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ORIGINAL PAPER

Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong

Vicky Cheng · Edward Ng · Cecilia Chan · Baruch Givoni

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Abstract This paper presents the findings of an outdoor thermal comfort study conducted in Hong Kong using longitudinal experiments—an alternative approach to conventional transverse surveys. In a longitudinal experiment, the thermal sensations of a relatively small number of subjects over different environmental conditions are followed and evaluated. This allows an exploration of the effects of changing climatic conditions on thermal sensation, and thus can provide information that is not possible to acquire through the conventional transverse survey. The paper addresses the effects of changing wind and solar radiation conditions on thermal sensation. It examines the use of predicted mean vote (PMV) in the outdoor context and illustrates the use of an alternative thermal index—physiological equivalent temperature (PET). The paper supports the conventional assumption that thermal neutrality corresponds to thermal comfort. Finally, predictive formulas for estimating outdoor thermal sensation are presented as functions of air temperature, wind speed, solar radiation intensity and absolute humidity. According to the formulas, for a person in light clothing sitting under shade on a typical summer day in Hong Kong where the air temperature is about 28°C and relative humidity about 80%, a wind speed of about 1.6 m/s is needed to achieve neutral thermal sensation.

Keywords Outdoor comfort · Thermal comfort · Wind · Longitudinal · Hong Kong

Introduction

In high density cities like Hong Kong where urban space is scarce, the quality of the urban environment is often traded off against maximizing urban land use. Nevertheless, prompted by the outbreak of the severe acute respiratory syndrome (SARS) in 2003, there has been strong public interest in recent years in the provision of a quality urban environment in Hong Kong. In response to increasing expectations from the public, the Planning Department of the Hong Kong Government initiated a study entitled *Feasibility study for establishment of air ventilation assessment system* (AVAS) in 2003 (Ng 2009), and a follow-up study entitled *Urban climatic map and standards for wind environment—feasibility study* (UCMap) in 2006 (Ng et al. 2006). The primary objectives of these studies were to explore the feasibility of establishing some protocols to assess the effects of major planning and development proposals on urban ventilation in Hong Kong. The ultimate goal is to create an acceptable macro wind environment in the city that would be conducive to our health and comfort.

V. Cheng (✉)
Department of Architecture, University of Cambridge,
1–5 Scroope Terrace,
Cambridge CB2 1PX, UK
e-mail: bkc25@cam.ac.uk

E. Ng
School of Architecture, The Chinese University of Hong Kong,
5/F Wong Foo Yuan Building,
Shatin, New Territories, Hong Kong

C. Chan
City University of Hong Kong,
Tat Chee Avenue,
Kowloon, Hong Kong

B. Givoni
Department of Architecture,
University of California Los Angeles (UCLA),
Los Angeles, CA, USA

Unlike most cities in the world where wind gust represents an important health and safety concern, the major problems in Hong Kong are wind stagnation and blockage. Especially in the sub-tropical climate of Hong Kong, where summers are hot and humid, wind is seen as a desirable quality. Although wind is important, there is a lack of detailed knowledge regarding the effects of wind on thermal sensation in the context of urban Hong Kong. The findings of the AVAS study opined that a mean wind speed of 1.5 m/s 50% of the time can provide a comfortable environment during summer months in Hong Kong for pedestrians walking under shade (Cheng and Ng 2006; Ng et al. 2004). This understanding is an approximation and is based on research conducted in similar tropical environments elsewhere with theoretical calculations. In order to establish a localized benchmark and standard for Hong Kong, it is necessary to confirm prior theoretical findings with original data from observations of local people and climate.

This paper presents a longitudinal outdoor thermal comfort study conducted in Hong Kong as part of the Wind for Comfort study within the scope of the UCMap project. The outcome may provide some useful insights for planners, architects and engineers to better optimize air ventilation for Hong Kong, and by and large shed light on urban wind comfort issues in high density sub-tropical cities.

Outdoor thermal comfort studies

Outdoor thermal comfort has attracted wide attention in the last decade. Research studies have been done elsewhere in the world to understand the thermal sensation of people in different outdoor spaces and under a wide range of climatic conditions (Ahmed 2003; Nikolopoulou and Lykoudis 2006; Spagnolo and de Dear 2003). These studies were conducted mostly by means of transverse questionnaire surveys, where a large number of subjects were interviewed in different environmental conditions. Based on this method, the responses gathered can provide a statistical estimated thermal sensation of an average person under static climatic conditions. Nevertheless, in terms of predicting thermal sensation under changing climatic conditions, this method has certain fundamental limitations.

Since each subject was sampled once only, his or her thermal sensation was captured under a relatively static climatic condition during the survey. The transverse approach cannot reflect the effect of changing climatic conditions, for example increased wind speed, on thermal sensation. The effect of changing climatic conditions may be deduced from a large sample of subjects surveyed in different climatic conditions. However, this approach gives rise to problems caused by individual differences such as age, gender, and personality, which vary from one individual to another (Gravetter and Wallnau 2008). These individual differences can influence the outcome of the thermal study.

In order to understand genuine changes in thermal sensation over different climatic conditions, the effects of individual differences need to be removed. The longitudinal approach can serve this purpose. In a longitudinal experiment, the thermal sensations of a relatively small number of subjects over different environmental conditions are followed and evaluated. As such, changes in thermal sensation over different climatic conditions can be observed. The method has been adopted in two studies conducted in Japan and Israel (Givoni et al. 2003; Uchida et al. 2009).

Although the longitudinal method is not as commonly used as the transverse approach, we believe that the longitudinal method has its own merits and can provide information that is not possible to acquire through the conventional transverse survey. In the UCMap project, both the transverse and longitudinal approaches have been applied. This work included (1) a large-scale outdoor thermal comfort survey carried out in many different urban areas in Hong Kong and comprising more than 2,700 samples (Ng et al. 2008), and (2) a longitudinal thermal comfort experiment that involved repeated survey of the thermal sensation of eight subjects under a set of experimental climatic conditions. We believe that the two methods can supplement each other and together will provide a more comprehensive picture of the effects of wind on thermal comfort. The findings of the transverse outdoor thermal comfort survey will be reported in another paper. The rest of this paper presents the details of the longitudinal experiments.

Study method

The experiment was conducted in an open plaza on the campus of The Chinese University of Hong Kong. Four experimental conditions were set up for the study (Fig. 1). In Setting 1, subjects sat under a sun shade. In Setting 2, subjects sat behind a vertical wind break (a U-shaped structure with sides covered by transparent polyethylene canvas). In Setting 3, subjects sat under a sun shade and behind a wind break. In Setting 4, subjects sat under direct sun and wind exposure.

The microclimatic condition in each experimental setting was measured using a mobile meteorological station (Fig. 2). The meteorological station included sensors for measuring air temperature, globe temperature, wind speed, relative humidity and solar radiation. Humidity ratio (kg/kg air) was derived by air temperature and relative humidity

Fig. 1 Set up of the four experimental climatic conditions

measurements during data analysis. These environmental factors have been identified in past research as the main determinants of outdoor thermal comfort (Penwarden 1973; Sasaki et al. 2000; Tacken 1989).

Wind speed, air temperature and relative humidity are measured using TESTO 3-function probes. Shading devices made of matt black vinyl films were used to protect the sensor probes from direct sun exposure. Nevertheless, it was found later that these shading devices were not adequate for the purpose of the study. This matter will be further discussed in the next section. New shading devices made of white Styrofoam were used in later experiments. In addition, Hobo air temperature and relative humidity sensors were installed for supplementary measurements.

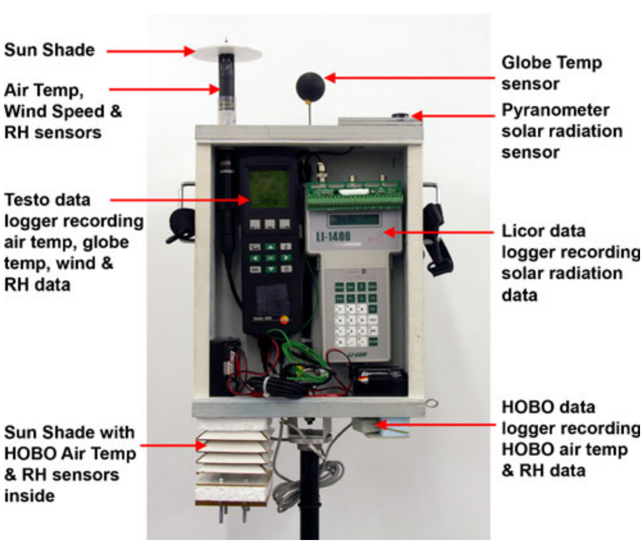


Fig. 2 The mobile meteorological station used in the study

Globe temperature was measured using a tailor-made globe thermometer consisting of a thermocouple wire (TESTO flexible Teflon Type K) held at the middle of a 38 mm diameter black table-tennis ball. The construction of these globe thermometers was made to improve response time with reference to prior studies (Humphreys 1977; Nikolopoulou et al. 1999). Solar radiation was measured using a standard pyranometer (LICOR LI-200SA). During the experiment, each set of instruments was mounted on a camera tripod adjusted to the height of the body of the subjects in sitting position.

The subject group consisted of eight participants, of which half were male and half were female. For each gender group, half of the subjects were in their twenties and half were in their fifties. The eight subjects worked in four pairs in the experiment, which consisted of a series of experimental sessions. In each session, each pair was instructed to sit still in one of the experimental settings for 15 min. Subsequently, each subject was asked to complete a thermal comfort questionnaire. They had 10 min to complete the questionnaire and rest before moving on to the next experimental settings (Fig. 3). The procedures were repeated until each pair has completed all four experimental settings. This experimental design eliminates order effects, which occur if an individual's participation in an earlier treatment influences his or her score in later treatments (Gravetter and Wallnau 2008). In this experiment, each subject pair was placed in the experimental settings in a different order. As a result, the order effects are counterbalanced.

The questionnaires dealt with the subjects' sensations with regard to the microclimatic conditions and their overall comfort. The subjective sensation votes included rating of the thermal environment on a 7-point scale, solar intensity on 3-point scale, wind speed on 7-point scale, humidity of air on 3-point scale and wetness of skin on 5-point scale. Overall comfort was rated on a four-point scale from −2 (very uncomfortable) to +2 (very comfortable). The middle point zero was deliberately taken out from the scale because we opined that the feeling of comfort cannot be neutral. In other words, one would feel either comfortable or uncomfortable with no middle ground.

Three longitudinal experiments were conducted in 2006: two were carried out in summer and one in winter. The weather conditions on the days of the summer experiments were fairly typical Hong Kong summer climate; whilst the winter experiment day was slightly cooler than normal (Table 1). Each experiment consisted of three experimental sessions, which were carried out at three different periods of the day (morning, afternoon and evening). A total of 288 questionnaires were received, of which 2 were discarded due to missing data. Finally, 286 questionnaires were included in the data analysis.

Fig. 3 Illustration of the experimental procedure

Results

Problems with air temperature measurement

Comparison of air temperatures measured in the four experimental settings during the summer experiments revealed a problem with the air temperature measurement. Given the close distance between the experimental settings, similar air temperature and humidity conditions in all settings were expected. However, the temperatures obtained in settings without sun shade were significantly higher than with sun shade. A series of calibration experiments were conducted to test the air temperature sensors and the tailor-made sun shading devices for the sensors. The findings suggest that a fault in the design of the sun shading device is the source of error. As a result, the design of the sun shading device was modified and the new design was adopted in the subsequent winter experiment. As for the summer data, the air temperature measurements of the affected settings were replaced by air temperature measured in Setting 1 (with sun shade and without wind break).

Seasonal characteristics in thermal sensation

Figures 4 and 5 show the distribution of thermal sensation votes across the four experimental settings in summer and winter, respectively. Thermal sensation was rated on a 7-point scale with −3 representing “cold” and +3 representing “hot”. The middle point “0” represents neutral thermal sensation, which is often associated with the state of comfort. The issue regarding comfort and neutral sensation will be discussed later in the paper.

The most common summer outdoor clothing in Hong Kong is a short-sleeved T-shirt and shorts or light trousers. In winter, a long-sleeved sweater and long trousers with a light jacket is commonplace. The average clothing index of the subjects is 0.45 clo in summer and 0.89 clo in winter.

In summer (Fig. 4), Setting 2 with windbreak was most frequently voted as hot by the subjects. Due to direct sun exposure and reduced wind, 85% of the responses received in Setting 2 were on the warm side of the scale (TS>0). Setting 1 with sun shade was least frequently voted as hot by the subjects; only 60% of the responses received were on the warm side. Apart from a single vote for slightly cool (TS=−1), the remaining 38% of responses received in Setting 1 were neutral (TS=0).

Comparing Setting 1 with Setting 4, where sun shade was removed and the subjects were exposed to direct sun, the percentage of neutral sensation dropped from 38%

Table 1 Summary of weather conditions on the days of the experiments

	Summer (August)			Winter	
	8 August	19 August	30-year average[a]	19 December	30-year average
Temperature (°C)					
Average	28.5	27.6	28.4	16.1	17.6
Maximum	31.1	29.8	31.3	18.9	20.5
Minimum	26.1	24.3	26.3	13.1	15.4
Relative humidity (%)	80	81	81	60	68
Solar radiation (W/m^2)	514	523	499	479	341

[a] Data source: Hong Kong Observatory—monthly weather summary

(Setting 1) to 29% (Setting 4). A similar comparison between Setting 1 and Setting 3, where the sun shade remained but the availability of wind was reduced by addition of the windbreak. The percentage of neutral responses decreased markedly from 38% (Setting 1) to 19% (Setting 3). Reducing wind results in a significant “warming effect”. In other words, wind is a very welcome factor for relieving heat stress in summer.

Similar trends were observed in winter (Fig. 5). Setting 2 was least frequently voted as cold by the subjects. Due to direct sun and reduced wind, only around 17% of the responses received in Setting 2 were on the cold side of the scale (TS<0). Setting 1 with sun shade and direct wind was most frequently voted as cold by the subjects; around 75% of the responses received were on the cold side.

The percentage of neutral votes is generally higher in winter than in summer, which suggests that people feel more comfortable thermally in winter than in summer. The overall percentage of neutral is about 25% in summer and 40% in winter. In order to understand the effect of sun and wind, the results of Setting 1 (no sun, direct wind), Setting 3 (no sun, no wind) and Setting 4 (direct sun and wind) were compared. The percentage of neutral votes was 21%, 58% and 33% respectively. Reducing wind results in a significant increase in neutral votes. This suggests that wind is a very influential factor in thermal sensation in winter. This finding is in line with the summer findings.

The effect of changing wind conditions

Figure 6 shows the effect of changing wind conditions on the thermal sensation of subjects in summer, as a function of air temperature and with corresponding regression lines. The average wind speeds in settings with and without wind break are about 0.3 m/s and 1 m/s, respectively. According to the regression lines, given the same air temperature, the subjects rated the settings with the windbreak about 0.43 units hotter than settings without the windbreak. The subjects generally rated the overall wind conditions during the experiments as less than desirable. The wind conditions were rated as too still in settings with the windbreak and slightly still without the windbreak.

In both settings with and without windbreak, the average slope of thermal sensation to air temperature is 0.23 units/°C. The difference in thermal sensation between the two settings is 0.43 units. Thus, it can be inferred that the effect of increasing wind speed from 0.3 m/s to 1 m/s is equivalent to a drop of about 1.9°C in air temperature. This appears to parallel

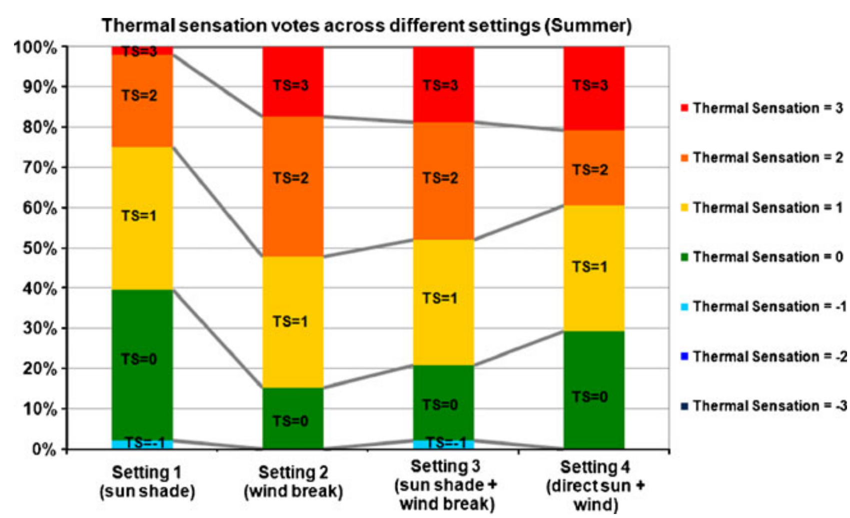


Fig. 4 Distribution of thermal sensation votes across different experimental settings in summer

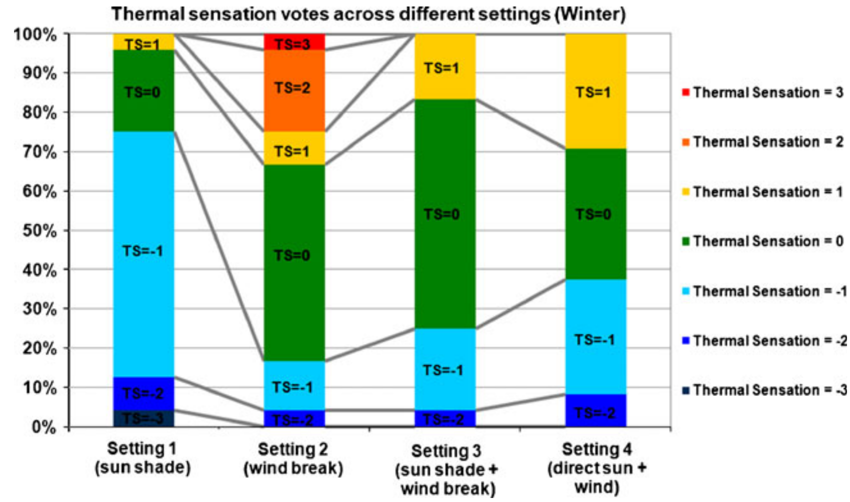


Fig. 5 Distribution of thermal sensation votes across different experimental settings in winter

the findings of a ventilation and comfort study conducted in Thailand, where a 2°C rise in comfort temperature was observed for an increase of wind speed in this range (Khedari et al. 2000). By extrapolating the regression lines to the *x*-axis, the neutral air temperatures can be determined. According to Fig. 6, the neutral air temperature at 0.3 m/s wind speed is about 24.2°C. When the wind speed is increased to 1 m/s, a higher neutral air temperature of 26.1°C is obtained.

A similar analysis was conducted with the winter data. The average wind speeds in settings with and without wind break are about 0.2 m/s and 0.9 m/s respectively, which are comparable to the summer wind speed range. Subjects generally felt cooler in settings with higher wind speed. However, no obvious trend was observed between thermal sensation and air temperature with respect to different wind conditions. This may suggest that the effect of changing wind conditions is less significant in winter than in summer. Nonetheless, the insignificant results may also be due to the smaller dataset available for the winter analysis.

The effect of changing solar radiation conditions

Figure 7 shows the effect of changing solar radiation conditions on the thermal sensation of subjects in summer, as a function of air temperature and with corresponding regression lines. The average solar radiation intensities in settings with and without sun shade are about 136W/m^2 and 300 W/m^2, respectively. According to the regression lines, given the same air temperature, the subjects rated the settings without sun shade about 0.55 units hotter than the settings with sun shade. The subjects under sun shade on average rated the solar exposure condition as just fine. When under direct sun exposure, they generally rated the solar exposure condition as slightly too much.

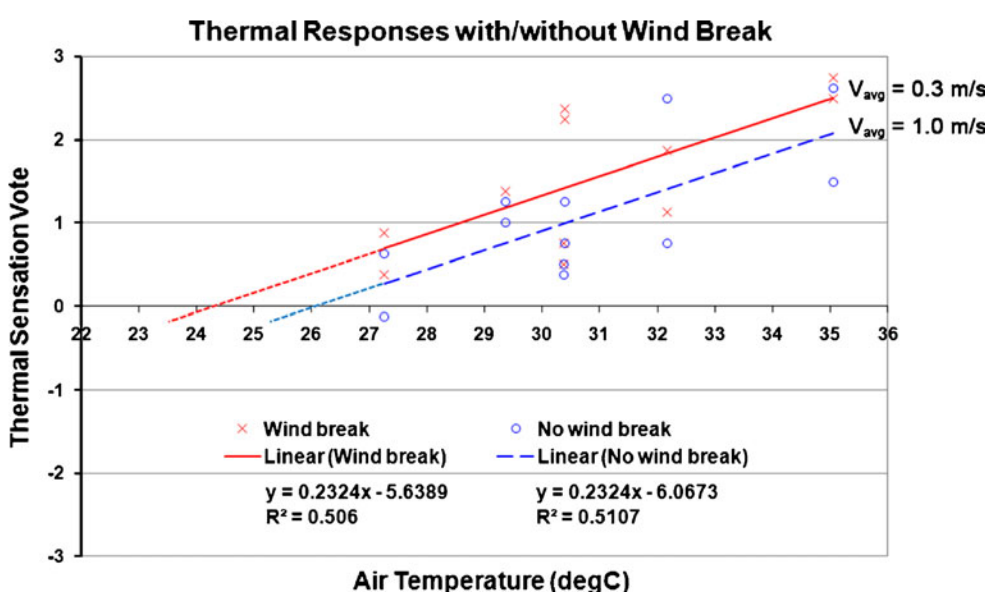


Fig. 6 Effects of changing wind conditions on thermal sensation in summer

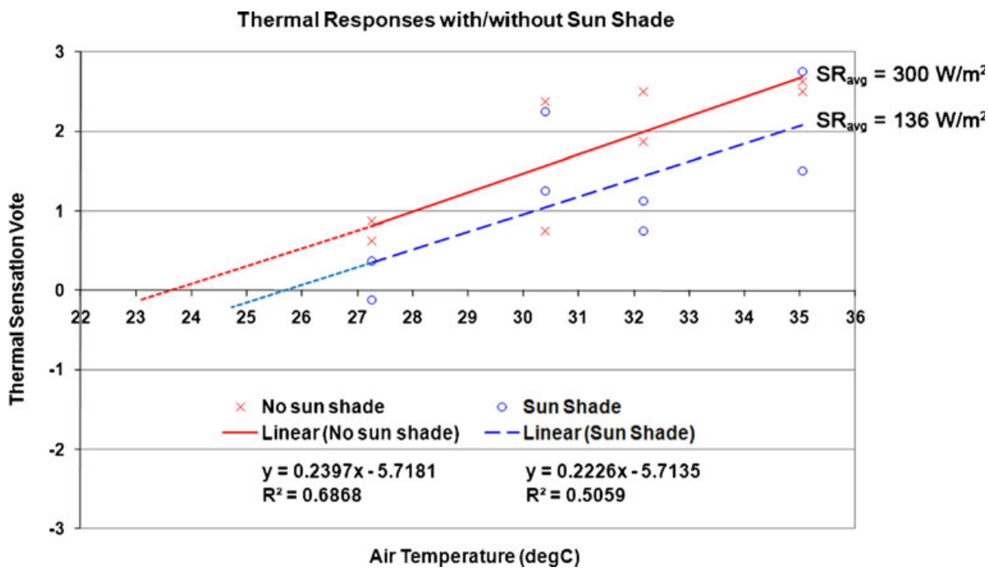


Fig. 7 Effects of changing solar radiation conditions on thermal sensation in summer

In settings both with and without sun shade, the average slope of thermal sensation to air temperature is about 0.23 units/°C. The difference in thermal sensation between the two settings is 0.55 units. Thus, it can be inferred that the effect of increasing solar radiation from 136 W/m^2 to 300 W/m^2 is equivalent to an increase of about 2.4°C in air temperature. Strictly speaking, the regression lines are not exactly parallel to each other but diverge towards high temperature. In other words, higher temperature enhances the effect of solar radiation. By extrapolating the regression lines to the *x*-axis, the neutral air temperature at 300 W/m^2 solar intensity is found to be about 23.5°C. When the solar intensity is reduced to 136 W/m^2, a higher neutral air temperature of about 25.7°C is obtained.

A similar analysis was conducted with the winter data. The average solar intensities in settings with and without sun shade are about 135 W/m^2 and 452 W/m^2, respectively. The shaded condition is similar whilst the unshaded condition is moderately higher than the summer one. The subjects generally felt warmer in settings with higher solar intensity. However, no obvious trend is observed between thermal sensation and air temperature with respect to different solar radiation conditions. This may suggest that the effect of changing solar radiation conditions is less significant in winter than in summer. As mentioned above, the insignificant results may also be due to the smaller dataset available for the winter analysis.

Calculation of mean radiant temperature

Mean radiant temperature (T_{mrt}) is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure' (ASHRAE 2001). T_{mrt} plays an important role in governing the energy balance of the human body and has crucial effect on thermal comfort. Many of the thermal comfort models in use today involve T_{mrt} (Auliciems and Szokolay 1997). In this study T_{mrt} is estimated using the globe temperature method. Thorsson et al. (2007) conducted a study to compare different methods for estimating outdoor T_{mrt}, and reported a relatively small difference in accuracy between the globe thermometer method and the more complicated method based on integral radiation measurements and angular factor. A standard black globe thermometer was used in this study. The spherical shape of the globe thermometer gives a reasonable approximation of the shape of the body in the case of a seated person (ISO 1998) although it has been reported that the use of a black-colored globe tends to overestimate the influence of short-wave radiation (Olesen et al. 1989). Thorsson et al. (2007) used a flat grey globe thermometer in their study and their findings showed that lowering the albedo of the globe thermometer slightly could improve accuracy. T_{mrt} is calculated based on the following formula:

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \left(T_g - T_a\right) \right]^{\frac{1}{4}} - 273$$

Where T_{mrt} is mean radiant temperature (°C), T_g is globe temperature (°C), T_a is air temperature (°C), V_a is air velocity (m/s), D is globe diameter (m) (= 0.038 m in this study), ε is emissivity (= 0.95 for black-colored globe).

According to Thorsson et al. (2007), in shaded conditions, and when changes in radiation flux, air temperature and air speed are small over time, T_{mrt} can be estimated reasonably using 5-min mean globe temperature. In exposed conditions with more rapid changes in radiation fluxes, air temperature and air speed, 10-min means should be considered. In this study, we used 15-min mean air temperature, globe temperature and air speed data in calculating T_{mrt}, which should be able to cope with different settings.

Predicted mean vote

Predicted mean vote (PMV) is a thermal index developed by Fanger (1972). It predicts the mean value of the thermal sensation votes of a large group of people based on six variables: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. Similar to thermal sensation vote, PMV is rated on a 7-point scale ranging from −3 (cold) to +3 (hot) (ASHRAE 2004). It has been used widely to estimate the subjective thermal comfort level of an indoor environment. However, PMV was developed specifically to address thermal comfort at steady state. It has been reported in past research that inaccurate prediction has occurred when applying PMV in more dynamic outdoor environments (Hoppe 2002; Nikolopoulou et al. 2001). PMV often overestimates the thermal sensation towards the warmer end of the scale in hot climates and vice versa in cold climates.

Figures 8 and 9 show comparisons between PMV and the actual thermal sensation votes obtained across the four settings in summer and winter, respectively. In summer, the subjects rated the conditions much cooler than PMV, especially in the morning and afternoon, where the PMV can be as much as 2.3 units hotter than the actual sensation. The opposite trend is observed in winter. The subjects generally rated the conditions warmer and closer to neutral than PMV, except in Setting 2 (direct sun, no wind) during the afternoon period, when the subjects felt “warm” (+2) whilst the PMV indicated “hot” (+3).

Combining the results of the summer and the winter experiments, it can be seen that whenever the sensation of the subjects was around ‘comfortable’ or lower, the PMV predicts colder sensation; and whenever the observed sensation was on the warm side, PMV predicts warmer sensation. The results of the comparison echo findings in past research and suggest that PMV cannot be used as a reliable indication of outdoor thermal comfort. We reckon that the main reason for this is the constantly fluctuating outdoor climatic conditions, which violate the steady state assumption in PMV. The adaptive behavior of people outdoors, and the presence of background psychological interference in the outdoor environment, may also affect judgment of thermal sensation.

Physiological equivalent temperature

Physiological equivalent temperature (PET) is a thermal index derived from the Munich Energy Balance Model for Individual (MEMI)—a heat balance model of the human body. PET is defined as equivalent to the air temperature in a typical indoor setting at which the heat balance of the human body is maintained, with core and skin temperatures equal to those under the conditions being assessed (Hoppe 1999; Matzarakis et al. 1999). PET is derived based on the human energy balance principle, which means that, like PMV, it inherits the steady state limitations when used in outdoor environments. However, the range of PET for different grades of thermal stress is not pre-calibrated.

The calculation of PET assumes constant values for clothing (0.9 clo) and activity (work metabolism of 80 W plus basic metabolism). Hence, it is independent of individual behavior and provides an objective evaluation solely of the effect of climate on the thermal state of the body. However, since our actual thermal sensations rely heavily on individual characteristics, PET in this sense cannot be readily used as an indication of thermal comfort

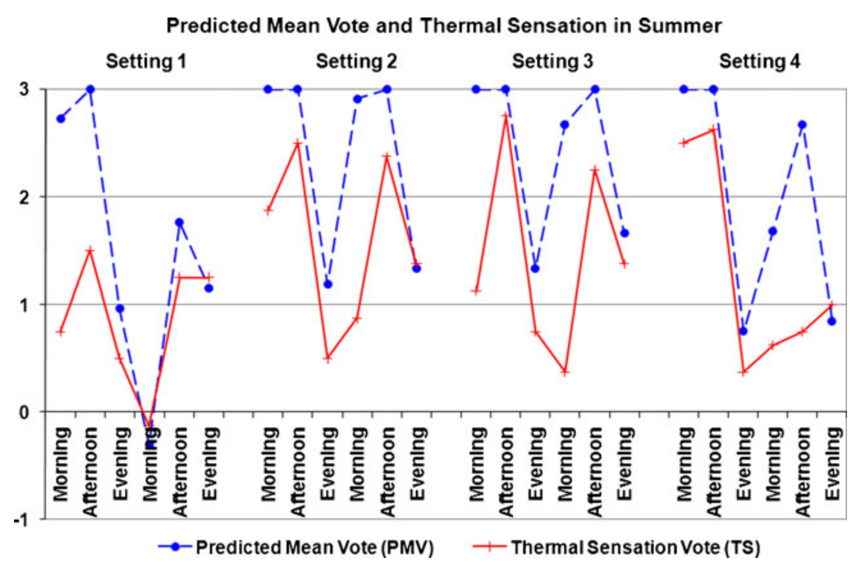


Fig. 8 Comparison of predicted mean votes (PMV) and actual thermal sensation votes in summer

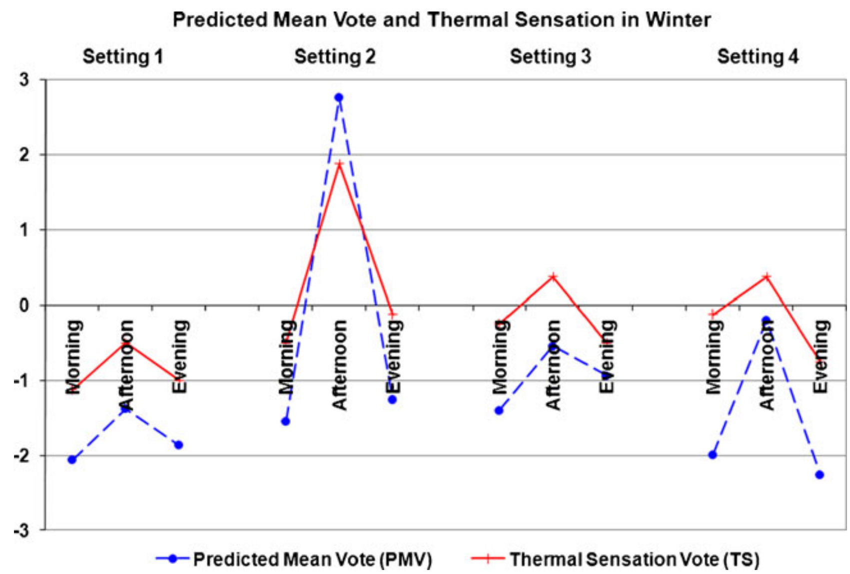


Fig. 9 Comparison of PMV and actual thermal sensation votes in winter

unless its relationship with actual thermal sensation is established. The data collected in our experiments provide a basis for a better understanding of this matter.

Figures 10 and 11 show the correlations between the actual thermal sensation vote and PET in summer and winter, respectively. According to the regression lines, the neutral PET in summer (25°C) is higher than that in winter (21°C). This appears to suggest that people accept higher temperatures in summer more readily than they do in winter. In other words, our thermal sensation varies with the prevailing climatic conditions. Table 2 shows the values of PET at different levels of thermal sensation.

The neutral PETs obtained in this study appears to match the findings obtained in the outdoor thermal comfort transverse survey, which was also conducted in Hong Kong as part of the UCMap project (Ng et al. 2008). The transverse survey, consisting of 2,700 samples, was carried out in three different types of environment, covering streets, housing estates and urban parks. The overall mean and median neutral PETs obtained in summer are 27°C and 29°C, respectively. Neutral PET, however, varies between different types of environment. The mean and median neutral PETs are 27°C and 28°C for streets; 29°C and 30°C for housing estates; and 26°C and 24°C for urban parks. The neutral PETs obtained in parks are significantly lower than in other environments. This is because ambient air temperature is an important variable in the PET model; provided that all other input variables stay constant, PET increases with increasing air temperature. Parks are generally cooler than other urban spaces. This results in a lower range of PETs and thus a potentially lower neutral PET. Our longitudinal experiment took place in an open plaza that

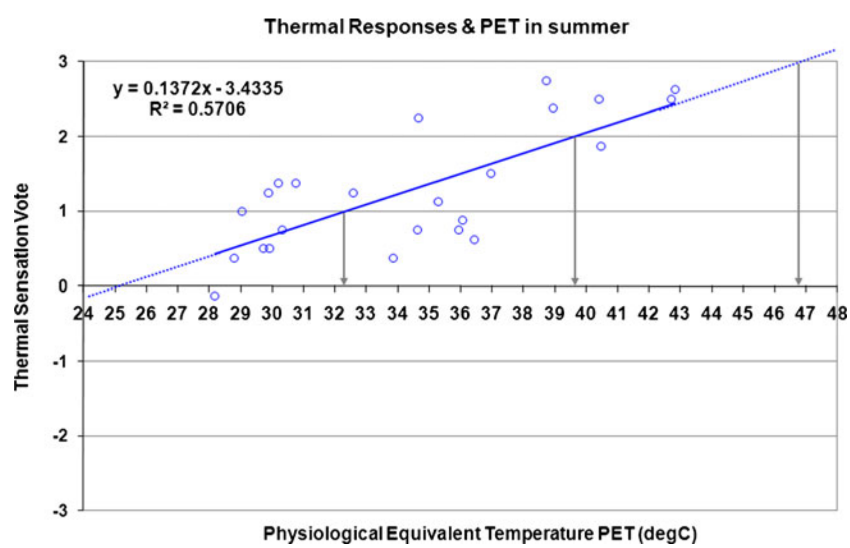
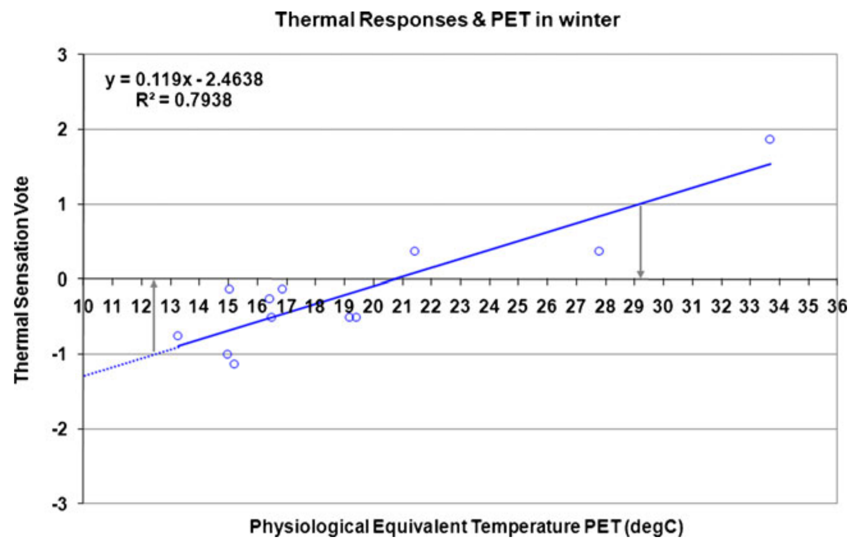


Fig. 10 Correlation between actual thermal sensation votes and physiological equivalent temperature (PET) in summer

Fig. 11 Correlation between actual thermal sensation votes and PET in winter



resembles an urban park. The neutral PET (25°C) obtained in this longitudinal experiment parallels the neutral PETs obtained in parks from the transverse survey (24–26°C).

Cooler neutral PETs are obtained in winter; the mean and median obtained in the transverse survey were 19°C and 20°C, respectively. This is comparable to the winter neutral PET (21°C) obtained in the current longitudinal experiment.

Thermal sensation and overall comfort

Conventionally, neutral thermal sensation (TS=0) is thought to correspond to a state of thermal comfort. This assumption is tested in our experiment. Figure 12 shows a scatter plot of overall comfort against thermal sensation comprising both summer and winter data. Overall comfort is rated on a 4-point scale from −2 (very uncomfortable) to +2 (very comfortable). The middle point zero was deliberately omitted from the scale for reasons explained in Study method.

Overall comfort exhibits a strong correlation with thermal sensation and, as one would expect, the correlation is non-linear. The subjects felt uncomfortable in hot conditions (TS>2) but overall comfort gradually increases as thermal conditions approach neutral. The subjects generally felt comfortable in the range between slightly warm (TS=1) and slightly cool (TS=−1). According to Table 2, this is equivalent to a neutral PET of up to 32°C in summer and down to 12°C in winter. Although there is not enough data beyond the slightly cool condition, the trend line in Fig. 12 seems flatten out and seems likely to go downward in cooler conditions. The results appear to back the assumption that neutral thermal sensation corresponds to comfort.

Table 2 Physiological equivalent temperature (PET) at different levels of thermal sensation

Thermal sensation		PET	
		Summer (°C)	Winter (°C)
-1	Slightly cool	-	12.3
0	Neutral	25.0	21.0
1	Slightly warm	32.2	29.2
2	Warm	39.7	-
3	Hot	46.8	-

Predictive formula for thermal sensation

Formulas for predicting thermal sensation were developed using linear regression analysis with four independent variables: air temperature, wind speed, solar radiation intensity and absolute humidity. Absolute humidity is used in the formulas instead of relative humidity because it truly represents the moisture content of air.

Summer data:

$$TS = 0.1895TA - 0.7754WS + 0.0028SR + 0.1953HR - 8.23 \text{ (correlation coefficient R = 0.87)} \quad (1)$$

Summer + winter data, with humidity:

$$TS = 0.1185TA - 0.6019WS + 0.0025SR + 0.1155HR - 4.77 \text{ (correlation coefficient R = 0.91)} \quad (2)$$

Summer + winter data, without humidity:

$$TS = 0.1185TA - 0.6019WS + 0.0025SR - 2.47 \text{ (correlation coefficient R = 0.90)} \quad (3)$$

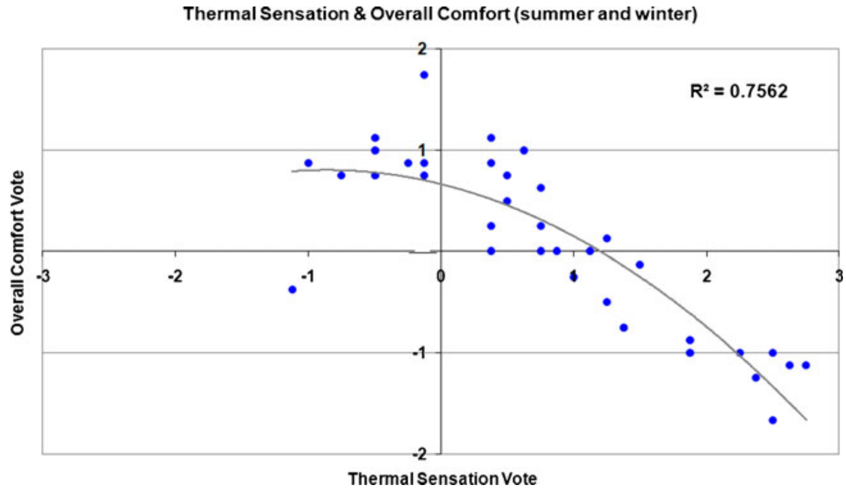


Fig. 12 Scatter plot of overall comfort against thermal sensation

Where TS is predicted thermal sensation vote on 7-point scale from −3 (cold) to +3 (hot) (the middle point zero representing neutral thermal sensation), TA is dry bulb air temperature (°C), WS is wind speed (m/s), SR is solar radiation intensity (W/m^2), and HR is absolute humidity (g/kg air).

Formula 1 was developed based on the summer data. Figure 13 shows the correlation between the measured and predicted thermal sensation. The regression line approximates the diagonal and the correlation coefficient is about 0.87, which suggests a strong agreement between measured and predicted values. According to the formula, wind has a negative effect, whilst air temperature, solar radiation, and humidity have positive effects on thermal sensation. In other words, more wind helps to relieve heat stress in summer while increases in air temperature, solar radiation or humidity enhance heat stress[1]. Wind is welcome in summer. The next question is "how much wind is needed for comfort?"

According to Formula 1, on a typical summer day in Hong Kong where air temperature is about 28°C and relative humidity about 80 % (absolute humidity=19.4 g/kg air), for a person with light summer clothing sitting under sun shade (clothing index: 0.45 clo, metabolic rate: 1 met and solar radiation intensity about 100 W/m^2), a wind speed of 1.5 m/s is required to attain neutral thermal sensation.

A similar analysis was conducted with the winter data and the results reveal an inverse effect of humidity: higher absolute humidity leads to cooler sensation. However, the effect of humidity is relatively small in winter compared to that in summer. Figures 14 and 15 show the differences in predicted thermal sensation with and without the inclusion of humidity in summer and winter, respectively. The inclusion of humidity marginally improves the prediction in summer (R^2 increased from 0.7029 to 0.7641), whilst its effect in winter is almost negligible.

Formulas 2 and 3 were developed based on the entire dataset comprising both summer and winter experiments. Formula 2 includes the effect of humidity. It is intended to be used in summer or in conditions where the outdoor air temperature is above 25°C. In winter, Formula 3, which excludes the effect of humidity, can be applied. As shown in Fig. 16, the correlation coefficients between the measured and predicted thermal sensation are very high (about 0.9) in both cases.

According to Formula 2, for a person with light summer clothing sitting under shade on a typical summer day in Hong Kong, a wind speed of 1.7 m/s is needed to achieve neutral thermal sensation. Comparing this with the result obtained from Formula 1, the wind speed for summer comfort in Hong Kong appears to be about 1.6 m/s. This finding is consistent with our preliminary study, where a summer comfort wind speed ranging from 1 m/s to 2 m/s was suggested (Cheng and Ng 2006). The finding is also comparable to the results of the transverse survey, where a comfort wind speed between 0.6 m/s to 1.3 m/s is recommended for typical summer conditions in Hong Kong (Ng et al. 2008).

Conclusion

This paper presents the findings of an outdoor thermal comfort study conducted in Hong Kong using longitudinal experiments—an alternative approach to the conven-

[1] Comparing Formula 1 with the findings in the sections on The effect of changing wind conditions and The effect of changing solar radiation conditions, the effects on thermal sensation are slightly stronger in Formula 1. However, the differences are fairly small. Based on Formula 1, an increase in wind speed from 0.3 m/s to 1 m/s is equivalent to a 2.4°C drop in air temperature; an increase of solar radiation from 136 W/m^2 to 300 W/m^2 is equivalent to a 2.9°C rise in air temperature. This discrepancy reflects the differences between the single-variable (wind and solar radiation) and multi-variables (Formula 1) regression models.

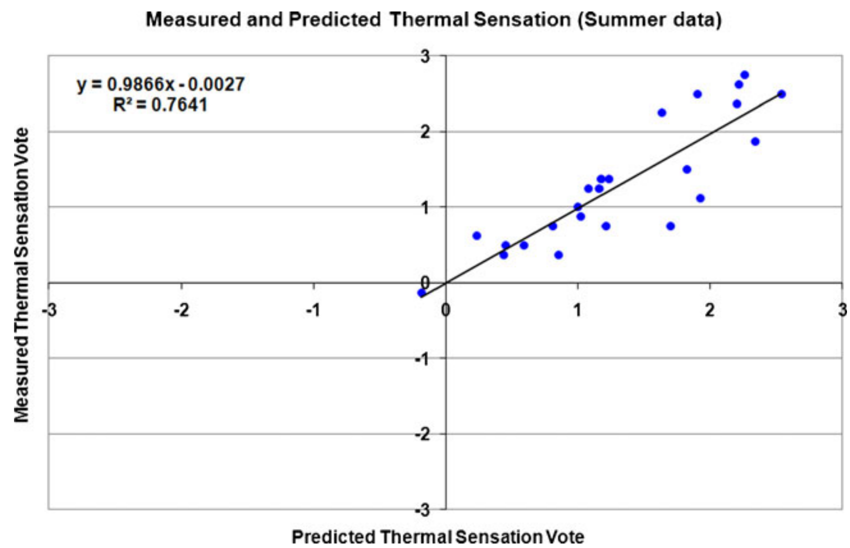


Fig. 13 Comparison of measured and predicted thermal sensation based on the summer analysis

tional transverse surveys. The results show that changing wind speed and solar radiation conditions have significant influences on thermal sensation, especially in summer. An initial analysis of the effects of wind and solar radiation on thermal sensation in summer shows that: (1) an increase in wind speed from 0.3 m/s to 1 m/s is equivalent to a drop of about 2°C in air temperature; (2) an increase in solar intensity from 136 W/m^2 to 300 W/m^2 is equivalent to a rise of 2.4°C in air temperature.

The results presented in this paper show that PMV generally overestimates the thermal sensation towards the warmer end of the scale in summer and vice versa in winter. The paper illustrates the use of PET as an alternative thermal index, and establishes its correlation with actual thermal sensation. According to the results, the neutral PETs in summer and winter are 25°C and 21°C, respectively. This finding corresponds to an urban park-like environment. The neutral PETs appear to vary in different types of environment. In using PET in this study, an underlying assumption is that PET can present accurately the heat exchange of human beings in a thermo-physiological significant way. We aware of the potential drawbacks of PET, which may underestimate the effect of latent heat fluxes, and overestimate radiant heat fluxes accordingly.

Our study reveals a high correlation between thermal sensation and overall comfort. The subjects generally felt

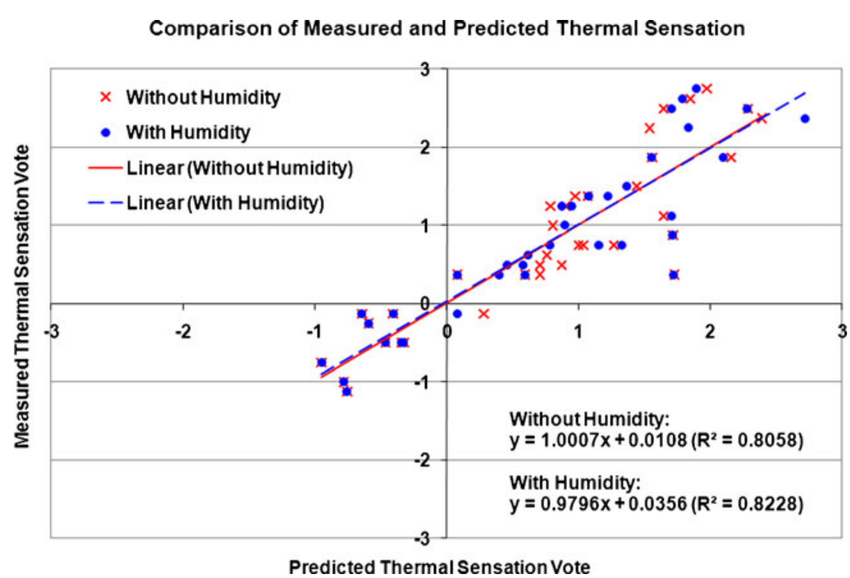


Fig. 14 Comparison of predicted thermal sensation with and without the inclusion of humidity based on summer data

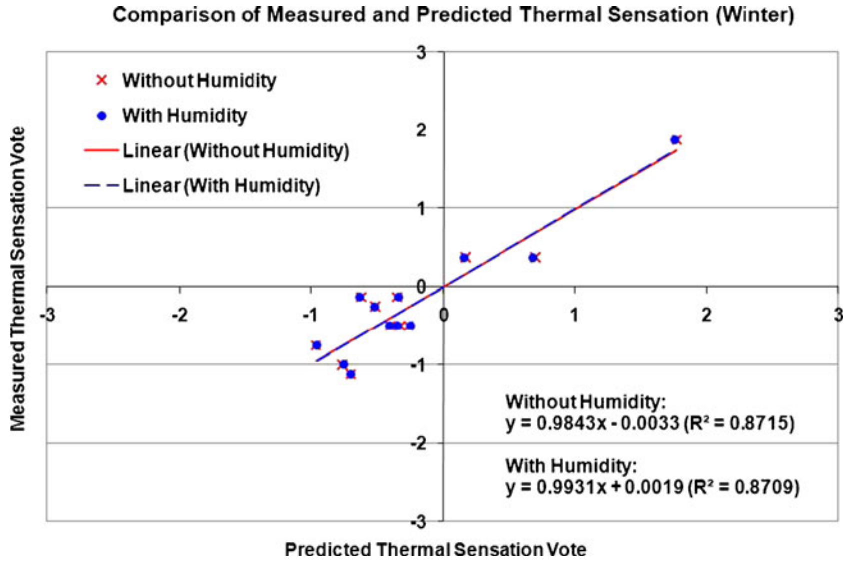


Fig. 15 Comparison of predicted thermal sensation with and without the inclusion of humidity based on winter data

comfortable within the range between slightly warm (TS=1) and slightly cool (TS=−1). This is equivalent to a neutral PET up to 32°C in summer and down to 12°C in winter. Our findings support the assumption that neutral temperature corresponds to thermal comfort.

The paper presents three formulas for predicting thermal sensation as a function of air temperature, wind speed, solar radiation intensity and absolute humidity. The formulas provide a means for estimating the wind speed required for outdoor thermal comfort in Hong Kong. According to these formulas, on a typical summer's day where the air temperature is about 28°C and relative humidity about 80%, a person with light summer clothing sitting under shade would require a wind speed of about 1.6 m/s to attain neutral thermal sensation.

This study represents an attempt to understand the effects of wind on thermal sensation of people in the outdoor environment in Hong Kong. We wish to emphasize that the findings are not intended to be transferred to other climates and locales as thermal comfort is not only a matter of physiology, it relates psychologically to the values, lifestyle, behaviors, tolerance and acclimatization of people. This is the reason why we believe that, certainly at the moment, many surveys need to be conducted. Hopefully, one day, we can collate the data comprehensively and find a way to unify them. This study illustrates a method and presents some results towards this goal.

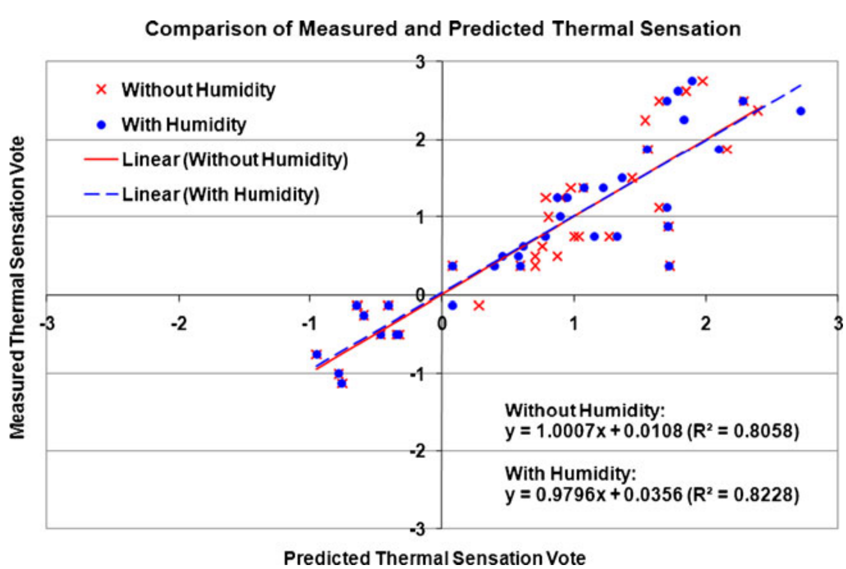


Fig. 16 Comparison of measured and predicted thermal sensation based on both summer and winter experiments

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