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Outdoor thermal sensation and logistic regression analysis of comfort range of meteorological parameters in Hong Kong

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Abstract

Warm and hot days account for most of the time in Hong Kong. Outdoor thermal comfort studies in Hong Kong should give its first consideration to warm and hot days. This study presents investigations about thermal comfort through 1600 human subject responses from the onsite survey with concurrent meteorological parameter measurements. Probit analysis was used for searching the thermal neutral range of Hong Kong residents in a year span. Logistic regression was used for locating the meteorological parameter ranges for thermal neutral and comfort conditions. It is shown that people had difficulties defining their actual thermal feelings near the thermal neutral status when being asked to use the nine-point thermal sensation scale. Obvious thermal adaptation effect for thermal neutral conditions were observed among Hong Kong residents over the seasons in a year. The transitional seasons had wider thermal neutral range than that of winter and summer. Summer had the narrowest thermal neutral range. Wind and solar radiation had an interaction effect with air temperature in determining thermal sensation and thermal comfort. Wind can effectively offset the negative effect of solar radiation in summer when the air temperature was lower than 31 °C. The thermal comfort condition allowed a higher limit of solar radiation than the thermal neutral condition when the air temperature was lower than 31 °C. The investigations in this study provide some unique insight into the way to assess urban thermal comfort in the building design stage.

Keywords:

Outdoor thermal comfort, Subtropical climate region, Thermal neutrality, Logistic regression, Comfort range of meteorological parameters

Nomenclature			
λ	Thermal stimulus	SET*	Standard effective temperature
μ	Mean value of the distribution	T_a	Air temperature (°C)
σ	The variance of the distribution	T_a'	Centered air temperature (°C)
$f(\lambda)$	Distribution function	T_{op}	Operative temperature (°C)
clo	Unit of the clothing value	T_{mrt}	Mean radiant temperature (°C)

dP	Increment of probability	${T_{mrt}}'$	Centered mean radiant temperature (°C)
dλ	The increment of thermal stimulus	TS*V*	Thermal sensation *v*ote
Berkeley Comfort model	The UC-Berkeley Thermal Comfort Model	TC*V*	Thermal comfort *v*ote
Centered-z	Centered independent *v*ariables	UTCI	The universal thermal climate index
P	Probability	*v*	Wind speed (m/s)
PET	Physiologically equivalent temperature	v'	Centered wind speed (m/s)
PMV	Predicted mean vote	WBGT	Wet bulb globe temperature
RH	Relative humidity	*Y*	Probit *v*ariable
ROC curve	Receiver operating characteristic curve	z_o	The original independent *v*ariable

1. Introduction

Hong Kong, being one of the highest density cities in the world, requires good planning and designing of the public open area [1]. According to the statistical data collected by the Hong Kong Housing Authority in 2009, the domestic living space in public housing was merely 12.4 m^2 per person [2]. Driving by such a high living compactness, residents have a stronger motivation to 'borrow' public open spaces for leisure activities [2], indicating that these spaces in Hong Kong act as a virtual extension of home [3]. To build a more pleasant and liveable public outdoor environment to stay, thermal comfort is one of the important considerations.

Time of the year is a significant factor that should be valued more in the outdoor thermal comfort study. Different time in the year has its own air temperature pattern and is unalterable. It is undeniable that air temperature is the most important factor that influences people's thermal feelings in a whole year span [4, 5]. Designing an outdoor thermal environment to satisfy hot conditions will have to sacrifice its benefit to the cold conditions and vice versa. Providing thermal comfort for the most of the time is the optimized decision to make strategically. The thermal comfort studies related to Hong Kong, a typical subtropical city known as having long summers and short winters with high humidity, should focus more on warm and hot days.

Outdoor thermal comfort of a human body can be achieved when the following factors are balanced: air temperature, wind speed, humidity, solar radiation, personal activity and clothing [1]. Many studies have focused on thermal comfort targeting at the subtropical area in recent years. Some studies focus on searching the most suitable thermal comfort model to evaluate the local thermal environment [6-10]. The differences of the predicted performance by some frequently used thermal indices, including PMV (predicted mean vote), WBGT (wet bulb globe temperature), PET (physiologically equivalent temperature), SET* (standard effective temperature), the Berkeley Comfort model and the UTCI (the universal thermal climate index), have been indicated for the subtropical climate [6-10]. On the other hand, some studies focus on evaluating the practical measures for improving thermal comfort. Liu et al. [11] proposed that the elevated building design can help provide better thermal comfort in the summer conditions in the open space underneath the building. Kong et al. [12] compared various types of trees on improving thermal comfort condition and found that trees grown in the high-density settings performed better than the open settings by reducing the similar amount of solar radiation incident on urban surfaces (maximum value 3.9 and 5.1 °C respectively) and at the same time maintaining the wind speed level. Chen and Ng [13] simulated the cooling effect of downtown greenery on the urban microclimate using ENVI-met and found both the greenery design scenarios with tree and grass can help reducing the average PET of the domain by 0.4 K. The other studies focus on the local characteristic of Hong Kong residents. Li et al. [14] investigated the UTCI ranges where wind or solar radiation would take the dominant places based on the desirability of Hong Kong residents and found the UTCI of 26 °C was the breaking point. Lam and Lau [15] examined the thermal perception differences in the summer of Hong Kong and Melbourne, and found that Hong Kong residents had higher UTCI (23.5 °C) for thermal neutrality than Melbourne residents (19.3 °C).

Many efforts aimed at providing a reference to the city planners by building up thermal comfort prediction models and improving the evaluation methods or simulation tools. The suitable ranges of meteorological parameters combination to achieve thermal neutrality and thermal comfort conditions targeted on Hong Kong residents can serve as an effective reference. For instance, Ng and Cheng [16] proposed a comfortable outdoor temperature chart of Hong Kong to guide the local urban design, which was based on the studies conducted in regions that had similar climate conditions like Hong Kong. Still, there is a need to provide such kind of reference based on the local characteristics of Hong Kong residents.

The scale of TSV (Thermal sensation *v*ote) built the relationship between a linguistic expression and a numeric voting, such as the explanation for "Neutral" was TSV = 0. However, the sensations on the ASHRAE scales were shown to have more than one meaning as discovered by Humphreys and Hancock [17]. The actual thermal sensation felt by human subjects might not always be the one they voted. Moreover, translating the TSV scale into different language environment might also cause ambiguity, such as the translation of "slightly" and "very". Thermal neutrality was widely discussed as a special kind of thermal sensation due to the fact that it is recognized as the most energy-saving status of the human body and its close relation with thermal comfort in the built environment [18-20]. "TSV = 0" was widely used to describe thermal neutrality in many studies [21, 22], while the others widened its span to [-0.5,0.5] or [-1, 1] [8]. The question of what is the proper way to evaluate thermal neutrality using thermal sensation scale is still in debate [23]. Moreover, it is not clear whether this status will always be the thermally comfortable status in the summer outdoor environment.

The present study aimed to answer the following questions.

1. Is it suitable to consider thermal neutrality as "TSV = 0"?
2. What are the ranges for thermal neutrality for Hong Kong residents in different seasons?
3. What are the suitable ranges of meteorological parameters for thermal neutrality and thermal comfort in the Hong Kong summer?

This paper is comprised of four main parts. The statistical data of ten-year air temperature of Hong Kong is presented as a background information. Then the unclear boundary of thermal neutral sensation is analysed based on the data of the Hong Kong residents. The change of thermal neutral range along with the seasons is revealed from the probit analysis. The suitable ranges for thermal neutrality and thermal comfort in Hong Kong will be located and discussed in the final part of results using the logistic regression.

2. Methods

This section first briefly describes the method of on-site data collection for meteorological data and survey response. Then the probit analysis method is introduced, followed by the logistic regression model.

2.1 On-site measurement and surveys

We collected thermal feeling response of human subjects with concurrent measurement of the meteorological parameters on the campus of the Hong Kong Polytechnic University located in

Hong Kong. Hong Kong is a crowded city with typical characteristics of the subtropical climate. It normally has long hot and humid summers and warm winters accompanied with the short and unobvious transitional seasons.

The on-site measurement was conducted from June 2016 to September 2018. The real-time meteorological data was collected by a micro-climate station as shown in Fig. 1. Parameters such as air temperature, globe temperature, relative humidity, wind speed, wind direction, long-wave irradiance, and short-wave irradiance were collected. The technical information of these sensors is listed in Table 1. The calculation method of the mean radiant temperature T_{mrt} and the operative temperature T_{op} can be referred in our previous study [24].

The human subjects were required to wear normal clothing to join the experiment. The average clothing value in summer was 0.35 clo as listed in Table 2. In total 1600 survey responses were collected during the experimental period. The survey focused on the perception of overall thermal sensation and thermal comfort, along with the collection of individual information (gender, age, height, weight, and clothing information). An extended nine-point scale was adopted to evaluate the subject's thermal sensation and thermal comfort. The extended thermal sensation scale followed the ASHRAE seven-point scale [25] with "very hot" and "very cold" added at the terminals. The thermal comfort scale was stated as very uncomfortable (-4), uncomfortable (-3), slightly uncomfortable (-2), just uncomfortable (-1), neutral (0), just comfortable (1), slightly comfortable (2), comfortable (3) and very comfortable (4).

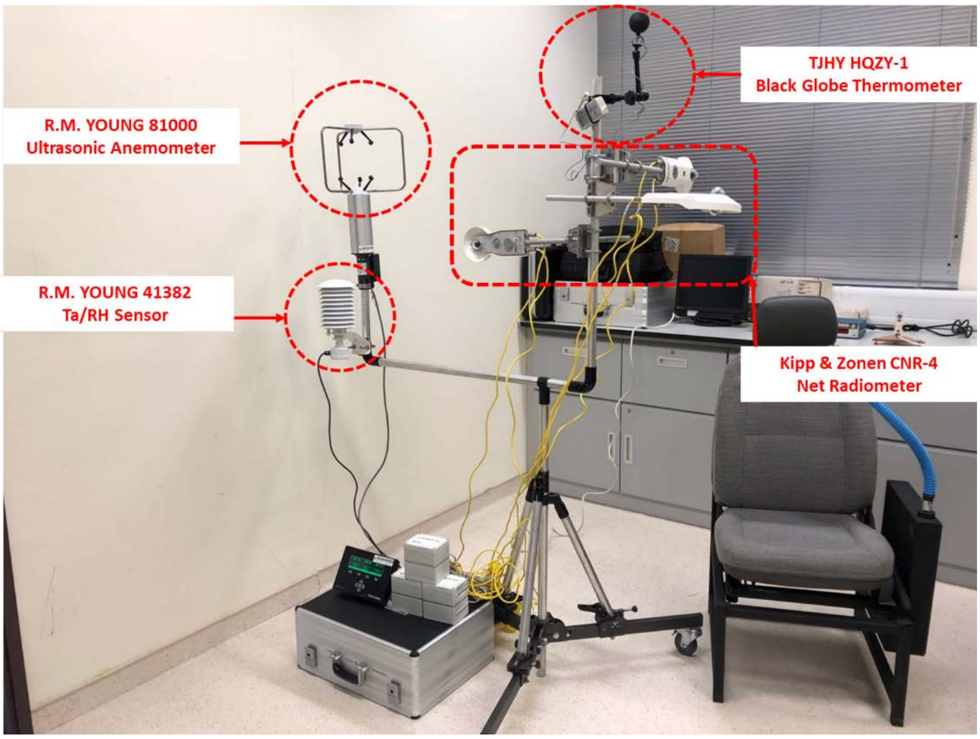

Fig. 1 Microclimate station [24]

Table. 1 Technical information of experimental equipment

Measured parameters	**Sensor/Equipment**	**Range of measurement**	**Accuracy**

Air temperature (T_a)	RM 41382	-50~50 °C	±0.3 °C
Relative humidity (RH)		0~100 %	±1 %
Wind speed (v)	R.M. YOUNG 81000	0~40 m/s	±0.05 m/s
Long-wave radiation (Q_l)	Kipp & Zonen CNR-4	-250~250 W	<10%
Short-wave radiation (Q_s)		0~2000 W	<5 %

Table. 2 General information of the participants

	Age	**Weight (kg)**	**Height (cm)**	**Clothing Value (clo) Winter / Summer**
Mean	24.5	59.3	166.8	0.68 / 0.35
Standard deviation	7.6	11.9	8.1	0.24 / 0.14
Minimum	15.0	40.0	148.0	0.18 / 0.16
Maximum	63.0	96.0	194.0	1.20 / 0.83

2.2 The statistical method

2.2.1 Locating the thermal neutral ranges

(a) Proof of unclear voting near the thermal neutral status

An independent t-test was used to prove people had unclear voting near neutral status. A null hypothesis that people make no distinction among the categories of "slightly cool", "neutral" and "slightly warm" was made. The voting of these three categories was selected out of all the on-site results. Then, the original places of these categories were replaced by a set of random integers in the target ranges. The set of data which comprised of the original voting and random integers within target ranges was compared to the original set of data using an independent t-test. The null hypothesis would be satisfied when two sets of data were regarded as selecting from the same population from a statistical point of view (p-value > 0.05).

(b) Locating the neutral thermal range using the probit analysis

The probit analysis was originally developed for the agricultural purpose, quantifying the toxicity of the pesticides. The response was binary: the insect was either dead or alive. This method was then extended with applications in analyzing thermal comfort field data starting from Charles Webb [26]. The requisite binary response was obtained by separating the thermal response data into two groups [20]. In this case, the nine-point thermal sensation votes could be arranged in eight ways of response following the patterns listed in Table 3. Take the fourth row in Table 3 as an example, the Group 1 of the fourth row is the total percentage of people voting "cooler than neutral" while the Group 2 represents the total percentage of people voting "neutral and warmer". Grouping the data in the form of either Group 1 and Group 2 can be analysed in the same way, it is preferred to group the data in the manner of Group 2 in the following analysis.

The meaning of "Probit" is the probability unit. It describes the response probability to the certain stimulus which follows the normal distribution [27]. In the field of thermal sensation, for any human subject, there will be a certain level of thermal stimulus intensity that below which the response does not occur and above which the response occurs. Such a value is designated as the threshold in this paper. Though this threshold value varies from person to person for a certain level of thermal stimulus, when a group reaches a certain population, the distribution of threshold over the stimulus should have its own quantitative characteristics. The surveyed thermal sensation voting follows a normal distribution which fits the basic assumption of probit analysis, hence the probit analysis is used to reveal the characteristic of neutral thermal sensation for the Hong Kong residents.

If the intensity of the thermal stimulus is measured by λ, the distribution of thresholds may be expressed by Eq. (2.1). dP is a proportion of the whole population that consists of individuals whose thresholds lie between λ and $\lambda + d\lambda$. If a thermal stimulus intensity λ_0 is given to the entire population, the proportion of response in the overall population is P, as stated in Eq. (2.2). If $\lambda \in [0, +\infty]$, Eq. (2.3) can be achieved. However, the physical explanation of one equation in the application of reality is what matters. For this consideration, the analysis shown in the result part will merely cover the real outdoor situation. When the response to the overall range of stimulus $f(\lambda)$ satisfied the assumption that it follow a normal distribution, Eq. (2.1) can be written as Eq. (2.4) and the sigmoid curve from probit regression can be generated [27].

$$dP = f(\lambda)\, d\lambda \qquad (2.1)$$

$$P = \int_0^{\lambda_0} f(\lambda)\, d\lambda \qquad (2.2)$$

$$\int_0^{\lambda_0} f(\lambda)\, d\lambda = 1 \qquad (2.3)$$

$$P = \int \frac{1}{\sqrt{2\pi}\sigma} exp[-\frac{(\lambda-\mu)^2}{2\sigma^2}]\, d\lambda \qquad (2.4)$$

$$P = \int_{-\infty}^{Y-5} \frac{1}{\sqrt{2\pi}} exp[-\frac{(\lambda)^2}{2}]\, d\lambda \qquad (2.5)$$

$$Y = 5 + \frac{1}{\sigma}(\lambda - \mu) \qquad (2.6)$$

Table. 3 Example of thermal sensation vote combination

Group 1	**Group 2**	**Abbreviation for Group 2**
P(-4)	P(-3)+P(-2)+P(1)+P(0)+P(+1)+P(+2)+P(+3)+P(+4)	P(TSV ⩾ -3)
P(-4)+P(-3)	P(-2)+ P(-1)+P(0)+P(+1)+P(+2)+P(+3)+P(+4)	P(TSV ⩾ -2)
P(-4)+P(-3)+P(-2)	P(-1)+P(0)+P(+1)+P(+2)+P(+3)+P(+4)	P(TSV ⩾ -1)
P(-4)+P(-3)+P(-2)+P(-1)	P(0)+P(+1)+P(+2)+P(+3)+P(+4)	P(TSV ⩾ 0)
P(-4)+P(-3)+P(-2)+P(-1)+P(0)	P(+1)+P(+2)+P(+3)+P(+4)	P(TSV ⩾ +1)
P(-4)+P(-3)+P(-2)+P(-1)+P(0)+P(+1)	P(+2)+P(+3)+P(+4)	P(TSV ⩾ +2)
P(-4)+P(-3)+P(-2)+P(-1)+P(0)+P(+1)+P(+2)	P(+3)+P(+4)	P(TSV ⩾ +3)
P(-4)+P(-3)+P(-2)+P(-1)+P(0)+P(+1)+P(+2)+P(+3)	P(+4)	P(TSV = +4)

The proportion P under a certain thermal stimulus intensity λ_0 (Eq. (2.4)) can be transferred to Eq. (2.6) by a probit function Eq. (2.5), Y is the probit value of P [27]. Y follows a normal distribution and has a mean value of 5 and a standard deviation of 1 [27]. Further mathematic description about the probit transformation can be referred from the book by DJ Finney [27].

The eight ways of responses listed in Table 3 will produce eight probit regression lines which follow the pattern shown as Eq. (2.6). $\frac{1}{\sigma}$ means the corresponding value change of the probability density function when the independent variable λ change by one unit. The set of probit regression lines derived from different batches of thermal sensation voting data should be parallel, because the data follow the same normal distribution and have the same residual standard deviation of thermal sensation voting across the thermal stimulus range.

2.2.2 Locating the suitable meteorological parameters combinations using logistic regression

Logistic regression was used in locating the meteorological parameters combinations for thermal neutral and thermal comfort status in the Hong Kong summer. Logistic regression was developed based on the logit transformation which was first introduced by Cox [28]. The logit transformation dealt with the odds ratio as shown in Eq. (2.7). Logit transformation was *ln (odds)* as shown in Eq. (2.8) [28]. The linear relationship between the independent variables and the dependent variables as shown in Eq. (2.9) was able to be achieved through the logit transformation [28]. Therefore, there is no need to make the linear relation assumption between the independent variables and the dependent variables. Eq. (2.10) and Eq. (2.11) were the transformations of Eq. (2.9).

$$odds = P/(1-P) \qquad (2.7)$$

$$Logit\ P = ln[\frac{P}{1-P}] \qquad (2.8)$$

$$Logit\ P = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_p x_p \qquad (2.9)$$

$$P = \frac{\exp(\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_p x_p)}{1+\exp(\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_p x_p)} \qquad (2.10)$$

$$1-P = \frac{1}{1+\exp(\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_p x_p)} \qquad (2.11)$$

$$Centered - z = z_0 - mean(z_0) \qquad (2.12)$$

As the logistic regression aimed at dealing with the problems with a binary response, the thermal response from the survey was divided into two groups. The dependent variable *P* was termed as the occurrence probability of the positive response in the logistic regression part. For the purpose of predicting thermal neutrality, the positive response was defined as when TSV was "-1 slightly cool", "0 neutral" and "+1 slightly warm"; other than the listed three TSVs were termed as zero response. For the purpose of predicting thermal comfort, the positive response was defined as TCV (thermal comfort vote) voted in the comfortable side; the zero response was defined as TCV voted in the uncomfortable side.

Only the meteorological parameters such as T_a (air temperature), T_{mrt}-T_a, v (wind speed) and the product of these parameters were included as the independent variables. RH (relative humidity) was not included as RH remained almost constant throughout the whole summer in Hong Kong, except for the rainy days. The RH in Hong Kong summer was around 60% to 75%. The difference between T_{mrt} (mean radiant temperature) and T_a, $(T_{mrt}-T_a)$ was used here to present the intensity of solar radiation. The higher the difference, the stronger the solar radiation is [29]. The training data was selected from the survey response obtained on-site for two summers in Hong Kong. The highest clothing value in the selected data was limited to 0.48 clo, which represented the normal dressing pattern of Hong Kong residents during summer time. The selected data covered the activity level up to 1.2 Met, mainly the sitting and standing conditions were considered.

As both the first-order parameters and their product terms were considered in the regression, multicollinearity problem should be considered. High level of multicollinearity was introduced by considering the product terms in the regression, which could produce large standard errors for the regression coefficients of the lower order variables [30]. To eliminate this effect, centered variables as the method in Eq. (2.12) were used both in forming the product terms of the interaction effect and in the first-order variables for the logistic regression analysis [30].

The concept of classification cutoff was used to distinguish the positive response from the logistic regression result. When P was larger than the classification cutoff, the predictive response was termed as a positive response. The classification cutoff point was defined as the point where there had the highest sensitivity and specificity. The ROC curve, which showed the relation between false positive rate and true positive rate, was utilized to find the classification cutoff [31]. The result of the ROC curve is shown and discussed in the result part.

3. Results and discussion

3.1 Hong Kong air temperature data analysis

The result and discussion part starts with the analysis of the air temperature collected in the King's Park observation point by the Hong Kong Observatory. The King's Park observation point is located in the Kowloon city of Hong Kong, where has a high density of high-rise buildings and living population. The data collected at this observation point is more appropriate in representing the air temperature within the city considered the heat island effect. Fig. 2 presents the monthly average air temperature throughout the past 10 years. It is noticeable that nearly half of the time of every year had a monthly recorded history higher than 26 °C, started from May and ended in October. The average air temperature within the city has been raising in the past 10 years. The most obvious increase occurs in summer, with an increase of 1.17 °C from the year of 2008 to 2017. Fig. 3 shows the number of days that have the air temperature recording over 30 °C. It is noticeable that both May and October had the air temperature recording over 30 °C while these two months were regarded as the transitional seasons in Hong Kong. This observation shows an obvious trend that the summer period in Hong Kong has been extended. The total number of days that had recording over 30 °C also showed an increasing trend from 98 days observed in 2008 to 119 days in 2017, with a slight fluctuation. The highest record of a total number of days over 30 °C was obtained in the year of 2014, which was 136 days. Though the recording of the following years showed a slight decrease, still there was almost one-third of the time over the year had such high air temperatures. Hence, when considering the practical measures to improve outdoor thermal comfort, more efforts should be placed at targeting the intolerable hot conditions.

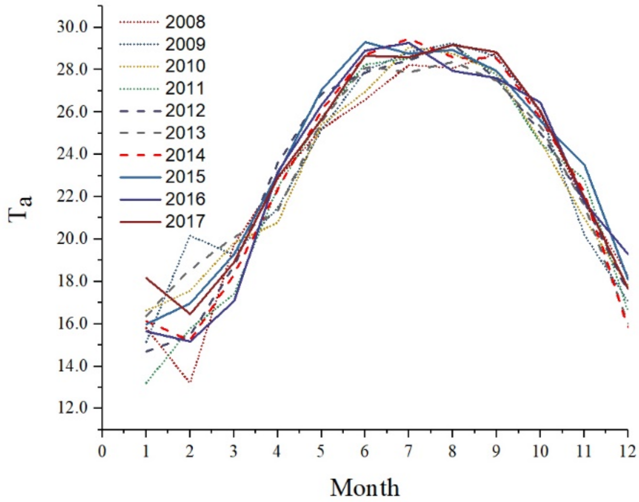

Fig. 2 Monthly average air temperature for the past 10 years in King's Park Observation point

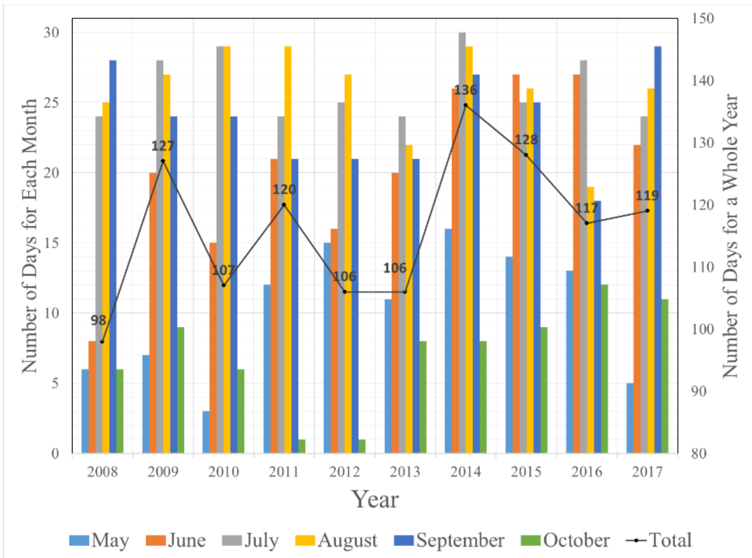

Fig. 3 The number of days that have air temperature recording over 30 °C

3.2 Data analysis related to the thermal neutral condition

3.2.1 Unclear voting around the thermal neutral range

To answer the question of whether TSV = 0 could represent "thermally neutral" or not, the original surveyed dataset was compared with the dataset including the generated random values. In the dataset with random values, the target values were replaced with the random integer generated by Matlab within a certain range. For example, the original voting ranging from "-2" to "0" were sorted out and replaced with a random integer ranging from "-2" to "0" to form a random dataset. In total, six new random datasets were built as shown in Table 4. These new datasets were compared with the original surveyed dataset by the independent t-test. The null hypothesis was that the two datasets were from the same population. If the null hypothesis was satisfied, the actual voting of the certain range had no difference with random voting. From the results shown in Table 4, it is noticeable that both replacing the actual voting "-1", "0" and "0", "1" with the random values in these two ranges created no differences when compared to the original voting group (p-value much higher than 0.05). But further replacing the range to "±2" or "±3" could create differences (p-value below 0.05). This comparison was able to illustrate a phenomenon that when people were in their thermal neutrality, they tended to vote from "slightly cool" to "slightly warm". People had confusion on deciding the appropriate voting to describe their thermal status when they were around thermal neutrality. However, when the thermal condition tended to the warm or cool side, their voting started to reflect their actual thermal feelings. Thus, TSV from "slightly cool" to "slightly warm" was used when considering the concept of "thermal neutrality" in the further analysis of this study. This present finding only used the data obtained from the outdoor environment, the data of indoor thermal sensation was not included, which makes this finding only applicable to the outdoor thermal environment so far.

Table. 4 Significant level of comparison between original data and random data

Cool side	***p*-value**	**Warm side**	***p*-value**
Random number [-1,0]	0.956	Random number [0,1]	0.413
Random number [-2,0]	0.015*	Random number [0,2]	0.023*
Random number [-3,0]	0*	Random number [0,3]	0*

* p-value<0.05.

3.2.2 Defining outdoor thermal neutral range in Hong Kong

Fig. 4 and Fig. 5 show the P-P plot (probability–probability plot) and the residual plot of the surveying TSV. The data points basically followed the theoretical line of $y = x$ as shown in Fig. 4. Fig. 5 shows the distribution of the difference between the calculated cumulative normal distribution value and the observed cumulative value. The data points were distributed evenly around $y = 0$ with a slight fluctuation. As the absolute deviation was lower than 0.05, which was within the range of allowable distribution probability difference, the on-site survey TSV data was considered as following the normal distribution.

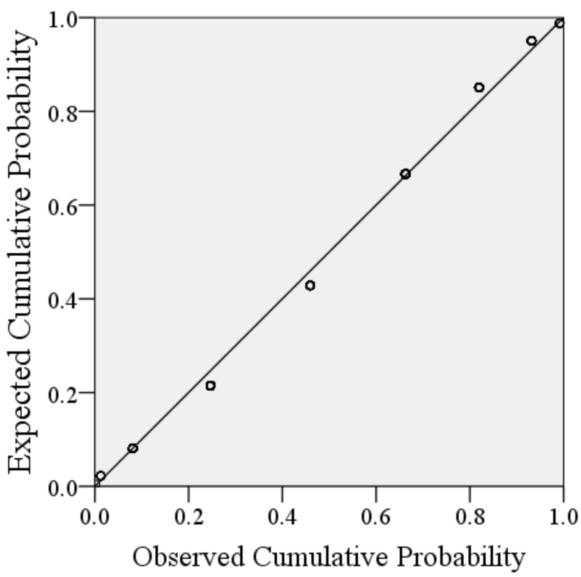

Fig. 4 P-P plot of on-site survey thermal sensation vote data

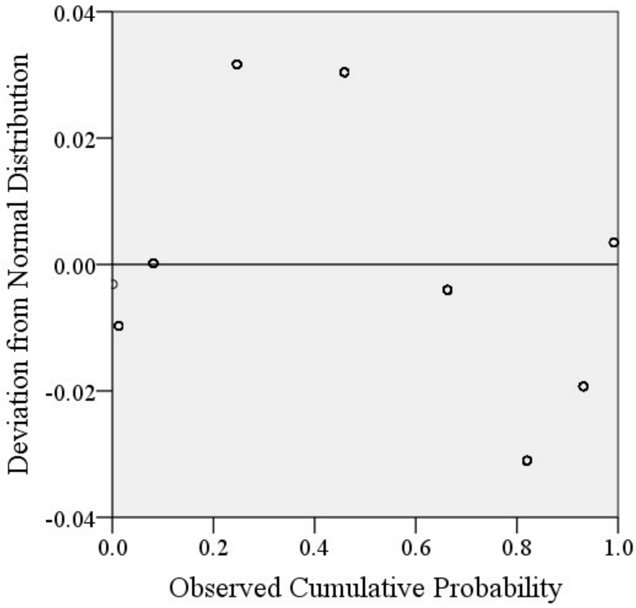

Fig. 5 Normal distribution residual plot of on-site survey thermal sensation vote data

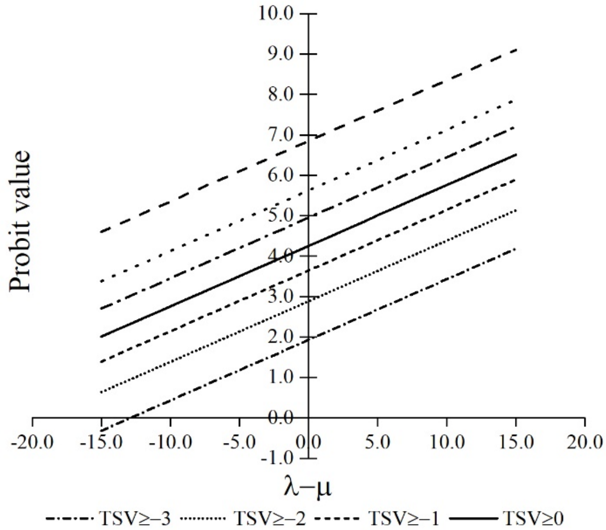

Fig. 6 The seven probit regression lines

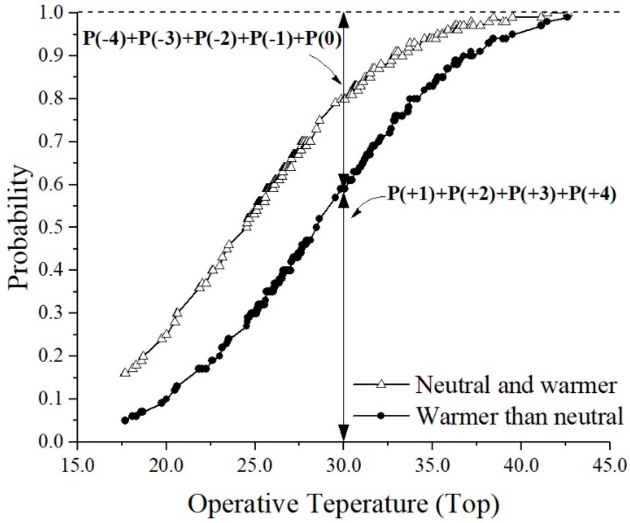

Fig. 7 Sigmoid curves of the “neutral and warmer” and “warmer than neutral” groups

The whole set of original data was used in the probit analysis. Totally seven out of eight probit regression lines were generated as shown in Fig. 6, because the data “TSV = +4”was very limited in the experiment in Hong Kong. These regression lines followed the same slope of 0.15 but different intercepts. The probit regression lines were translated to the sigmoid curves by probit transmission. Fig. 7 shows two of the sigmoid curves. These were the cumulative distribution curves of the corresponding normal distributions. In the example of the “warmer than neutral” curve, *P* here represents the probability of people voting for “TSV ≥ +1” at a certain T_{op}, *1-P* represents the probability of people voting for “TSV ≤ 0”. Defined in the study of Nikolopoulou and Lykoudis [23], the “neutral and warmer” curve was the transition curve describing the probability of someone changing the voting from the cool side to the neutral and warm side; and the “warmer than neutral” curve was the transition curve describing the probability of someone changing the voting from the cool and neutral side to the warm side [23].

Along the two transition curves, the points where the probability equaled 50% were what needed to be concerned with. Because of the physical feature of the normal distribution curve, the derivation of the cumulative distribution curve was the rate of increase in the response for such groups against per unit increase in the operative temperature. Take the “neutral and warmer” curve as an example, the derivation of it namely described the percentage of people who would change their voting from “cooler than neutral” to “neutral and warmer” at a certain unit of operative temperature. Along the line of 50% in the *y*-axis shown in Fig. 8, when T_{op} reached the threshold of stimulating 50% probability of the “neutral and warmer” transition curve, it was termed entering the neutrality zone; and when T_{op} reached that of the “warmer than neutral” curve, leaving the neutrality zone. The definition of neutrality zone using probit analysis was first brought by Ballantyne et al. [32], who also introduced the concept of defining the point of thermal neutral temperature as the midpoint of these two values [32]. However, it was hard to decide whether people just cannot tell the difference when the voting was around thermal neutral status, or this status might last for a certain range of thermal stimulus in the outdoor environment. The concept of the thermal neutral zone could be an alternative, which was also used in the present study.

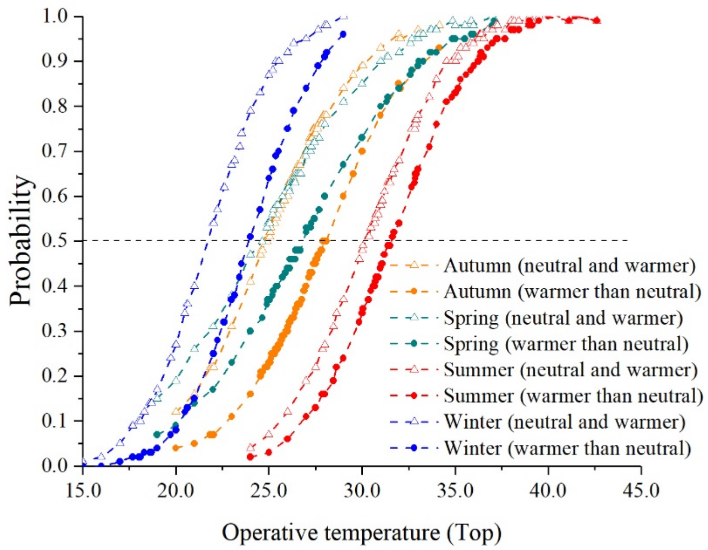

Fig. 8 Transitional curves of thermal neutral for different seasons in Hong Kong

Fig. 8 shows four sets of transition curves for different seasons in Hong Kong. The thermal neutral zones for transitional seasons were much wider among four seasons. Thermal adaptation can be found when comparing the thermal neutral ranges of two transitional seasons. Almost similar T_{op} (around 24.5 °C) started to stimulate thermal neutral feeling for spring and autumn, but the T_{op} for leaving the thermal neutral zone (28.0 °C) in autumn was slightly higher than that of spring (26.8 °C). This phenomenon might be due to the recent thermal history of the previous season. The thermal sensation feeling in autumn was affected by the thermal history in summer, which made people more tolerable to high temperature. However, the warm winter during our experiment in Hong Kong made it not able to provide a strong contrast for cold thermal sensation feeling, thus the starting point of T_{op} to enter the thermal neutral zone in spring was very close to that in autumn.

It is noticeable that the thermal neutral zone increased from winter to summer. The thermal neutral zone for winter was the lowest, ranging from 21.5 to 23.7 °C; while for summer it was the highest, ranging from 30.1 to 31.6 °C. The similar increasing pattern was also found in the study of Nikolopoulou and Lykoudis [23] which focused on thermal comfort for the open area of European countries. The thermal neutral zone for summer was within that of autumn from their observation, and the upper limit of the thermal neutral zone in summer was the same as in autumn (around 32.0 °C) [23]. However, the thermal neutral zone in summer was much higher than the other seasons for Hong Kong residents. Observed in Fig. 8, the T_{op} for entering the neutrality zonein the Hong Kong summer was 30.01 °C while T_{op} for leaving the neutrality zone for the other seasons was merely 28.0 °C.

Though winter and summer were both not as pleasant as the transitional seasons, the thermal neutral zone in summer was much narrower compared to winter. The temperature difference between two transition curves for winter was 2.2 °C while for summer it was merely 1.5 °C. This phenomenon illustrates that achieving thermal neutrality was the hardest in summer through the whole year in Hong Kong and that the thermal condition of the outdoor environment was the severest in summer. Therefore, when city planners try to make effort to improve the thermal conditions in the public open area, summer should be given the top priority. The upgrade projects targeted at the warm and hot conditions will be the optimized ones for the consideration of both resource utilization and solving the most serious problem.

3.3 Thermal neutral and comfort ranges of meteorological parameters in Hong Kong summer

Facing the fact that the air temperature in the outdoor environment was non-adjustable and that almost one-third of the whole year had air temperature over 30 °C in Hong Kong, improving the outdoor thermal environment should rely on improving the wind and solar radiation condition by the arrangement of buildings and the greenery. If the air temperature, wind, and solar radiation were treated as a whole system, achieving its best performance by driving each parameter to the best level might be inefficient and impracticable. The rational way is to find out the tolerable ranges that enable the target condition to be achieved. Therefore, this part will focus on searching for the suitable ranges of the meteorological parameters that can provide thermal neutrality or thermal comfort.

Logistic regression was used to predict the combination of wind and solar radiation conditions covering the whole air temperature range (from 25 to 35 °C) in summer. The maximum radiant temperature was up to 65 °C as observed in our on-site measurement; while that of the mean wind speed was up to 3 m/s. The positive response of thermal neutral condition was termed as “TSV = -1, 0 and +1” because of the proven wider range of thermal neutral in the previous part. The positive response of thermal comfort was defined as the TCV voting in the comfort side.

Our previous study has assessed the change of sensitivity of solar radiation and wind speed toward a one-unit change of TSV under different ranges of air temperature [24]. The effect of wind and solar radiation on outdoor thermal sensation has also been revealed a dependent relationship with air temperature in literature [23, 33, 34]. Namely, the conditional effect exists between the variables. The effect of wind on thermal sensation depends on the level of air temperature and so is the effect of solar radiation. As a kind of heat source that has a similar effect as air temperature to thermal sensation, it is reasonable to infer that wind and solar radiation also have an interaction effect on thermal sensation. Therefore, both the main effects and the interaction effects should be considered in the logistic regression model. Centered variables were used for the interaction terms and further in the regression to avoid the multicollinearity problem.

The prediction of response depended on the calculated probability of the logistic regression model. The default classification cutoff for a positive response was $P \geq 0.5$. It should be refined by the ROC curve to increase the true positive rate and reduce the false positive rate as well. The ROC curves are generated by the saturated logistic models and its results are shown in Fig. 9 (a-b). The area under the ROC curves of the thermal neutral and thermal comfort logistic regression results were 0.830 and 0.889, respectively. The higher area under the curve, the better the regression fitted with the original data. Fig. 9 (c-d) present the difference between the sensitivity and 1-specificity in the ROC curves. The largest difference meant the highest true positive rate and the lowest false positive rate, and the classification cutoff points corresponded to what was chosen in the further regression. The classification cutoffs for thermal neutral and thermal comfort logistic regression were 0.415 and 0.701, respectively.

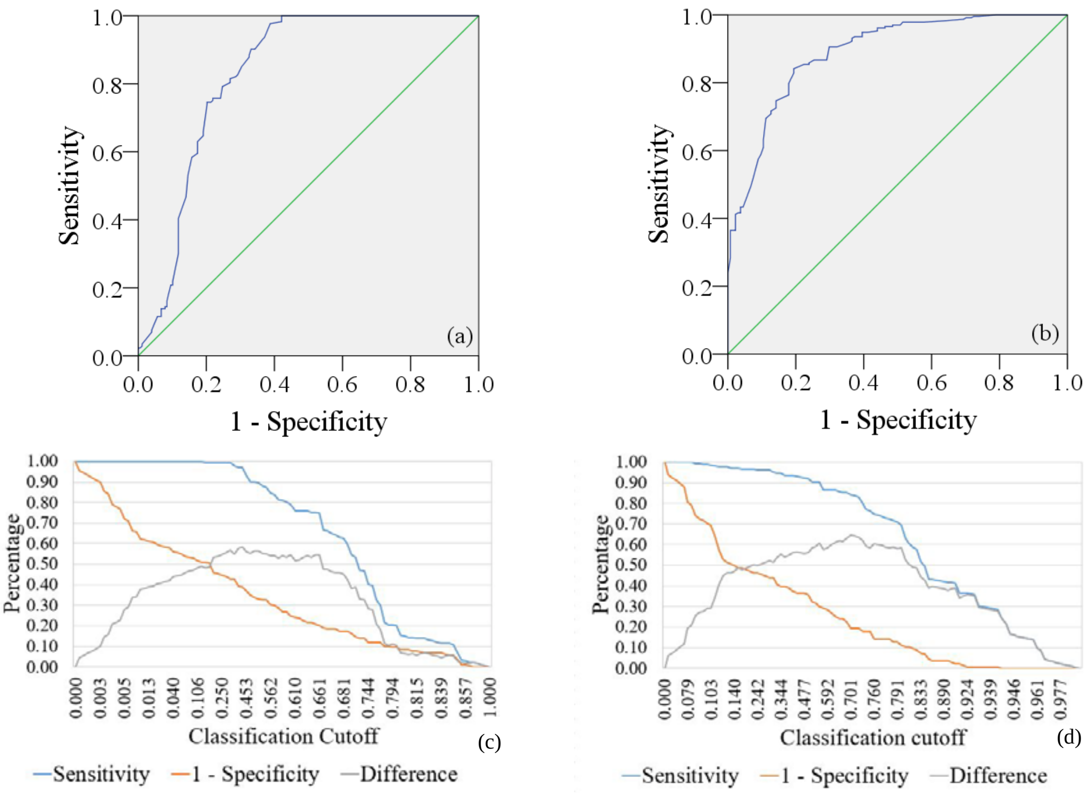

Fig. 9 Determining the classification cutoff points (a) ROC curve of thermal neutral from the saturated logistic model; (b) ROC curve of thermal comfort from the saturated logistic model; (c) the difference between the sensitivity and 1-specificity in the ROC curve of thermal neutral logistic regression result; (d) the difference between the sensitivity and 1-specificity in the ROC curve of thermal comfort logistic regression result

Table. 5 Independent variables and the evaluation index in the logistics regression of thermal neutrality

Overall accuracy	**Independent variables**	**-2 Log likelihood**	**Cox & Snell R^2**	**Nagelkerke R^2**
49.3%	v'^{**}	486.497	0	0
66.1%	T_a'	429.858	0.149	0.199
78.1%	$[T_{mrt} - T_a]'$	334.464	0.352	0.469
76.4%	$[T_{mrt} - T_a]', v'$	330.668	0.359	0.478
65.5%	T_a', v'	426.216	0.158	0.210
76.9%	$T_a', [T_{mrt} - T_a]'$	327.748	0.364	0.485
76.6%	$T_a', [T_{mrt} - T_a]', v'^{**}$	326.932	0.365	0.487
76.6%	$T_a', [T_{mrt} - T_a]', v', T_a' \times v'$	315.321	0.386	0.515
78.9%	$T_a'^{**}, [T_{mrt} - T_a]', v'^{**}, [T_{mrt} - T_a]' \times v'$	322.273	0.374	0.498
76.9%	$T_a'^{*}, [T_{mrt} - T_a]', v'^{**}, T_a' \times [T_{mrt} - T_a]'^{**}$	326.422	0.366	0.488
78.1%	$\boldsymbol{T_a', [T_{mrt} - T_a]', v', T_a' \times v', [T_{mrt} - T_a]' \times v'^{*}}$	**313.139**	**0.390**	**0.520**
78.1%	$T_a', [T_{mrt} - T_a]', v', T_a' \times v', T_a' \times [T_{mrt} - T_a]'^{**}$	315.183	0.386	0.515
78.9%	$T_a'^{**}, [T_{mrt} - T_a]'^{**}, v'^{**}, [T_{mrt} - T_a]' \times v', T_a' \times [T_{mrt} - T_a]'^{**}$	322.040	0.374	0.499

78.1%	$T_a'^{**}$,$[T_{mrt}-T_a]'$, v', $[T_{mrt}-T_a]'\times v'^{**}$, $T_a'\times v'$, $T_a'\times[T_{mrt}-T_a]'^{**}$	312.874	0.390	0.520
79.2	T_a', $[T_{mrt}-T_a]'$, v'^{*}, $T_a'\times[T_{mrt}-T_a]'\times v'$	316.358	0.384	0.512
78.1%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'^{*}$, $T_a'\times v'^{*}$	312.602	0.391	0.521
79.2%	T_a', $[T_{mrt}-T_a]'$, v'^{*}, $T_a'\times[T_{mrt}-T_a]'\times v'$, $[T_{mrt}-T_a]'\times v'$	312.147	0.392	0.522
79.2%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'$, $T_a'\times[T_{mrt}-T_a]'$	316.326	0.384	0.512
78.1%	T_a', $[T_{mrt}-T_a]'$, v'^{**}, $T_a'\times[T_{mrt}-T_a]'\times v'^{**}$, $T_a'\times v'^{**}$, $[T_{mrt}-T_a]'\times v'^{**}$	312.123	0.392	0.522
78.1%	$T_a'^{*}$, $[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'$, $T_a'\times v'$, $T_a'\times[T_{mrt}-T_a]'^{*}$	312.310	0.391	0.522
79.2%	$T_a'^{*}$, $[T_{mrt}-T_a]'$, v'^{*}, $T_a'\times[T_{mrt}-T_a]'\times v'$, $[T_{mrt}-T_a]'\times v'$, $T_a'\times[T_{mrt}-T_a]'^{*}$	311.865	0.392	0.523
79.2% (Saturated model)	$T_a'^{*}$, $[T_{mrt}-T_a]'$, v'^{**}, $T_a'\times[T_{mrt}-T_a]'\times v'^{**}$, $[T_{mrt}-T_a]'\times v'^{**}$, $T_a'\times v'^{**}$, $T_a'\times[T_{mrt}-T_a]'^{**}$	311.808	0.392	0.523
Classification cutoff: $P = 0.415$ **$p > 0.1$; *$0.1 > p > 0.05$				

Table. 6 Independent variables and the evaluation index in the logistics regression of thermal comfort

Overall accuracy	**Independent *v*ariables**	**-2 Log likelihood**	**Cox & Snell *R*²**	**Nagelkerke *R*²**
41%	v'^{*}	461.829	0.007	0.010
67.8%	T_a'	351.770	0.272	0.373
85.9%	$[T_{mrt}-T_a]'$	262.759	0.434	0.594
85.6%	$[T_{mrt}-T_a]'$, v'^{*}	262.284	0.435	0.595
64.1%	T_a', v'	340.956	0.294	0.403
83.3%	T_a', $[T_{mrt}-T_a]'$	235.117	0.477	0.652
83.3%	T_a', $[T_{mrt}-T_a]'$, v'^{**}	234.504	0.478	0.654
84.7%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times v'$	223.135	0.494	0.676
83.3%	T_a', $[T_{mrt}-T_a]'$, v'^{*}, $[T_{mrt}-T_a]'\times v'^{*}$	228.347	0.487	0.666
83.3%	T_a', $[T_{mrt}-T_a]'$, v'^{*}, $T_a'\times[T_{mrt}-T_a]'^{**}$	234.229	0.478	0.654
84.7%	$\mathbf{T_a'}$, $\mathbf{[T_{mrt}-T_a]'}$, $\mathbf{v'}$, $\mathbf{T_a'\times v'}$, $\mathbf{[T_{mrt}-T_a]'\times v'^{*}}$	**220.606**	**0.498**	**0.681**
85.9%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times v'$, $T_a'\times[T_{mrt}-T_a]'$	222.043	0.496	0.678
83.3%	T_a', $[T_{mrt}-T_a]'$, v'^{*}, $[T_{mrt}-T_a]'\times v'$, $T_a'\times[T_{mrt}-T_a]'^{**}$	227.757	0.487	0.667
85.0%	T_a', $[T_{mrt}-T_a]'$, v', $[T_{mrt}-T_a]'\times v'^{*}$, $T_a'\times v'$, $T_a'\times[T_{mrt}-T_a]'^{**}$	219.279	0.500	0.684
84.2%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'$	225.816	0.490	0.671
85.3%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'^{*}$,$T_a'\times v'$	220.105	0.498	0.682
84.7%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'$, $[T_{mrt}-T_a]'\times v'$	221.681	0.496	0.679
84.2%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'$, $T_a'\times[T_{mrt}-T_a]'^{*}$	225.357	0.491	0.672

84.7%	T_a', $[T_{mrt}-T_a]'$, v'^{*}, $T_a'\times[T_{mrt}-T_a]'\times v'^{**}$, $T_a'\times v'^{**}$, $[T_{mrt}-T_a]'\times v'^{**}$	219.630	0.499	0.682
84.7%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'$, $T_a'\times v'$, $T_a'\times[T_{mrt}-T_a]'^{*}$	221.146	0.497	0.680
85.0%	T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'^{*}$, $[T_{mrt}-T_a]'\times v'$, $T_a'\times[T_{mrt}-T_a]'^{**}$	218.826	0.500	0.685
85.0% (Saturated model)	T_a',$[T_{mrt}-T_a]'$, v', $T_a'\times[T_{mrt}-T_a]'\times v'^{**}$, $[T_{mrt}-T_a]'\times v'^{**}$, $T_a'\times v'^{*}$, $T_a'\times[T_{mrt}-T_a]'^{**}$	218.461	0.501	0.685
Classification cutoff: P = 0.701 **p > 0.1; *0.1 > p > 0.05				

Table 5 and Table 6 list all the tested independent variables in the thermal neutral and thermal comfort logistic regression model and the index for regression evaluation as well. The overall accuracy shows how well is the regression model fit with the original data. The value of $-2\,ln\,L$ (-2 Log likelihood) was the deviance from the likelihood function of the logistic model and it was able to evaluate the prediction effect of the logistic model. The regression model gave better prediction when $-2\,ln\,L$ was lower compared to the others. Specifically, the saturated model had the lowest value of $-2\,ln\,L$. Cox & Snell R^2 and Nagelkerke R^2 [31] evaluated the ratio of the total variation of the dependent variable being described by the independent variables in the given model. The model was better in fitting with the original data when the Cox & Snell R^2 and Nagelkerke R^2 were higher [31]. The saturated model had the highest value of Cox & Snell R^2 and Nagelkerke R^2 but introduced some redundant independent variables into the model. All the independent variables including the first-order variables (T_a', $[T_{mrt}-T_a]'$, v'), the second-order product terms ($[T_{mrt}-T_a]'\times v'$, $T_a'\times v'$, $T_a'\times[T_{mrt}-T_a]'$) and the third-order product term ($T_a'\times[T_{mrt}-T_a]'\times v'$) were tested in the logistic regression model. In the model of thermal neutral prediction, $[T_{mrt}-T_a]'$ had the highest fitting accuracy of 78.1% and the lowest value of $-2\,ln\,L$ value of 334.464 among all the first-order independent variables. However, decreasing two degrees of freedom by accounting for T_a' and v' into the model could further reduce the value of $-2\,ln\,L$ to 326.932. A difference of 7.532 in $-2\,ln\,L$ was significant at the level of α = 0.025 ($>x^2{}_{(df\,=\,2,\alpha\,=\,0.025)}$), which means the model including independent variables of $[T_{mrt}-T_a]'$, T_a' and v' could predict better than the model contains only $[T_{mrt}-T_a]'$. Considering the interaction terms, decreasing one degree of freedom by accounting for $T_a'\times v'$ or $[T_{mrt}-T_a]'\times v'$ could decrease the value of $-2\,ln\,L$ to a further level of 315.321 ($>x^2{}_{(df\,=\,1,\alpha\,=\,0.005)}$) and 322.273 (($>x^2{}_{(df\,=\,1,\alpha\,=\,0.05)}$), respectively. Though the first-order variable v' itself showed no statistical significance at the level of α = 0.05, its interaction terms $T_a'\times v'$ and $[T_{mrt}-T_a]'\times v'$ were non-negligible in the regression. Thus, the first-order variable v' itself should also be included in the regression [30, 35, 36]. The interaction term $T_a'\times[T_{mrt}-T_a]'$ did not make a statistical difference when it was compared with the first-order variable model (T_a', $[T_{mrt}-T_a]'$, v'). The second-order interaction terms $T_a'\times v'$ and $[T_{mrt}-T_a]'\times v'$ with its first-order parameters together had the closest $-2\,ln\,L$ value (313.139) to the saturated model (311.808) while the least independent variables were needed. Further decreasing the degree of freedoms could not make any statistical difference at the level of α = 0.05. Therefore, the model containing independent variables of T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times v'$ and $[T_{mrt}-T_a]'\times v'$ was used in the thermal neutral prediction of different combinations of meteorological parameters (shown as bold in Table 5).

The similar analytical method was used in filtering the independent variables for the thermal comfort logistic regression model. The model containing independent variables of T_a', $[T_{mrt}-T_a]'$, v', $T_a'\times v'$

and $[T_{mrt} - T_a]' \times v'$ was selected in the thermal comfort prediction as well (shown as bold in Table 6). In general, the logistic regression model for thermal comfort prediction had higher accuracy than that for thermal neutrality with lower $-2\,ln\,L$ value (220.606) and higher pseudo R^2 (0.498 and 0.681). Equation (3.1) and (3.2) describe the logistic regression equations for thermal neutrality and thermal comfort prediction, respectively.

$$P_{thermal\ neutral} = \frac{\exp(0.662-0.240T_a{}'-0.293[T_{mrt}-T_a]'+1.686v'-0.309(T_a'\times v')+0.078([T_{mrt}-T_a]'\times v'))}{1+\exp(0.662-0.240T_a{}'-0.293[T_{mrt}-T_a]'+1.686v'-0.309(T_a'\times v')+0.078([T_{mrt}-T_a]'\times v'))} \quad (3.1)$$

$$P_{thermal\ comfort} = \frac{\exp(3.714-0.632T_a{}'-0.254[T_{mrt}-T_a]'+2.825v'-0.487(T_a'\times v')+0.054([T_{mrt}-T_a]'\times v'))}{1+\exp(3.714-0.632T_a{}'-0.254[T_{mrt}-T_a]'+2.825v'-0.487(T_a'\times v')+0.054([T_{mrt}-T_a]'\times v'))} \quad (3.2)$$

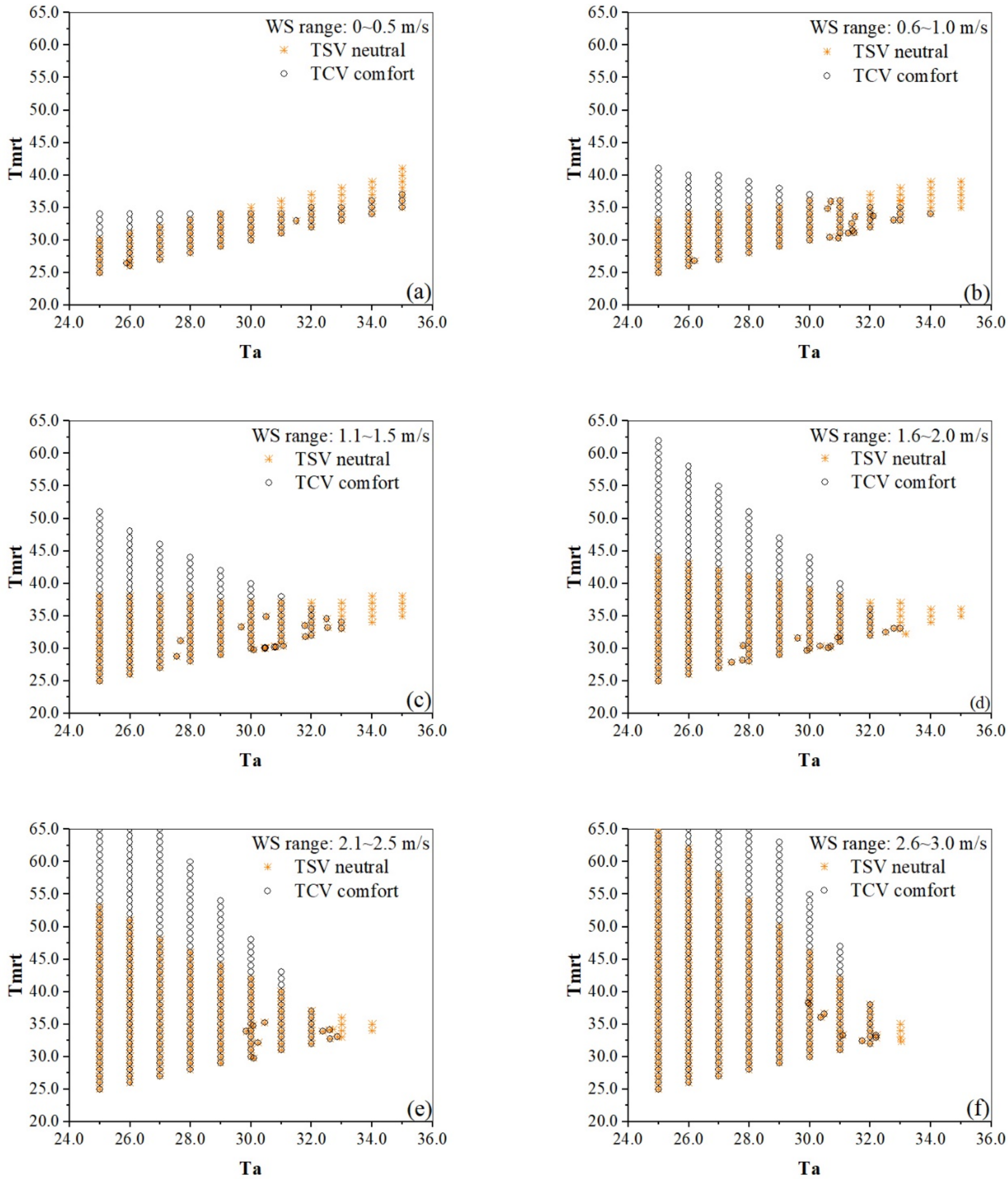

Fig.10 The meteorological parameters combinations for thermal neutrality and thermal comfort in the Hong Kong summer (a) Wind speed range: 0~0.5 m/s; (b) Wind speed range: 0.6~1.0 m/s; (c) Wind speed range: 1.1~1.5 m/s; (d) Wind speed range: 1.6~2.0 m/s; (e) Wind speed range: 2.1~2.5 m/s; (f) Wind speed range: 2.5~3.0 m/s.

The prediction result of thermal neutrality and thermal comfort cases is shown in Fig. 10. The result covers the T_a from 25 to 35 °C. An increase level of 0.5 m/s of wind speed was used as a partition zone. Increasing wind speed could counterbalance the effect of T_{mrt} have on bringing the thermal sensation feelings to the hotter level when T_a < 32 °C. In low wind speed zone (0 to 0.5 m/s), the allowable T_{mrt} for thermal neutrality was only 5 °C higher than T_a and was free of influence from the increase of T_a level. However, when wind speed was as high as the range of 2.6 to 3.0 m/s, the feeling of thermal neutrality could be achieved in the condition of T_{mrt} up to 65 °C provided that T_a was 25 °C. But when T_a was 30 °C, the upper limit of T_{mrt} for thermal neutrality was only limited to around 46 °C. The rate of decrease in the allowable upper limit of T_{mrt} for thermal neutrality in per unit increase of T_a became larger with the increase of wind speed zone. This phenomenon indicates that providing thermal neutrality under direct solar radiation condition by the means of increasing wind speed was more promising when T_a was in a pleasant range than that in a severe hot range. In the severe hot conditions, increasing wind speed might bring negative effect when achieving thermal neutrality was considered. Increasing wind speed was almost useless on offsetting the hot feelings resulted from T_{mrt} when T_a = 32 °C. The upper limit for thermal neutrality of T_{mrt} remained unchanged at around 37 °C when T_a = 32 °C regardless of the increase of wind speed. When T_a was above 32 °C, thermal neutral feeling became less or even disappeared although wind speed was increased. This is possible if the surrounded T_a was almost similar to the skin temperature, less cooling effect would be provided by only increasing wind speed on enhancing convective heat transfer in this case. The wind would be felt as hot wave in this case.

The influence of increasing wind speed in achieving thermal comfort was more obvious than achieving thermal neutrality. When T_a = 25 °C, every 0.5 m/s raise of wind speed could offset the discomfort feeling by at least 10 °C raise of T_{mrt} (Fig. 10 (a)). The strongest observed solar radiation level (T_{mrt} close or equal to 65 °C), which was the condition of direct solar radiation from a clear sky in the midday of Hong Kong summer, was also able to provide the thermal comfort feeling in the condition of $v \geq 2.1$ m/s and $T_a \leq 27$ °C or of $v \geq 2.6$ m/s and $T_a \leq 28$ °C. Increasing wind speed could still enable extra solar radiation acceptance when $T_a \geq 30$ °C, but its influence was less than that of the cases of $T_a <$ 30 °C. The highest allowable T_{mrt} condition for thermal comfort limited to only 5 °C higher than T_a when T_a = 32 °C, which was a typical cloudy day in Hong Kong summer.

The conditions which were able to provide thermal comfort did not necessarily coincide with those able to provide thermal neutrality. It has been suggested in indoor environment [37, 38] and recently indicated in an outdoor study that people felt thermally comfortable in slightly warm status in the cold season and slightly cool status in the hot season [5]. From the result of the present study, the thermal comfort condition covered much wider combination of meteorological parameters, which indicates that the requirement to achieve thermal comfort was not as strict as achieving thermal neutrality. It can be discovered from both the coefficient of wind speed in the Equation (3.2) and the rate of change of the upper limit of T_{mrt} with the increase of wind speed level. In the cases of $T_a \leq 31$ °C, the conditions for achieving thermal comfort was less strict than that for thermal neutrality. Wind speed amplification could improve the range of thermal comfort but not thermal neutrality in the cases with higher solar radiation. Meanwhile, thermal comfort was harder to be achieved than thermal neutrality when $T_a \geq$ 32 °C. It is not easy to achieve thermal comfort in the windy environment when $T_a > 32$ °C. With such high air temperature and high humidity in Hong Kong summer, the wind is felt hot and sticky and hence uncomfortable when T_a > 32 °C. Notably, this aforementioned analysis is not able to conclude which kind of thermal sensation feeling it is in the cases of achieving thermal comfort but not thermal neutrality due to the limitation of the category. Last but not least, as relative humidity was not included as one of the independent variables in the logstic regression, the above results and discussions are only applicable to the citis located in the subtropical area with high relative humidity level in summer.

4. Conclusions

This study discussed the outdoor thermal comfort issues in Hong Kong. The changes of air temperature in Hong Kong from the past 10 years were presented along with the number of days over 30 °C based on the statistics from the Hong Kong Observatory. The confusion of defining thermal sensation feeling around thermal neutral status was studied using the independent t-test. Hong Kong residents could not tell the difference from "slightly cool" to "slightly warm" when they were around thermal neutrality but could have explicit thermal sensation voting when the thermal condition was away from thermal neutrality. The probit analysis was utilized to figure out the thermal neutral zone in four seasons in Hong Kong. Obvious thermal adaptation effect was found in Hong Kong residents from the phenomenon that autumn had higher thermal neutral range than spring. Summer had the narrowest thermal neutral range of merely 1.51 °C in operative temperature, making the thermal comfort problem the severest in this season for Hong Kong. Therefore, logistic regression was used to search for the meteorological parameter combination to achieve thermal comfort and thermal neutrality focusing on the warm and hot conditions in Hong Kong. The model contains independent variables of Ta', $[\mathrm{Tmrt}-\mathrm{Ta}]'$, v', $\mathrm{Ta}'\times v'$ and $[\mathrm{Tmrt}-\mathrm{Ta}]'\times v'$ had the best prediction effect in both thermal neutrality and thermal comfort. Wind could offset the negative effect of solar radiation on both thermal neutrality and thermal comfort, but its effect decreased with the increase of air temperature. Thermal comfort was easier to be achieved than thermal neutrality when the air temperature was no higher than 31 °C, with higher upper limit solar radiation acceptable. When the air temperature was higher than 32 °C, it was hard to achieve either thermal neutrality or thermal comfort by increased wind speed. The combination of meteorological parameters suitable for achieving thermal neutrality or thermal comfort is only applicable to the subtropical area with high relative humidity.

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