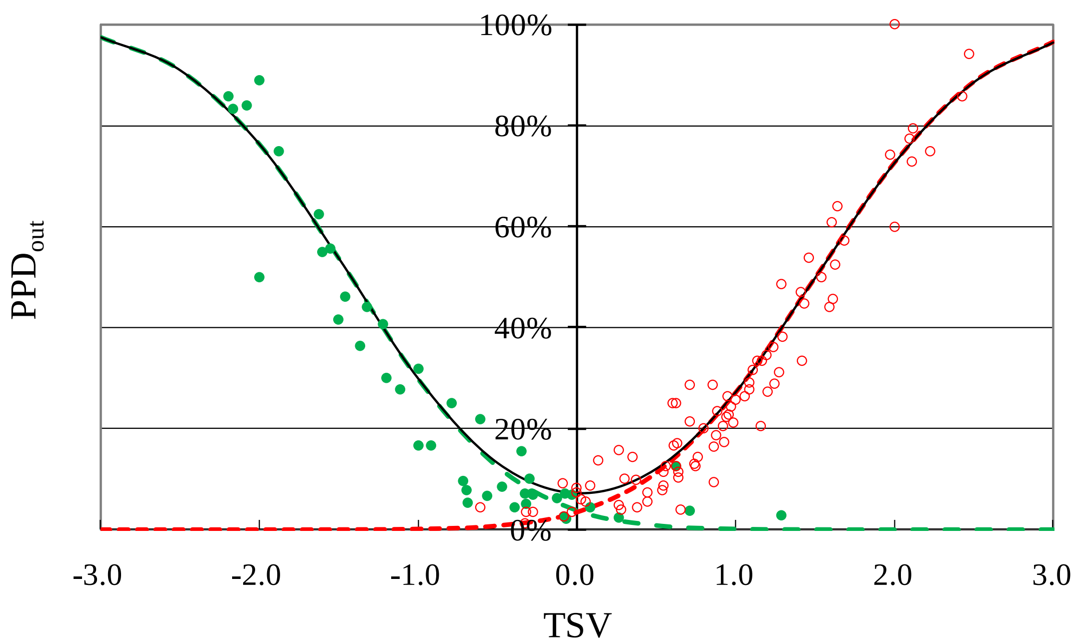

Figure 6. The derivation of the TSV-PPD$_{out}$ curve from long term surveys.

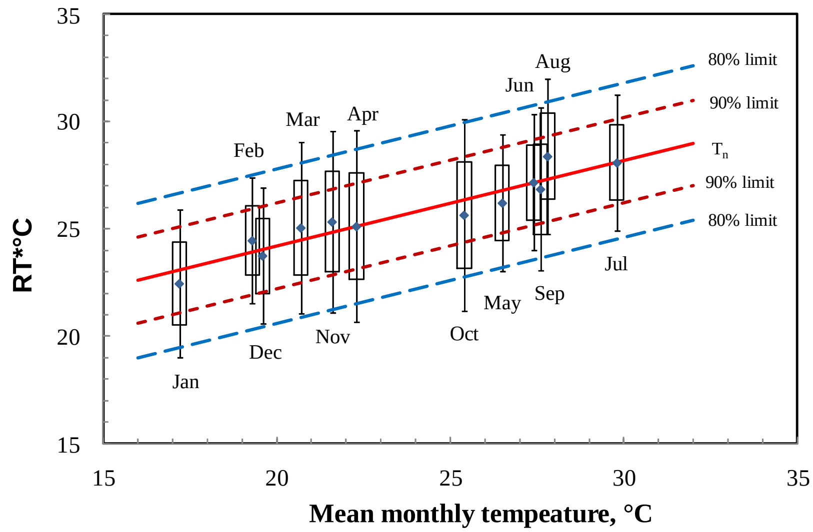

Figure 7. Adaptive comfort model derived from long term field surveys in Taiwan.

coolness, respectively. Finally, the sum of the respective probabilities of dissatisfaction due to coldness and warmness are related to the percentage of dissatisfied with respect to a certain TSV. According to the calculated percentages of dissatisfied (PPD_{out}), a new best-fitting formula, Equation 5, is established in a form similar to classic PPD equation.

$$PPD_{out} = 100 - 95 \times e^{-0.2814 \times TSV^2 - 0.0117 \times TSV^4} \qquad R^2 = 0.99 \tag{5}$$

According the Equation 5, the TSV limits for 90 and 80% acceptability are ±0.42 and ±0.76, respectively. When compared to the classic PMV = ±0.5 for 90% acceptability and ±0.85 for 80% acceptability, it seems that people in outdoor spaces have a narrower range on TSV for both 90 and 80% acceptability.

Limits of thermal comfort band

By substituting the TSV = ± 0.42 and ± 0.76 criteria into the regression model, a 90 and 80% acceptable comfort zone was produced, respectively, for each month.
Statistically, averaging all those comfort zone widths produced a mean comfort band, centralizing on the neutral temperature, of 5°C for 90% acceptability and 7°C for 80% acceptability, respectively. The resulting 90 and 80% acceptability limits are shown in Figure 7.

Air movement

During the period of field experiment performed, it was often to hear subjects that had complaint of strong or weak wind speed, so the subjects' wind sensation votes (WSV) were equivalent with the degree how the feeling actual wind speed deviated from optimal value. Thus, an acceptable range of wind speed can be determined from the results of subjects' wind sensation votes. All subjects were grouped into 56 subgroups with different air temperature and wind speed. By counting, respectively, the votes of WSV = -1, 0 and +1 for various subgroups, the percentage of people, who feel the wind is weak, neutral and strong, at each condition can be obtained (Table 3). Table 3 shows a trend that percentage of subjects complaining against the low wind speed increased as temperature raised. And, the lower the wind speed is, the more obvious the trend is. It can be seen that wind speed in the range of ≤0.5 m/s, except for the conditions of air temperature less than 22°C, is not a well received condition with having more than one-third subjects who felt the wind is too weak.

According to result of voting, when air temperature is in the range of ≤31°C, and wind speed in the range of 0.5 to 2.0 m/s, the percentage of satisfaction remains around 80% or above. In the cases of wind speed higher than 2.0 m/s, more than 20% the subjects were unsatisfied by the strong wind speed. A briefly summary can be drawn from the aforementioned discussions. A wind speed between 0.5 and 2.0 m/s can be considered as acceptable with a percentage of satisfaction over 80%. It is noteworthy that the correct method of relieving complaint of low wind speed is to cool the ambient temperature, but not to raise the wind speed, when ambient temperature is above 31°C, which will make people have a thermal sensation vote hotter than "warm". Table 3 list the distribution of percentage of votes for WSV = 0 at various combinations with different temperature and wind speed.

Table 3. Summary of subjects' wind sensation votes.

	t_a ≤19 (%)	19<t_a≤22 (%)	22<t_a≤25 (%)	25<t_a≤28 (%)	28<t_a≤31 (%)	31<t_a≤34 (%)	34<t_a (%)
v≤0.5	84 (16, 0)*	93 (2, 5)	64 (36, 0)	76 (21 ,3)	63 (34, 3)	65 (35, 0)	43 (57, 0)
0.5<v≤1	97 (0, 3)	84 (2, 14)	87 (12, 1)	82 (13 ,5)	76 (22, 2)	71 (26, 3)	56 (43, 1)
1<v≤1.5	96 (4, 0)	70 (14,16)	87 (6, 7)	93 (3 ,4)	83 (10, 7)	77 (20, 3)	68 (13, 19)
1.5<v≤2	100 (0, 0)	90 (3, 7)	85 (7, 8)	87 (6 ,7)	76 (17, 7)	80 (15, 5)	42 (55 ,3)
2<v≤2.5	52 (0, 48)	34 (13, 53)	66 (3, 31)	81 (3 ,16)	62 (0, 38)	69 (0, 31)	78 (0 ,12)
2.5<v≤3	10 (0, 90)	64 (0, 36)	45 (5, 50)	88 (0 ,12)	70 (0, 30)	37 (0, 63)	50 (0, 50)
3<v≤3.5	14 (0, 86)	11 (0, 89)	13 (0 ,87)	33 (33, 34)	38 (15, 47)	63 (26, 11)	63 (0 ,37)
3.5<v	0 (0, 100)			38 (0, 62)	67 (0, 33)	40 (0, 60)	25 (0, 75)

t_a: air temperature in °C; v: wind speed in m/s. * the numbers in the bracket are the % of votes on strong and weak wind speed, respectively.

The numbers in the bracket are arranged in an order of percentage for unsatisfied with wind too weak or strong.

The role of comfort model in the design of outdoor spaces

By computer simulation or measurements, comfort conditions in different types of outdoor space design can be tested during longer periods (season or year). Before doing this, its need here is to have a quantitative analysis tool for them to use in evaluating the thermal comfort level of outdoor spaces they designed. The adaptive comfort model we established in this study took the place to solve this problem, because it played the role of linking outdoor environment design strategies with actual human thermal comfort. The role of thermal comfort model in the design of outdoor spaces is illustrated in Figure 8 and explained as follows:

A dynamic computer simulation or on-site measurement can be applied to a particular design strategy to quantify its effect on thermal environmental conditions. After hourly simulated, or measured, values of those parameters for outdoor thermal comfort (including air temperature, humidity, wind velocity, mean radiation temperature and solar radiation) being integrated into an adaptive comfort model (Nikolopoulou and Lykoudis, 2007; Oliveira and Andrade, 2007; Lin et al., 2011; Hwang et al., 2011), the thermal sensation of people in the virtual or real outdoor environment at any given time can be well recognized. Some suggestions on how to take measures to ameliorate the microclimate of the outdoor space and enhance human thermal comfort can be made from analyzing the results of long-term evaluation, in order to help designers to design more attractive new spaces. In this regard, the outdoor adaptive comfort model we established is important and practical.

CONCLUSIONS

The results of the present study showed that the respondents achieved thermal comfort throughout the year in outdoor spaces. The main findings of the study were the variability of acceptable conditions at different times of the year, a good relationship between neutral and mean monthly outdoor temperatures. The study also recommended an adaptive thermal comfort model for

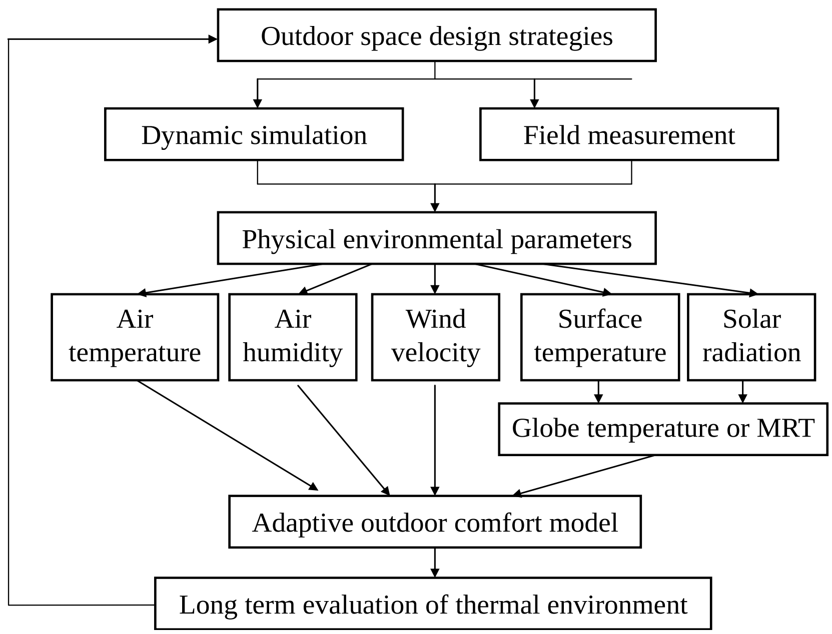

Figure 8. Relationship between outdoor thermal comfort evaluation model and outdoor.

outdoor spaces from long-term field surveys in Taichung, Taiwan. Some key conclusions were found as follows:

1). The results of regressive analysis of subjects' thermal sensation votes on ET* (or operative temperature) indicated that the people have a shift in thermal neutrality. Investigated neutral temperatures showed a variation of nearly 6°C on a yearly basis, 22.6°C for January and 28.5°C for August. With each monthly mean temperature representing the climatic changes, results of their linear regression analysis indicate that a significant linear correlation exists between subjects' neutral temperature and the outdoor mean temperature. This provides a way for determining the outdoor thermal neutral temperature for cities in Taiwan from their mean monthly outdoor temperature.

2). By applying the Probit model of logistic regression on the percentages of dissatisfied by hot and cold, we derived a new relationship between thermal sensation votes and predicted percentage of dissatisfied in outdoor spaces, named $TSV\text{-}PPD_{out}$. Based on the $TSV\text{-}PPD_{out}$ curve, the limits of TSV corresponding to 80 and 90% thermal acceptability occurred at ±0.42 and ±0.76, respectively. And, we established a comfort band of 5°C for 90% acceptability and 7°C for 80% acceptability, respectively, both centering on the neutral temperature.

3). A briefly summary had been drawn from the analysis on subjects' wind sensation votes: a wind speed between 0.5 and 2.0 m/s was considered as acceptable with a percentage of satisfaction over 80%. Attention to the role of thermal comfort model in outdoor space design may not only to help the designers on the design of attractive outdoor spacer, but also to contribute to the use of outdoor spaces, to give life back to cities' open spaces and to increase residents' social interaction.

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