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ORIGINAL PAPER

Dynamic response of pedestrian thermal comfort under outdoor transient conditions

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Abstract

Outdoor thermal comfort studies have proved that urban design has a great influence on pedestrians' thermal comfort and that its assessment helps one to understand the quality and usage of the pedestrian environment. However, the majority of outdoor thermal comfort studies perceive pedestrian thermal comfort as "static". The dynamic multiple uses of urban spaces and the highly inhomogeneous urban morphology in high-density cities of the tropics are seldom considered, which leads to a lack of understanding about how pedestrians respond to the changes of the outdoor environment. This study contributes to the understanding of the dynamic thermal comfort using a longitudinal survey that was conducted to obtain information about how thermal sensation changes throughout the walking route and how it is affected by micro-meteorological conditions and the urban geometry. The large variations in micro-meteorological conditions throughout the walking routes are predominantly influenced by the urban geometry. Additionally, the spatial pattern of thermal sensation varies based on the weather conditions, emphasizing the need to account for such variations in the assessment of pedestrian thermal comfort. The results also show that thermal sensation was associated with participants' short-term thermal experience (2–3 min) and that the urban geometry plays an important role in the time-lag effect of meteorological variables on thermal sensation. The findings of this study contribute to improving urban geometry design in order to mitigate the thermal discomfort and create a better pedestrian environment in high-density cities.

Keywords Outdoor thermal comfort · Transient · Pedestrian environment, high-density cities

Introduction

The outdoor thermal environment is important to urban liveability and the health and well-being of urban inhabitants. Pedestrianization is a popular issue regarding urban liveability as it promotes a healthier lifestyle and a more sustainable urban environment (Castillo-Manzano et al. 2014). Pedestrian activities are associated with the level of thermal comfort experienced by pedestrians, which is influenced by the large variations of microclimatic conditions in urban areas due to the complex urban geometry (Krüger et al. 2011). Therefore, the assessment of outdoor thermal comfort is important to ensure the quality of the outdoor thermal environment and enhance the use of outdoor spaces (Maruani and Amit-Cohen 2007).

The assessment of thermal comfort is generally based on the heat balance of the human body and its heat exchange with the surrounding environment. Numerical indices, such as predicted mean vote (PMV; Fanger 1972), physiological equivalent temperature (PET; Höppe 1999), and Universal Thermal Climate Index (UTCI; Bröde et al. 2012), were developed to incorporate environmental and personal parameters, including the air temperature, air humidity, air velocity, mean radiant temperature (T_{mrt}), clothing insulation, and level of activity, into the prediction of thermal sensation (Taleghani et al. 2015). These indices are based on the assumption that the human body is exposed to steady environmental conditions that are rarely true in outdoor environments (Höppe 2002). Therefore, the dynamic nature of outdoor environmental

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conditions must be considered in the assessment of outdoor thermal comfort.

Previous studies were conducted to investigate how thermal sensation changes in response to a transient environment. Gagge et al. (1967) first discovered the overshooting in thermal sensation when a human body moves from a warm environment to a neutral environment and the lags in up-step conditions, i.e., from a neutral environment to a warm or cold environment. Such a phenomenon was also reported in similar studies (de de Dear et al. 1993; Nagano et al. 2005; Chen et al. 2011). Thermal responses are also associated with the magnitude of the step change (Xiong et al. 2015; Yu et al. 2015), while subjective thermal sensations tend to stabilize faster than physiological responses, such as skin temperature (Arens et al. 2006; Chen et al. 2011). Potvin (2000) suggested that thermal transients result in different responses of the thermal regulation of human bodies. Therefore, the rate of transition is important to maintaining or improving thermal comfort under changing environmental conditions.

Conventional studies of outdoor thermal comfort focused on the effect of meteorological conditions on instantaneous subjective thermal sensation or comfort (Spagnolo and de Dear 2003; Pantavou et al. 2013). However, in outdoor environments, pedestrians are exposed to constantly changing environmental conditions due to the urban geometry. Höppe (2002) discussed the thermophysiological differences between outdoor and indoor thermal comfort using the Instationary Munich Energy-Balance Model (IMEM). Based on the model simulation using a “sunny street segment” scenario that a pedestrian leaving a shaded area of a sidewalk and entering a sunny segment of 200 m long, he argued that steady-state thermal comfort models are only applicable for persons in an outdoor environment for more than 30 min because skin temperature gradually increases when a person enters an outdoor environment and approaches the skin temperature predicted by the steady-state model after 180 s (Fig. 1). This implies that it is possible to avoid a hot thermal sensation if the urban geometry is carefully designed without exceeding this threshold.

Similar results were also observed in a subsequent study that investigated the human thermal response of subjects leaving an indoor environment and entering different outdoor scenarios (Katavoutas et al. 2015). Walking routes were previously performed in European cities to study the variations of pedestrian thermal comfort in outdoor environments (Vasilikou and Nikolopoulou 2013). It was shown that pedestrians could perceive the variations in the environmental conditions during walks. A mobile measurement system was previously employed to record the micro-meteorological conditions and individuals’ physiological responses along a predefined pedestrian route covering a wide range of urban geometries and surface environments (Nakayoshi et al. 2015). It was suggested that thermal sensation was influenced by the cutaneous thermoreceptors responding to subtle environmental changes (de Dear 2011), reiterating the importance of pedestrians’ physiological responses and thermal histories.

The objective of this study is to compare the dynamic changes of pedestrians’ thermal sensations between two designated routes in a high-density commercial area of Hong Kong. The effects of the urban geometry and associated micro-meteorological conditions were also investigated. A longitudinal survey was conducted to obtain information about how thermal sensation changes throughout the walking route and how it is affected by micro-meteorological conditions and the urban geometry. The findings of this study will provide information about how the urban geometry design affects outdoor thermal comfort and how people may tolerate the discomfort during their walk. Urban designers will then be able to design better outdoor spaces to enhance the walking environment in high-density cities.

Experimental design

Survey campaign

To acquire information about the dynamic response of pedestrians when they are traveling within the urban environment, a longitudinal survey was conducted to obtain information about how thermal sensation changes throughout the walking route and how it is affected by micro-meteorological conditions and the urban geometry. The survey campaigns were conducted in a high-density commercial area of Hong Kong. Two walking routes, with the same starting and destination points, were designed to cover the variations of the urban geometry (Fig. 2a). Route 1 generally consists of narrow street canyons with occasionally open spots at street intersections and open spaces, while route 2 basically follows the two main roads along the E-W orientation and then the N-S orientation. It takes approximately 60 min to complete each of the two walking routes (approximately 1.5 km), and they were instantaneously conducted in order to avoid temporal differences of the background meteorological conditions.

Fifteen survey points were designated to conduct the thermal comfort survey. At each survey point, the subjects were asked for their thermal sensation vote (TSV) for the environment; they were situated according to the ASHRAE seven-point scale with cold (− 3), cool (− 2), slightly cool (− 1), neutral (0), slightly warm (+ 1), warm (+ 2), and hot (+ 3). Fifteen TSV values were obtained for each subject during each walking route. Sky view factor (SVF) was used to represent the compactness of the urban geometry, and the SVF values were calculated for each survey point using the Rayman model (Matzarakis and Rutz 2010) based on fisheye photos taken during the survey (Fig. 2b).

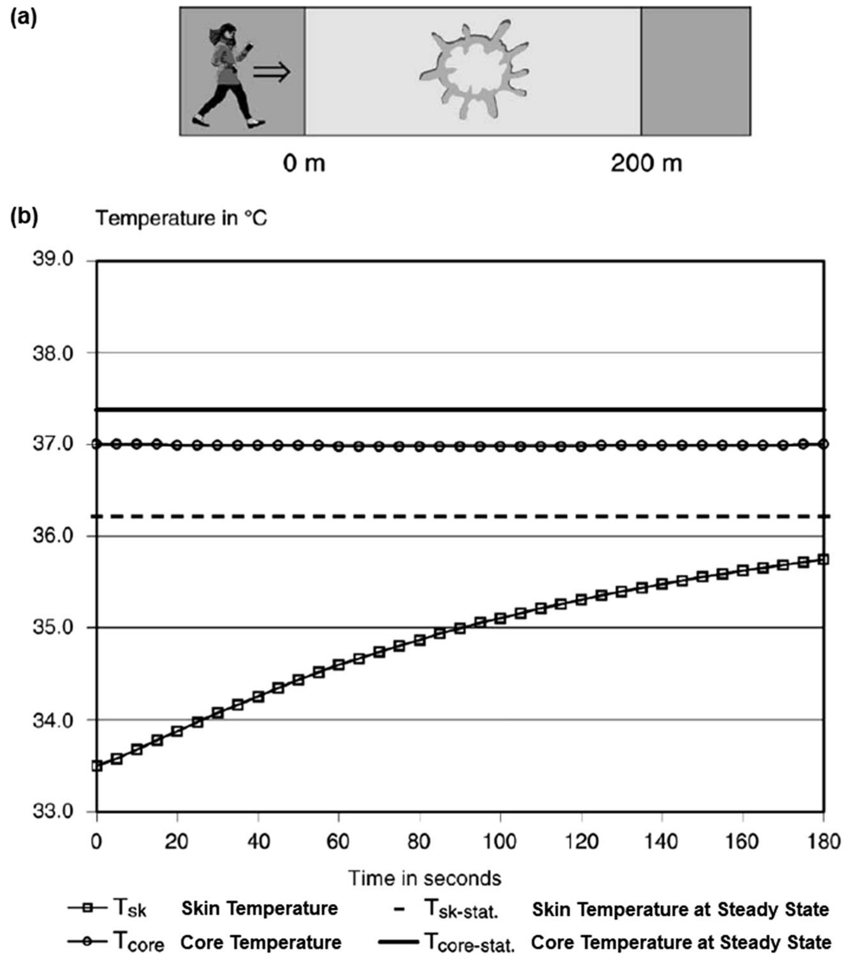

Fig. 1 **a** The "sunny street segment" scenario used for the IMEM model simulation. **b** Temporal variation of the skin (T_{sk}) and core (T_{core}) temperature calculated from the IMEM model after entering a sunny segment on a hot summer day. The horizontal lines represent T_{sk} and T_{core} at steady-state levels (Höppe 2002)

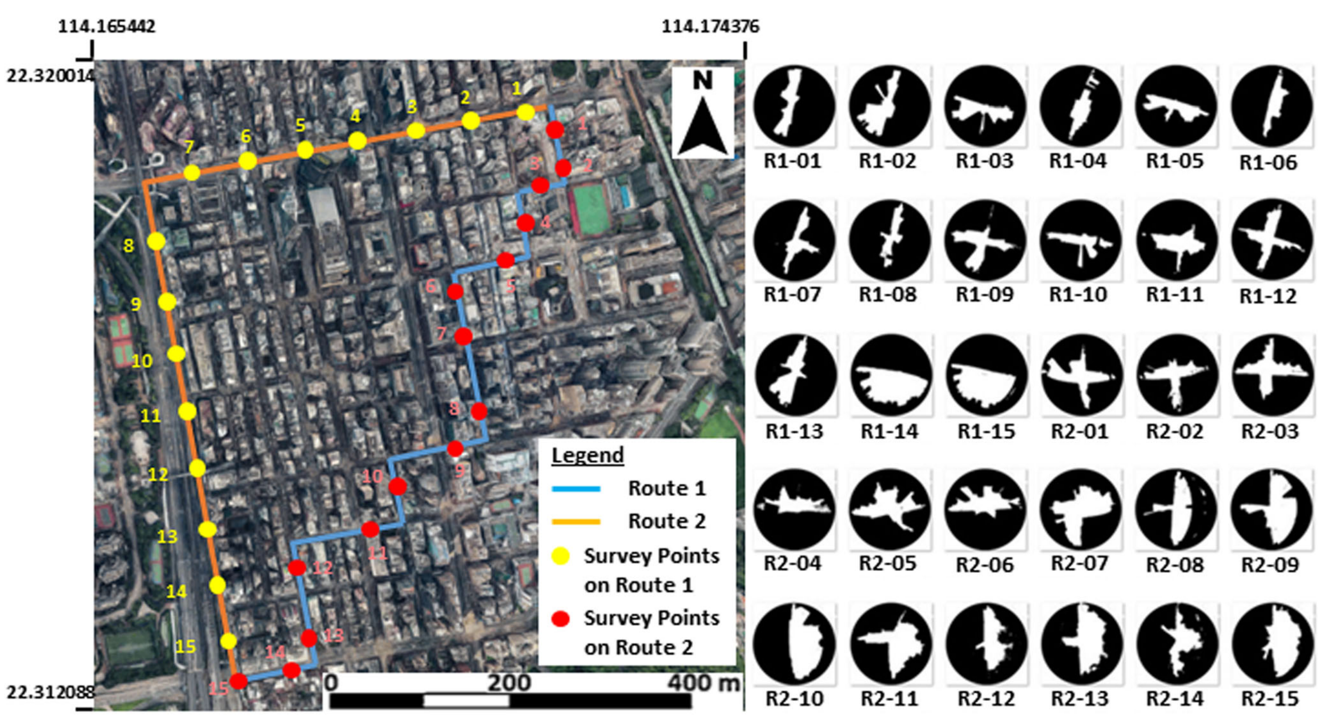

Fig. 2 **a** Two walking routes and 15 surveys points along each route of the present study. **b** Fisheye photos of each survey point

Table 1 Meteorological conditions of the days when the survey being conducted

Date	Time	Air temp (°C)	Relative humidity (%)	Wind direction	Mean wind speed (m/s)	Sky condition	Mean amount of cloud (%)
8 Aug 16	14:22–15:22	31.6–32.8	69–73	NW	3.6	Overcast sky	83
22 Aug 16	14:21–15:10	31.3–31.8	64–72	SE	3.1	Clear sky	27
13 Sep 16	13:54–14:54	29.5–30.5	70–76	SE	2.8	Partially cloudy	61
14 Sep 16	13:53–14:39	31.7–32.8	50–60	N, W	1.9	Partially cloudy	59

The surveys were conducted during four late summer days (8 and 22 August 2016, 13 and 14 September 2016) to capture three types of weather conditions, namely, clear, partially cloudy, and overcast skies. Six male and eight female university students with ages ranging from 19 to 21 participated in the survey. The survey campaigns were conducted from 2 p.m. to 4 p.m. to represent the critical summer conditions in Hong Kong. Table 1 shows the meteorological conditions of the days when the survey was conducted. The data were based on the weather record of the ground-level meteorological stations operated by the Hong Kong Observatory, which is situated less than 1 km away from the study area.

Mobile measurements

A backpack-type of mobile meteorological station was developed for the micro-meteorological measurements during the survey campaigns (Fig. 3). It consists of a set of microclimatic sensors for the measurements of air temperature (T_a), relative humidity (*RH*), and wind speed (v). *RH* was then converted into absolute humidity (AH) using Eq. (1):

$$\mathrm{AH} = \frac{6.112 \times e^{\left[\frac{17.67 \times T}{T + 243.5}\right]} \times RH \times 2.1674}{273.15 + T} \quad (1)$$

Globe temperature (T_g) was measured using a tailor-made globe thermometer composed of a thermocouple wire held in the middle of a 38-mm black table tennis ball, which is designed for the purpose of decreasing the response time during mobile measurements (Humphreys 1977; Nikolopoulou et al. 1999). Table 2 details the information about the instruments used in the present study and their corresponding range and parameters. Mean radiant temperature (T_{mrt}) was then estimated using Eq. (2) (Thorsson et al. 2007):

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.10 * 10^8 * v^{0.6}}{\varepsilon * D^{0.4}}\left(T_g - T_a\right)\right]^{1/4} - 273.15 \quad (2)$$

where ε is the emissivity (0.95 for a black globe) and D is the globe diameter. The backpack was carried by a student helper to avoid additional load on the participants.

Participants were asked to wear typical summer clothing to maintain a clothing value below 0.5 clo and no observable change in clothing was recorded during the survey. The level of metabolic activities is assumed to be 2.0 met, which represents a slow walking speed of 2.0 km/h for pedestrian activities in a commercial/shopping district (Fanger 1973). PET was then calculated from the above meteorological and human parameters and

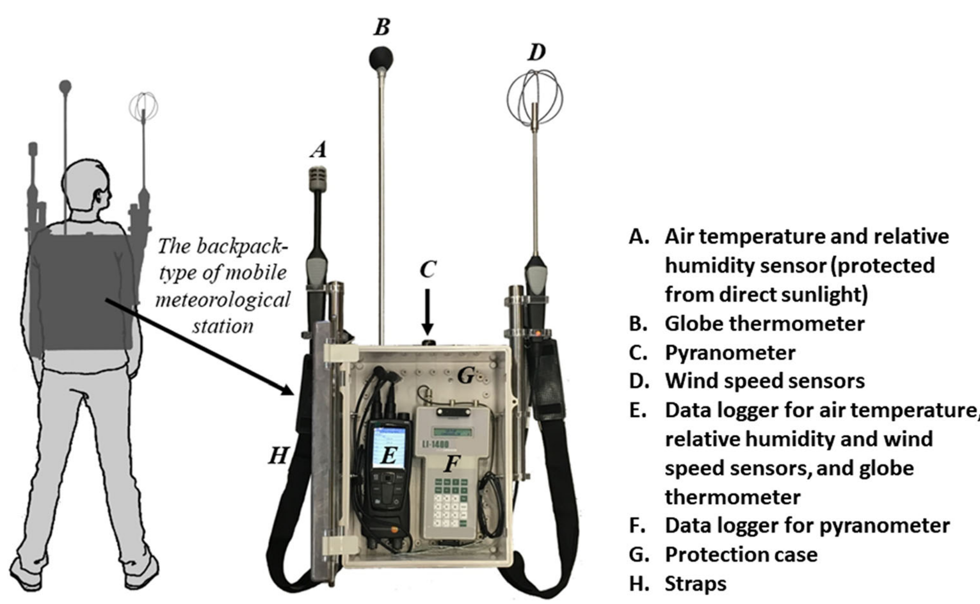

Fig. 3 Instrumental setup of the mobile meteorological station used in the present study

Table 2 Sensors used to measure meteorological parameters in the present study

Parameter	Sensor	Measurement range	Accuracy	Measured interval
T_a	Air temperature and relative humidity sensors	− 20 to + 70 °C	± 0.2 °C (+ 15 °C to + 30 °C) ± 0.5 °C (remaining range)	1 s
RH	Air temperature and relative humidity sensors	0 to 100% RH	± (1.0% + 0.7% of measured value) (0 to 90% RH) ± (1.4% + 0.7% of measured value) (90 to 100% RH) ± 0.03% RH/K (based on 25 °C)	1 s
v	Wind speed sensor	0 to + 5 m/s	± (0.03 m/s + 4% of measured value)	1 s
T_g	Globe thermometer	− 50 to + 250 °C	± 1.1 °C-or 0.4% of reading)	1 s

T_a air temperature, *RH* relative humidity, *v* wind speed, T_g globe temperature

was used as an objective indicator of pedestrian thermal comfort. It is based on the "Munich Energy-balance Model for Individuals (MEMI), which models the thermal conditions of the human body in a physiologically relevant way" (Höppe 1999; p.71). PET is defined as the air temperature that "in a typical indoor setting, the heat

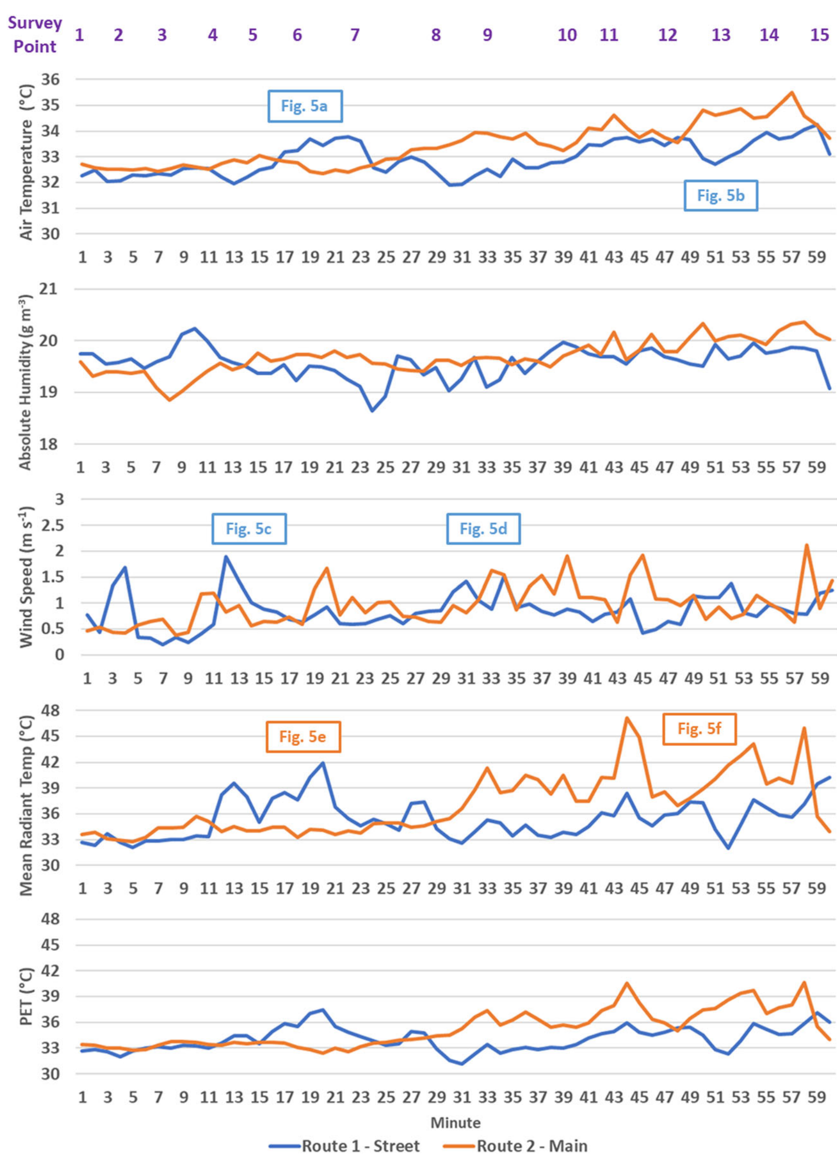

Fig. 4 Temporal variation of the meteorological parameters measured in the present study. Survey points and the location of the photos in Fig. 5 were also denoted

Fig. 5 **a** A long section of a N-S orientated street along route 1, **b** Shading provided by buildings in the latter half of route 1. **c** Exposed environment due to the presence of a large sports ground, **d** open street intersection in the middle section of route 1. **e** Shaded side of the first half of Route 2, **f** Tree shades along the latter half of route 2

balance of the human body is maintained with core and skin temperatures equal to those under the conditions being assessed." (Höppe 1999; p.73).

Statistical analysis

Autocorrelation analysis was used to investigate the possible time-lag effect of thermal sensation, i.e., the immediate thermal experience of participants. Average TSVs obtained at survey points served as the inputs of the autocorrelation analysis represented by Eq. (3):

$$r_k = \frac{\sum_{i=1}^{N-k}\left(X_i - \overline{X}\right)\left(X_{i+k} - \overline{X}\right)}{\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^2} \quad (3)$$

r is the autocorrelation which measures the linear dependency among the process variables X_i and X_{i+k}, and k represents the number of lags concerned in the analysis. N represents the total number of survey points. The partial autocorrelation at lag k is also defined as the direct correlation between X_i and X_{i+k} with the linear dependence between the intermediate variables removed. The entire time series was considered in the autocorrelation analysis and significant correlations would be determined in order to examine whether immediate thermal history plays a role in instantaneous thermal sensation.

Additionally, TSV was used as the dependent variable for the cross-correlations with meteorological variables, such as T_a, AH, v, and T_{mrt}, as well as thermal comfort indicator, PET, in order to determine the time lag(s) of the effect of the meteorological variables preceding the thermal sensation reported by subjects. The cross-correlation

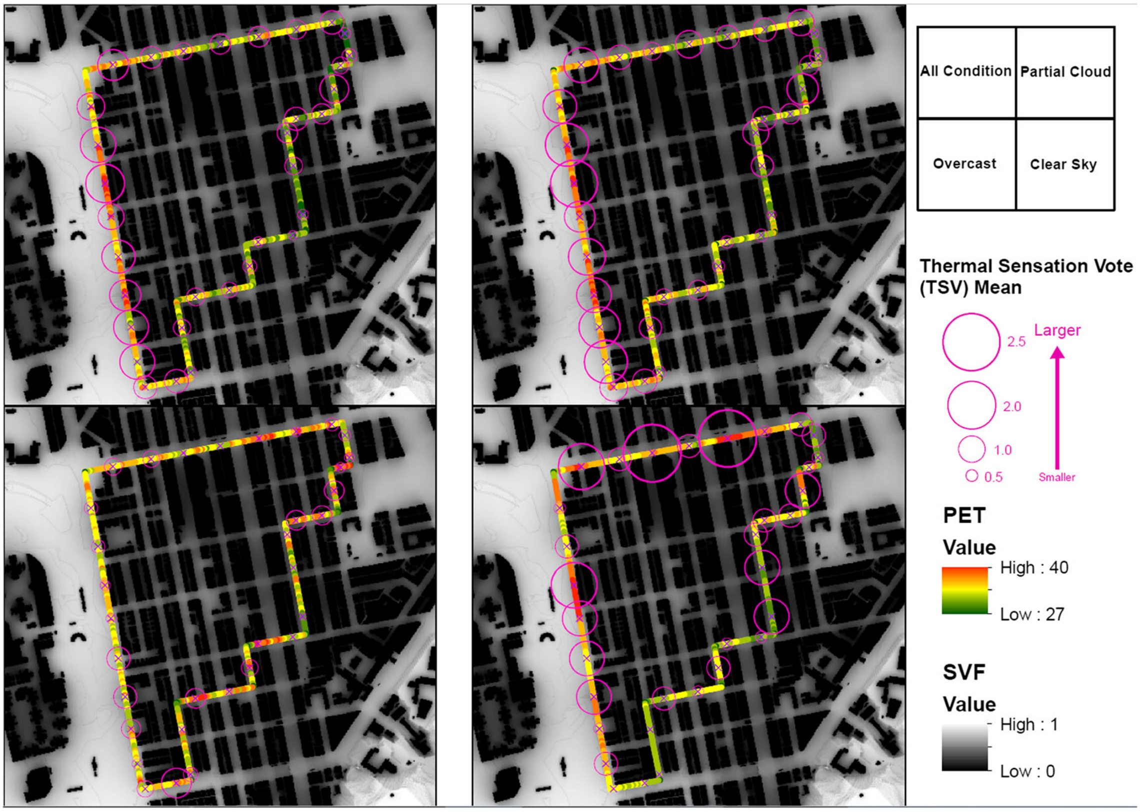

Fig. 6 Spatial variation of PET for the two walking routes and the corresponding thermal sensation votes reported by the respondents

function between the two sequences x and y (r_{xy}) is represented by Eq. (4):

$$r_{xy} = \frac{1}{L\sigma_x\sigma_y}\sum_{t=0}^{L-1} x(t)y(t+h) \qquad (4)$$

σ_x and σ_y are the corresponding standard deviation of the two sequences, and L is the length of sequence. 95% of confidence interval was employed in the present study to assess the significance of autocorrelations and cross-correlations.

Results and discussion

Micro-meteorological measurements

There were considerable spatiotemporal variations in meteorological conditions along the two walking routes during the survey. Figure 4 shows the spatiotemporal variations in T_a, AH, v, T_{mrt} and the PET on 13 September 2016 (partly cloudy day). The high fluctuation of T_a and T_{mrt} emphasized the importance of the urban morphology and street geometry. T_a is found to be higher in more open sections of the walking routes. For instance, a higher T_a (> 32 °C) is observed from the 10th to 22th minute while traveling route 1 when the subjects pass through a long section of a N-S orientated street (Fig. 5a). A high sun altitude results in direct exposure to intense solar radiation, which corresponds to the level of T_{mrt}. Higher level of pedestrian activities is also a reason for a high T_a. The street environment of the study area is characterized by high pedestrian and vehicle traffic, retail activities including hawkers and street food stalls, which result in high level of anthropogenic heat release. It affects the air temperature in certain sections of the study area. The latter half of route 1 mostly covers narrow streets, which provide sufficient shading (Fig. 5b). A lower T_a is found in this section except at the 45th minute when the subject reached an open intersection. Nonetheless, there are no large variations in the absolute humidity due to the relatively lower variation in activities that lead to considerable changes of the moisture content of air.

The wind speed (v) was highly variable throughout the walking route due to the complex urban morphology of the study area. It was found to be relatively higher (> 1 m/s) in the section next to a large sports ground (12th to 14th minute; Fig. 5c) and the intersection with a main road (30th to 34th minute; Fig. 5d) along route 1. Interestingly, v was relatively higher in the E-W narrow streets in the latter half of route 1 (up to 1.5 m/s) possibly due to the closer proximity to a waterfront and an alignment with the prevailing wind direction in the study area. In a compact urban environment, the air movement

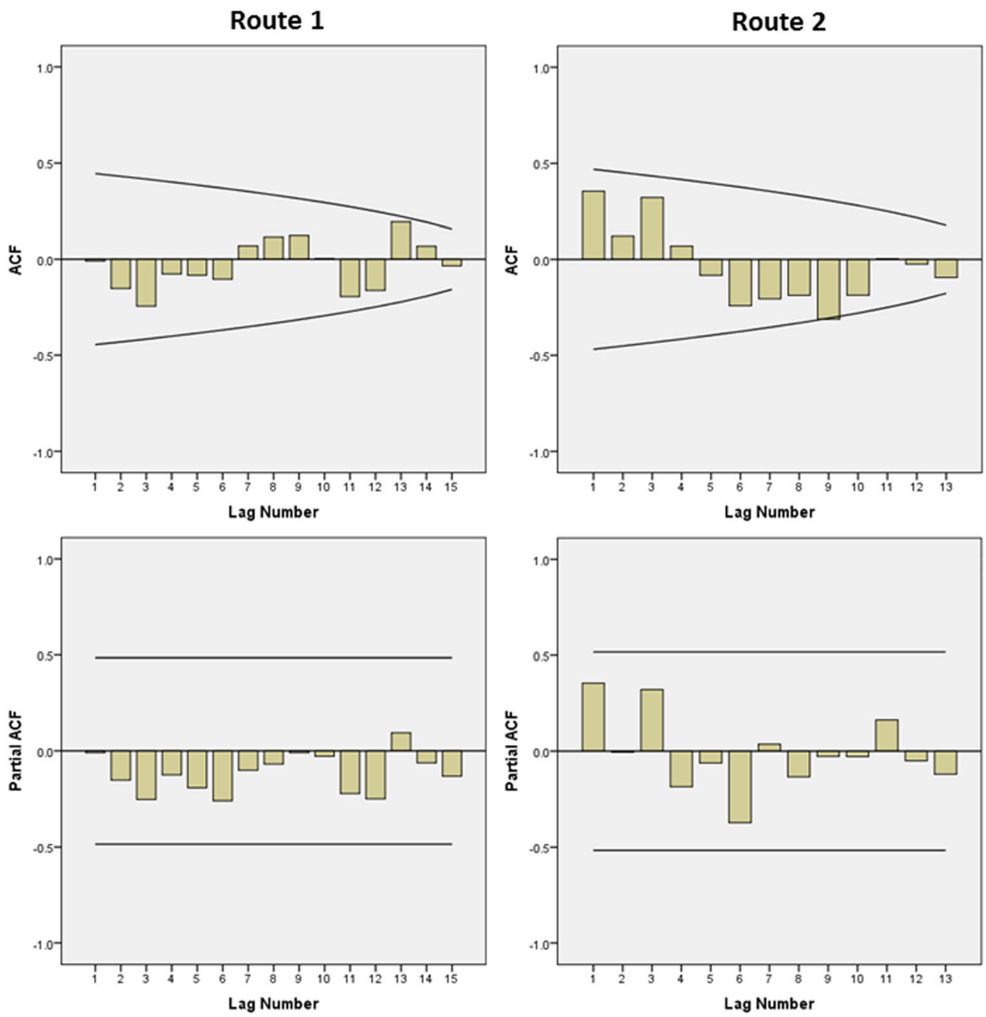

Fig. 7 Autocorrelation function (ACF) and partial ACF of thermal sensation votes reported by the respondents for the two walking routes. The solid lines denote the 95% confidence interval which determines whether the null hypothesis is rejected

is highly influenced by the permeability of urban fabrics, which is largely determined by urban planning and building design (Yuan and Ng 2012).

Lower T_a and T_{mrt} were found along the first half of route 2 because the subjects were walking along the shaded side of an E-W orientated main road (Fig. 5e). When the subjects turned onto a N-S orientated road, T_a and T_{mrt} increased to 33.8 °C and 36.2 °C, respectively. However, there were roadside trees that occasionally provide shading to this particular section of the route (Fig. 5f), resulting in a considerable decrease of T_{mrt} (by approximately 5 °C). Additionally, the higher wind speed along the latter half of route 2 also corresponds to the lower air temperature, emphasizing the importance of shading and ventilation in the microclimate of street environments in high-density cities.

Spatial variation of the PET and subjective thermal sensation

Figure 6 shows the spatial variation of the PET along the two designated routes under different sky conditions. In general, high values of TSVs were observed along the more exposed main road and areas close to large open spaces, except for during overcast conditions for which the variations of the TSV and PET diminished. Under partially cloudy conditions, PET values were up to 36 °C along the main road (route 2), where the subjects were largely exposed. The corresponding TSV that was reported by the subjects is up to + 2.5, indicating a thermally uncomfortable environment. Locations with trees present show lower PET values of approximately 28 °C and serve as a "break" for urban dwellers to recover from the heat stress they had experienced. The PET values are consistently low in the narrow streets (route 1) due to the shading by surrounding high-rise buildings. The subjects reported mostly neutral thermal sensation throughout the entire route.

Under clear sky conditions, PET values were found to be consistently high along route 2, and most of the thermal sensation votes were warm (+ 2) to hot (+ 3). However, there were some lower TSVs reported between the higher TSV values. Such a large contrast is likely because of their

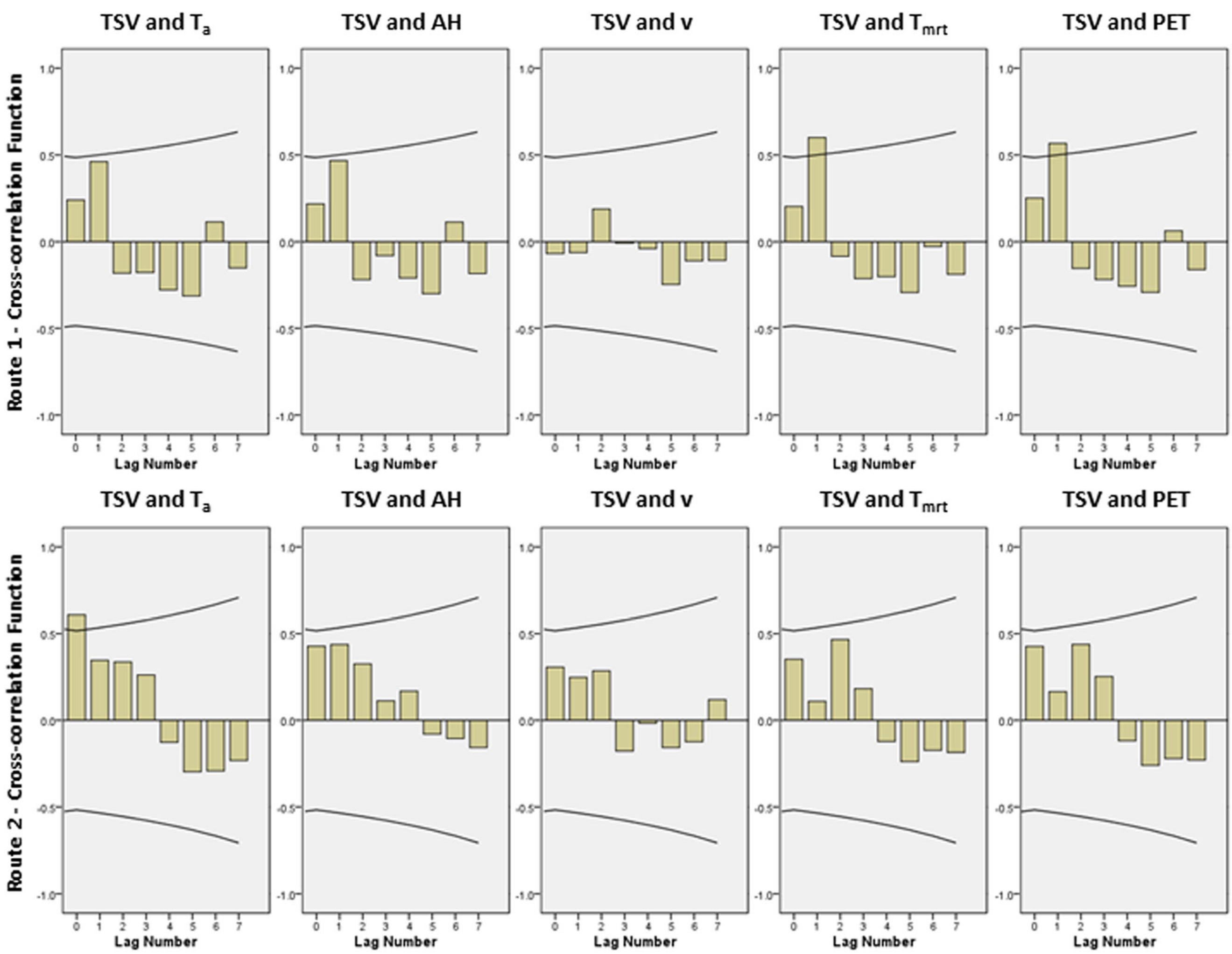

Fig. 8 Cross-correlation between thermal sensation votes and measured meteorological parameters. The solid lines denote the 95% confidence interval which determines whether the null hypothesis is rejected

immediate thermal history, resulting in the much lower TSVs that were reported by the subjects. This phenomenon was previously suggested as "thermal alliesthesia" (Parkinson and de Dear 2015), which implies that there are certain thresholds that pedestrians may be able to tolerate. Such information is important to the design of urban geometries since it offers greater flexibility to the design without compromising the thermal comfort of pedestrians.

Autocorrelation of subjective thermal sensation

Nikolopoulou and Steemers (2003) argued that the immediate short-term thermal experience affects a person's thermal sensation due to the conditions of the surrounding environment, which is particularly relevant to the design of an urban geometry. The short-term thermal experience can range from minutes to hours and influence the thermal sensation of a new environment through involuntary comparison with the previous experience (Ji et al. 2017). Using the data from all weather conditions, Fig. 7 shows that insignificant autocorrelations were found for both walking routes as the autocorrelations were within the 95% confidence interval (i.e., null hypothesis is not rejected). However, the lag-1 autocorrelation (0.355, *p* value = 0.129) is marginally insignificant for the trajectory of thermal sensation obtained from route 2, which indicates that there is a possible effect of the thermal sensation of the previous survey point (2–3 min before) on the instant one reported by the subjects. Such an effect was also demonstrated by the high correlation observed in the partial autocorrelation function, indicating that there is potentially a direct, positive correlation between the instantaneous and preceding thermal sensations. This implies a possible level of tolerance to changing environmental conditions that can be incorporated into the design of an urban geometry and is particularly useful to areas with environmental constraints. It also suggests that future studies can further look into the effect of immediate thermal history on people's thermal sensation in the outdoor environment.

Time-lag effect of meteorological variables on the TSV

Cross-correlation analysis was conducted to examine the time-lag effect of meteorological variables on the TSV throughout the walking route under all weather conditions (Fig. 8). For route 1, there are no significant correlations between the TSV and the instantaneous values of the meteorological variables. However, significant correlations were found between the TSV and the lag-1 values of T_{mrt} and the PET ($r = 0.600$ and 0.567, respectively). The correlations between the TSV and the lag-1 T_a and AH are marginally insignificant, suggesting that meteorological conditions may induce a delayed response to human thermal sensation when pedestrians are in motion and that the "memory" of recent conditions affects satisfaction with the thermal environment (Nikolopoulou et al. 2001). This short-term "memory" of the thermal experience is further confirmed by the insignificant correlations between the TSV and the lag-2 values (and thereafter) of the meteorological variables.

For route 2, a significant correlation was observed between the TSV and the instantaneous value of T_a ($r = 0.608$), while the cross-correlations with the instant T_{mrt} and the PET are less significant. In contrast, the cross-correlations are insignificant between the TSV and the lag-1 values of T_{mrt} and the PET. A more homogeneous and exposed environment may reduce the influence of short-term changes of the environmental conditions since the pedestrians were continuously exposed to solar radiation in the latter half of the route, which is a wider road exposed to the sun in the afternoon. This fact suggests that, in a continuously exposed environment, thermal sensation may be overwhelmed by instantaneous environmental conditions, while a constantly changing environment may have a higher potential to allow pedestrians to seek favorable conditions during their walk.

Conclusions

In this study, the dynamic nature of outdoor thermal comfort was investigated using a longitudinal survey and field measurements of micro-meteorological conditions using a mobile measurement system. Survey campaigns consisting of two designated walking routes were conducted in a dense urban area of Hong Kong. The results show that there are considerable variations in the meteorological conditions and the corresponding thermal sensation reported by subjects. Openness is one of the predominant factors influencing pedestrians' thermal comfort. Subjects were also shown to feel more comfortable when moving from sunlit to shaded places. The improvement of thermal comfort is greater when the difference in the PET is higher. The spatial pattern of thermal sensation was also found to vary with the weather conditions, demonstrating the need account for such variations in the assessment of pedestrian thermal comfort. The results also show that thermal sensation was associated with participants' short-term thermal experience (2–3 min) and that urban geometry plays an important role in the time-lag effect of meteorological variables on thermal sensation. This implies that more careful geometry design is important to pedestrian-level thermal comfort, accounting for the level of tolerance to thermal discomfort. Further data collection will be conducted to refine the understanding of such time-lag effects of tolerance and the physiological mechanism behind them.

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