Architectural Science Review

ISSN: 0003-8628 (Print) 1758-9622 (Online) Journal homepage: http://www.tandfonline.com/loi/tasr20

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ARCHITECTURAL SCIENCE REVIEW
https://doi.org/10.1080/00038628.2018.1495612

Design for climate resilience: influence of environmental conditions on thermal sensation in subtropical high-density cities

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ABSTRACT
Although outdoor thermal comfort has gained increasing research attention, meteorological conditions and thermal sensation in different urban settings in high-density cities have not been systematically studied from the perspective of urban planning and design. Considering the potential relationship between environmental quality and thermal sensation in outdoor spaces— an emerging topic in perceived comfort, this study offers a new approach for planning and design for climate resilience in cities. This paper presents the results of an outdoor thermal comfort survey conducted on hot summer days in Hong Kong. Diverse patterns of PET-comfort ratings relationships were found in different urban settings. The study revealed that air temperature, subjective assessments of solar radiation and wind environment were strong determinants of thermal sensation and evaluation. In our analysis, wind condition showed a significant indirect effect on comfort through subjective perception. Statistical modelling showed that subjective perceptions on microclimate condition and comfort are moderated by various aspects of environmental quality. The findings of this study help inform future design for climate resilience in outdoor urban spaces in hot-humid subtropical cities.

ARTICLE HISTORY
Received 29 March 2018
Accepted 28 June 2018

KEYWORDS
Outdoor thermal comfort; thermal sensation; urban microclimate; environmental quality; high-density

1. Introduction

Outdoor thermal environments and comfort sensation of pedestrians are important aspects to be considered in the design and planning of urban spaces (Ng and Cheng 2012). Numerous studies have been conducted in hot-humid regions to evaluate the effect of meteorological conditions on the perception of thermal comfort. The effects of thermal comfort on activities in outdoor urban spaces (Thorsson et al. 2007), influential meteorological factors linked to thermal sensation (Ng and Cheng 2012), comfort ranges in semi-outdoor and outdoor environments (Hwang and Lin 2007), as well as adaptive thermal comfort standards (Nicol et al. 2006), have been studied in cities with tropical and subtropical climates. The built environment in Asian metropolises is often dense and environmental quality diverse (Cerin et al. 2014). These features are closely linked to pedestrian comfort and thermal perception. Although Krüger, Minella, and Rasia (2011) have concluded that urban geometry and building density would create a profound impact on pedestrian comfort, the effect of building density on outdoor comfort and thermal sensation has not been systematically studied in ultra-dense Asian metropolises like Hong Kong. Numerous studies have been done to investigate the variations of urban climate such as urban heat island intensity and heat stress in urban areas. With the mapping of urban climate zones, the climate behaviour of urban environments can be better understood at spatial and temporal scales (Houet and Pigeon 2011; Ren et al. 2013; Scherer et al. 1999). However, it is necessary to cross-relate meteorological conditions and thermal sensation in different urban settings by climatic map classifications and compare their respective comfort thresholds in order to assess the influence of urban planning on human comfort and well-being.

Despite being a decisive factor, meteorological conditions cannot fully account for changes in subjective thermal comfort (Nikolopoulou and Steemers 2003; Han et al. 2007). In particular, outdoor areas tend to give a wider range of thermal comfort than indoor spaces because of psychological effects (Spagnolo and de Dear 2003; Hwang and Lin 2007). Psychological adaptation takes place in outdoor environments as people expect greater temperature fluctuation (Nikolopoulou and Steemers 2003).

Beyond this, there may be multisensory interactions affecting thermal comfort (Candas and Dufour 2005). While the hue-temperature hypothesis appears to have been disproved (Fanger, Breum, and Jerking 1977) and strong colours seemingly have no practical effects on thermal comfort, lighting is found to have some effect. Warm environments are more comfortable in 5000 K colour temperature light than 2700 K (Candas and Dufour 2005), suggesting that a 'cooler' light makes people feel cooler. Bright light increases body temperature through melatonin release (Badia et al. 1991). This leads to people rating the environment warmer in bright light. Similarly, there appears

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to be interactions between thermal comfort and perceived air quality and acoustic noise. Clausen et al. (2004) found that a one-degree change in temperature had the same effect on comfort as a 2.4 decipol change in perceived air quality or a 3.9 dB change in background noise level.

In addition, psychological comfort in general is affected by the ability to see nature (Aries, Veitch, and Newsham 2010). In contrast to urban settings, natural environments lead to more positive emotions, which can improve ratings of physical comfort. Park et al. (2011) found that the contrasting psychological responses to forests and urban environments influence thermal comfort significantly. Furthermore, this relationship appears to be bidirectional, where the perception of beauty can also be influenced by thermal conditions (Knez 2003; Eliasson et al. 2007). However, it was found that this relationship could be modified by cultural factors. For instance, respondents from different countries presented different ratings on thermal comfort at the same location and under the same physical conditions, thus leading to a difference in evaluation of beauty (Knez and Thorsson 2006).

Despite the continuously increasing research interest in outdoor thermal comfort due to climate change, these issues should be further addressed in specific contexts such as climate type and urban setting (Chen and Ng 2012). Firstly, a better understanding of the integration of various bio-meteorological indices is needed to provide a comprehensive bioclimatic assessment of the outdoor urban spaces, both shaded and unshaded (Spagnolo and de Dear 2003; Lin, Matzarakis, and Hwang 2010). Secondly, the direct and indirect influences of non-temperature variables on outdoor comfort thresholds require further investigation (Santos Nouri et al. 2018). Moreover, psychological factors associated with thermal perceptions provide new research questions in the qualitative criteria of pedestrian comfort outdoors (Nikolopoulou and Steemers 2003). To fill the research gap and inform design for climate resilience in subtropical high-density cities, this study aims to look into the influences of urban settings and perceived environmental quality on the subjective evaluation of urban microclimate and outdoor comfort. The main objectives of this study are described below:

(1) To study the patterns of microclimate conditions and outdoor thermal comfort within various urban settings in a high-density city;
(2) To identify key microclimate variables that affect thermal sensation and thermal comfort under unshaded and shaded conditions during hot summer days in the subtropics;
(3) To investigate the moderating effects from perceived environmental quality on correlations between urban microclimate and subjective evaluation / thermal comfort.

2. Methodology

During June-September 2017, a thermal comfort field survey was conducted in the urban areas of Hong Kong. In site selection, references were made to the existing urban settings classified by the Hong Kong Urban Climatic Analysis Map (UC AnMap) (Ren, Ng, and Katzschner 2011). Thirteen urban sites that can be categorized into different types of geometry and UC AnMap classes were selected (Figure 1). They range from open spaces and water front areas with relatively low building coverage (UC AnMap Class-3, 'low thermal load and good dynamic potentials') to very compact building volumes and high-rise, high-density geometry (UC AnMap Class-8 'very high thermal load and low dynamic potentials'). These sites are representative examples of the diverse built environments in the city (Table 1).

Transverse surveying is a well adopted method in outdoor thermal comfort studies (Spagnolo and de Dear 2003; Nicol et al. 2006). In this study, a transverse thermal comfort survey was employed to assess pedestrians' response to particular environmental conditions in different UC AnMap zones (Raja et al. 2001). On each study urban site, spot measurement was conducted to record micro-meteorological data and face-to-face questionnaire interviews were performed to collect subjective information from pedestrians on sensation of thermal comfort, and perception of environmental quality. With data from the survey, two widely applied thermal indices, physiological equivalent temperature (PET) and mean radiant temperature (T_{mrt}), were calculated (Thorsson et al. 2007; Van Hove et al. 2015). Statistical analyses using ANOVA, bivariate correlation and mediation and moderation analysis, were performed to explore the interrelationships between outdoor microclimatic conditions, perceived environmental quality, and sensation of thermal comfort.

2.1. On-site spot measurement

Outdoor microclimate measurements were conducted on 13 sites with mobile meteorological stations (Figure 2). Each station contains a TESTO-480 instrument and sensors measuring air flow (m/s), dry-bulb air temperature (°C) and relative humidity (%) with 1 sec sampling interval. Globe temperature (°C) was measured with a 38 mm diameter grey-colour table-tennis ball containing a K-type thermocouple wire digital thermometer, an improved construction designed for outdoor use with short response time (Nikolopoulou, Baker, and Steemers 1999). T_{mrt} was then calculated with the measured variables using the recalibrated equation for hot regions in Tan, Wong, and Jusuf (2013).

To capture the critical thermal conditions during the hot summer season (June-September) in Hong Kong, all measurements were conducted on days when the Hong Kong Heat Index (Lee et al. 2016) hit 30 and the 'very hot weather warning' was issued by the Hong Kong Observatory. For each study site, two stations were set at a height of 1.1 m (the average centre of mass of an adult man) on the same spot, one in shade and one exposed, during the hot period between 10:00 and 16:00(Ali-Toudert and Mayer 2006; Lin, Matzarakis, and Hwang 2010; Konarska et al. 2014).

2.2. Questionnaire survey

The questionnaire survey was conducted in 13 urban sites to obtain subjective assessments from pedestrians on outdoor thermal comfort and perceived environmental quality. The selected sites include a park, water front areas, open spaces, streets and foot paths in new towns and old districts. The study sites present a wide range of environmental characteristics in microclimate, ground coverage, building height, green ratio, traffic and pedestrian volume, and view. They reflect the diversity of outdoor urban environments in Hong Kong in the survey.

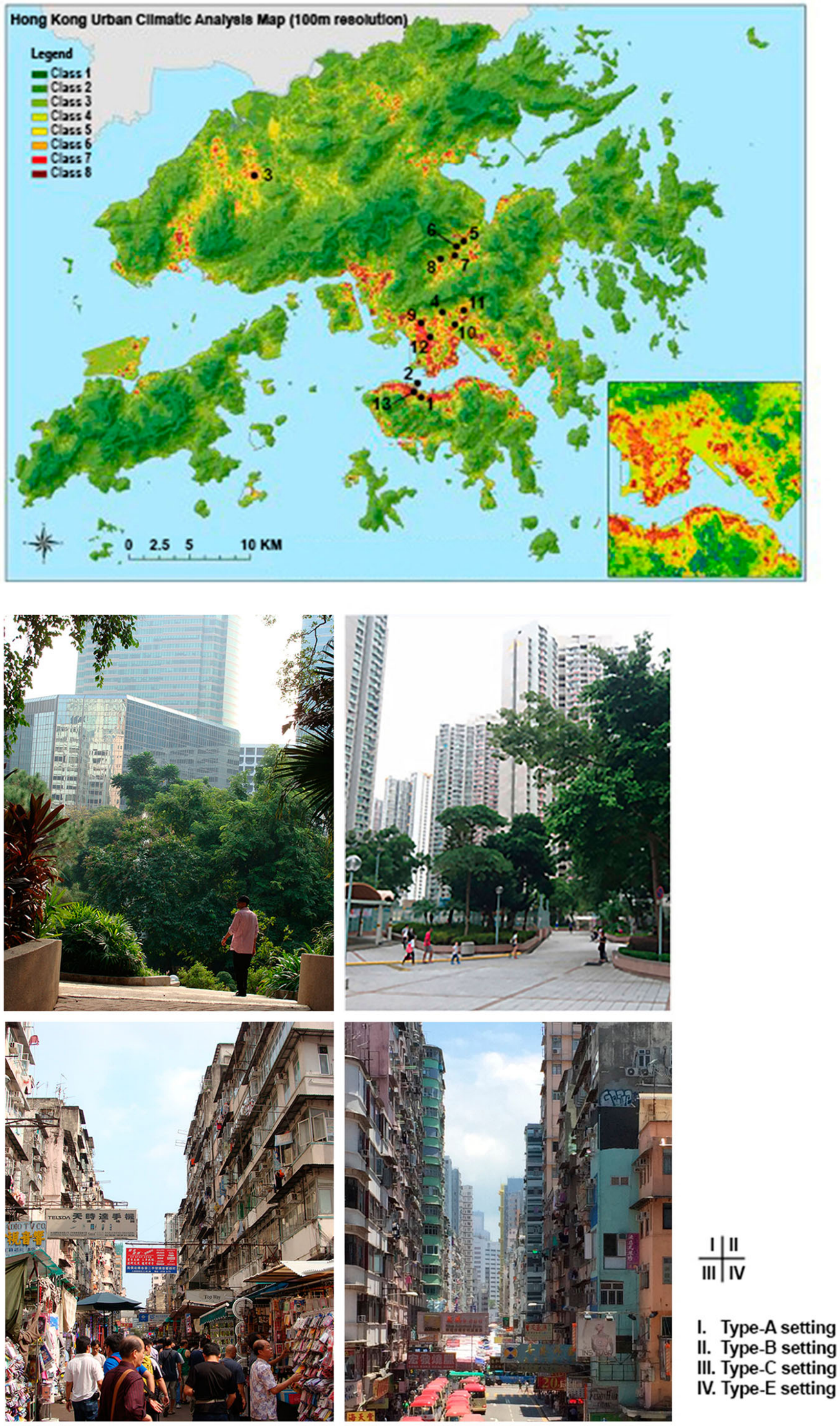

Figure 1. Selected study sites on Hong Kong Urban Climatic Analysis Map and site photos of different types of urban settings.

A total of 1998 participants (54% females and 46% male) completed a face-to-face questionnaire survey, with a response rate of 37%. Interviews took place at the same location as the measurement stations. The survey questionnaire, designed according to previous thermal comfort research and environmental assessment surveys, is comprised of three parts. Part One was mainly completed by the surveyor to record the time and location of the survey, weather condition during the interview (sunny, cloudy, raining), and the subject's information including (i) whether the individual was in shaded (505 participants) or unshaded (1493 participants) condition, (ii) clothing (in accordance with ASHRAE Standard 55), (iii) activity before interview (sitting/standing/walking/exercising), (iv) gender and (v) age (provided by the participant). Such records would be used to synchronize the responses with the measured meteorological data. With the measured meteorological variables and records

Table 1. Selected sites for the study.

Urban Setting	UC AnMap Classes	Selected Sites	Mean SVF	NO. of Participants
Type-A Open space and water front area with low building coverage (urban parks and piers)	UC AnMap Class-3 Low thermal load, good dynamic potentials	1. Hong Kong Park	0.76	154
		2. Central Pier	0.90	149
Type-B Medium building volumes (new town and low-density residentials)	UC AnMap Class-5 Moderate thermal load, some dynamic potentials	3. Yuen Long	0.70	56
		4. Kowloon Tong	0.62	91
Type-C Medium to high building volumes (public estates in developed new town)	UC AnMap Class-6 Moderately high thermal load, low dynamic potentials	5. Wo Che Estate	0.51	74
		6. Lek Yuen Estate	0.54	111
		7. Town Hall Plaza	0.38	239
		8. Tai Wai	0.33	201
Type-D High density, high building volumes (highly-developed old town areas)	UC AnMap Class-7 High thermal load, low dynamic potentials	9. Sham Shui Po	0.32	100
		10. Kowloon City	0.61	180
		11. Wong Tai Sin Estate	0.35	175
Type-E High-rise high-density, very compact building volumes (CBD and densely-built city centre)	UC AnMap Class-8 Very high thermal load, low dynamic potentials	12. Mong Kok	0.38	299
		13. Central	0.26	169

Figure 2. Meteorological stations for measurement (left) and questionnaire survey in urban site (right).

of the subjects' clothing indices and activities, the PET value was calculated in MATLAB (Höppe 1999). Part Two adapted outdoor thermal comfort survey questions from previous studies (Hwang and Lin 2007; Ng and Cheng 2012). Questions on residency in the past six months, number of hours spent outdoors daily, and whether they stayed in air-conditioned areas in the past 15 mins were put forward to interpret acclimatization and immediate past thermal experience of participants. The interviewees were asked to give a subjective evaluation of thermal sensation (7-point scale from −3 'very cold' to + 3 'very hot', ASHRAE scale), perception of thermal comfort (4-point scale from −2 'very uncomfortable' to + 2 'very comfortable'), and perception on four climatic parameters closely linked to thermal comfort (air temperature, radiation, humidity, wind speed). Part Three of the questionnaire addresses participants' perception of environmental quality at a particular site. With a five-point scale with a neutral midpoint, participants were asked to assess accessibility, the aesthetic quality, acoustic environment, air quality, and perceived safety of the location. They are key aspects in pedestrian satisfaction (King, Murphy, and McNabola 2009; Cerin et al. 2014).

3. Result and analysis

3.1. Microclimate and thermal comfort in different urban settings

The numbers of participants interviewed on each study site are presented in Table 1. A total 1088 female participants and 910 male participants were recruited across 13 sites. The average clothing insulation values for female participants and male participants were 0.32 and 0.29, respectively. Of the participants, 25% (505 persons) were exposed to solar radiation during the interview, while the others (75%; 1493 persons) were under shade.

Very strong correlations between T_{mrt} and PET were obtained for both shaded ($r_s = 0.98$, $p < .001$) and unshaded ($r_s = 0.95$, $p < .001$) conditions, indicating that T_{mrt} is one of the most important meteorological parameters governing human body energy balance and thermal comfort in outdoors in hot regions (Thorsson et al. 2007). To investigate variations in microclimate and the thermal stress in different urban settings, one-way analysis of variance (ANOVA) was used to compare T_{mrt} and PET values obtained in the urban sites under study. The results showed a statistically significant difference ($p < .001$) in mean PET values between the five types of urban settings. The urban setting of Type A (open space and low ground coverage) presented the lowest average PET of 33.2°C (Figure 3). It was followed by Type C (medium to high building volumes) at 35.9°C, Type D (high building volumes) at 36.3°C and Type E (very high building volumes and compact setting) at 36.3°C. The Type B setting (medium building volumes) with relative high sky view factor (SVF) values (approximately 0.6–0.7, see Table 1) resulted in the highest mean of 37.2°C. A significant difference ($p < .001$) was also found between the mean values of T_{mrt} obtained from different urban settings. A similar pattern was observed: The open space setting of Type A had the lowest averaged T_{mrt} of 35.1°C, while the very compact urban setting of Type E and medium building volumes of Type B both measured very high values of average T_{mrt}, at 39.0 and 38.9°C, respectively. The results revealed that even during the most critical period of summer season, the microclimate conditions formed under the urban setting of Type A were very close to local comfort (neutral) standards (PET of 32°C, T_{mrt} of 34°C, (Cheng et al. 2012; Ng and Cheng 2012).

Ratings of thermal comfort acquired from the 12 urban sites showed a very significant negative correlation with PET values ($p < .001$). Figure 4 shows the results of thermal comfort rating plotted against PET values. Patterns of the regression lines indicate that with the same PET value, ratings of thermal comfort differ in the five types of urban settings. Within the same PET range, Type E (very compact urban setting and very high building volumes) tends to associate with the lowest comfort rating (purple line), while Type A (open spaces with low building volumes) tends to yield the highest comfort rating (blue line).

3.2. Environmental variables and aspects related to outdoor thermal comfort

3.2.1. Thermal sensation and perceived comfort in unshaded conditions

To identify the key environmental variables and aspects that influence thermal comfort sensation in outdoor environments,

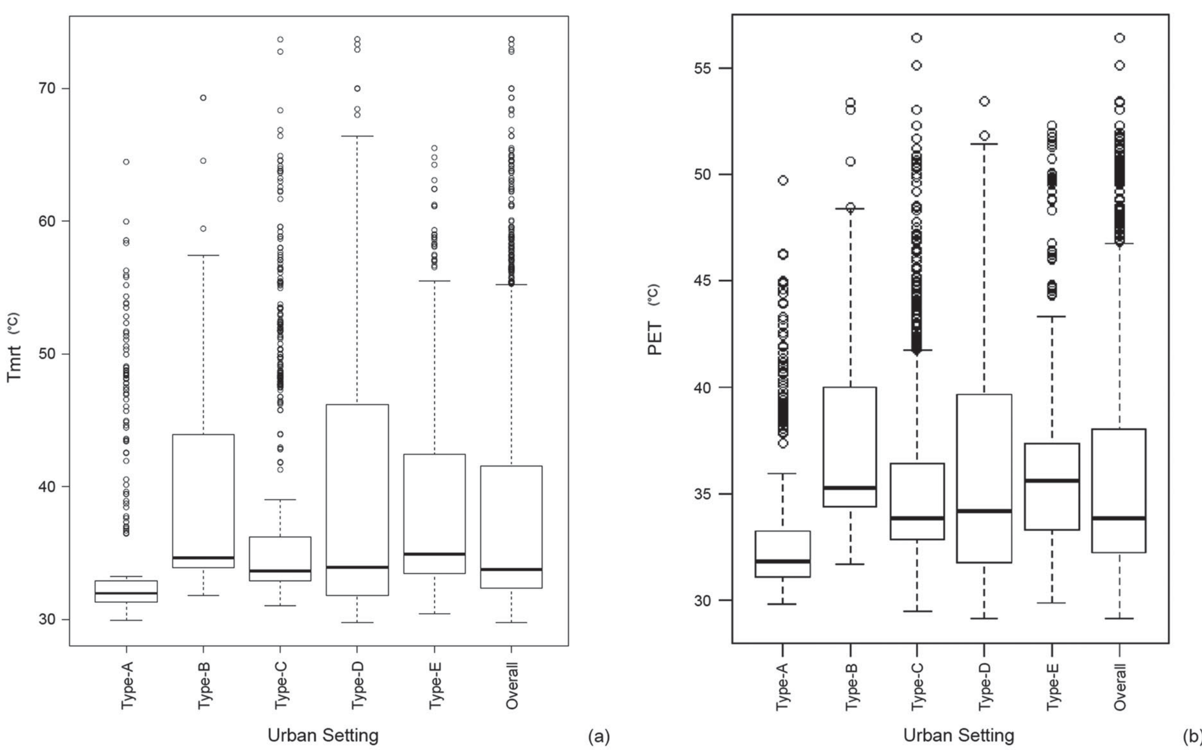

Figure 3. Boxplots of T_{mrt} (a) and PET (b) captured in different urban settings.

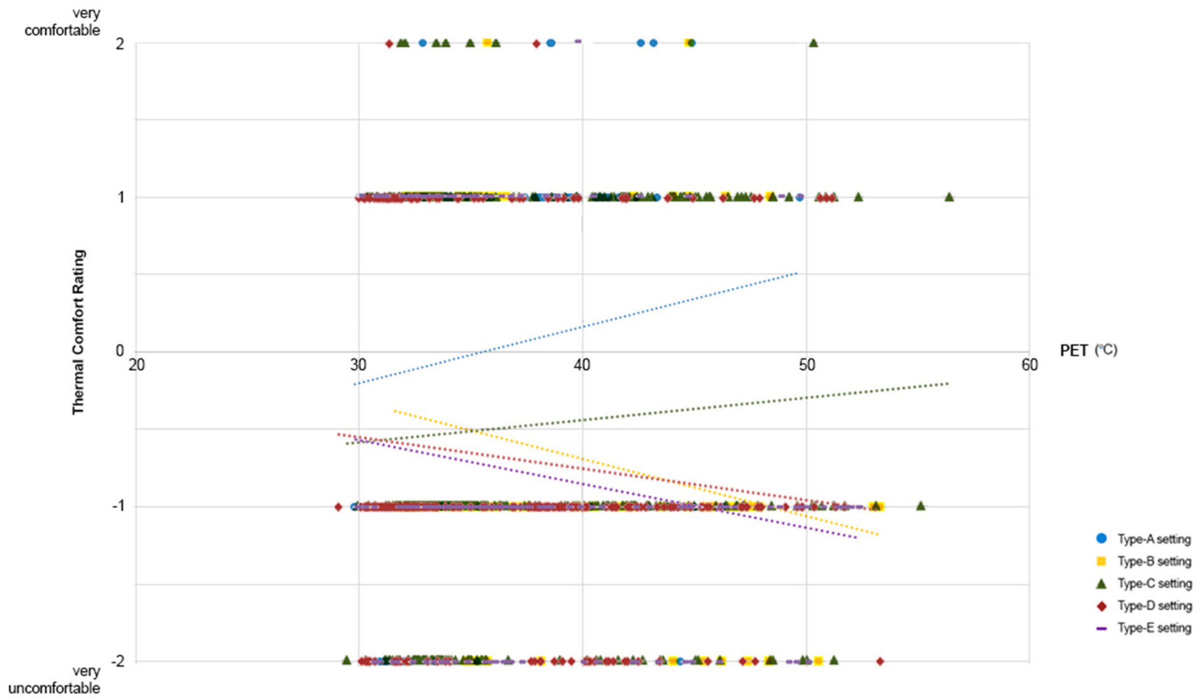

Figure 4. Correlations between PET-thermal comfort rating in different urban settings.

Table 2. Summary of meteorological parameters recorded during the survey period.

	T_a (°C)		$T_{a\_max.}$ (°C)		T_g (°C)		RH (%)		v (m/s)	
	exposed	shaded	exposed	shaded	exposed	shaded	exposed	shaded	exposed	shaded
Jun. (3 days)	33.7	33.1	36.9	35.7	37.6	34.4	62	64	1.1	1.1
Jul. (2 days)	32.0	31.3	34.2	32.9	34.9	32.9	70	75	0.9	0.6
Aug. (6 days)	34.9	34.6	39.1	38.2	39.1	35.6	55	56	0.9	0.8
Sept. (3 days)	34.2	33.3	37.8	36.1	36.6	34.2	60	64	0.8	0.7

T_a: air temperature, $T_{a\_max.}$: maximum air temperature, T_g: globe temperature, RH: relative humidity, v: wind speed.

correlations between microclimatic variables and thermal comfort sensation were calculated using Spearman's rank correlation tests (Porter, Gyi, and Tait 2003; Srinavin and Mohamed 2003) for both shaded and un-shaded conditions (Lin, Matzarakis, and Hwang 2010). For unshaded conditions, thermal sensation (7-point scale from 'very cold' to 'very hot') was positively related to globe temperature and PET (Table 2) and was very significantly correlated to measured air temperatures ($r_s = 0.15$, $p = .001$). The results showed that subjective assessment of radiation intensity (7-point scale from 'not enough' to 'too much') was the strongest determinant of thermal sensation in unshaded conditions ($r_s = 0.55$, $p < .001$). Subjective assessment of wind (7-point scale from 'very insufficient' to 'very sufficient') also showed a highly significant, negative correlation with thermal sensation ($r_s = -0.19$, $p < .001$, see Table 3).

The rating of thermal comfort (4-point scale from 'very uncomfortable' to 'very comfortable') for unshaded conditions, on the other hand, was very significantly related to two microclimatic variables— air temperature ($r_s = -0.22$, $p < .001$) and globe temperature ($r_s = -0.13$, $p = .004$), as well as to the subjective assessment of radiation intensity. Although rating of thermal comfort was not significantly related to measured wind speed on site, it showed a significant relationship with subjective assessment of wind ($r_s = 0.364$, $p < .001$). Meanwhile, subjective assessment of wind was very highly significantly related to wind speed ($r_s = -0.14$, $p = .001$).

3.2.2. Thermal sensation and perceived comfort in shaded conditions

Similar to the unshaded conditions, thermal sensation and rating of thermal comfort in shaded conditions were linked to globe temperature, air temperature, and PET. T_{mrt}, which was not a correlated variable in unshaded conditions, showed a very significant relationship to both thermal sensation ($r_s = 0.16, p < .001$) and rating of thermal comfort ($r_s = -0.15$, $p < .001$) in shaded conditions. Thermal sensation was found to be associated with subjective assessment on radiation intensity and wind. Even for participants in the shaded conditions, subjective assessment of radiation intensity was still the most significant aspect related to thermal sensation during hot days ($r_s = 0.52$, $p < .001$). Rating of thermal comfort, on the other hand, was very significantly related to subjective assessment on radiation, wind, and RH.

3.2.3. Interrelationship between measured wind speeds, subjective assessment on wind, and rating of thermal comfort

Mediation analysis with nearly 2,000 samples in the study was conducted to further explore the interrelationship between

Table 3. Results for bivariate Spearman rank correlation test.

		T_g	v	T_a	T_{mrt}	PET	$S_{\_rad.}$	$S_{\_wind}$
Unshaded	Thermal sensation	.114*	.051	.150**	.082	.101*	.547**	−.185**
	Perceived comfort	−.129**	−.040	−.217**	−.021	−.070	−.343**	.364**
Shaded	Thermal sensation	.185**	.119**	.159**	.158**	.142**	.523**	−.107**
	Perceived comfort	−.110**	−.004	−.150**	−.152**	−.156**	−.237**	.238**

*$p < .05$, **$p < .01$.
T_g: globe temperature, v: wind speed, T_a: air temperature, $S_{\_rad.}$: subjective assessment on radiation, $S_{\_wind}$: subjective assessment on wind.

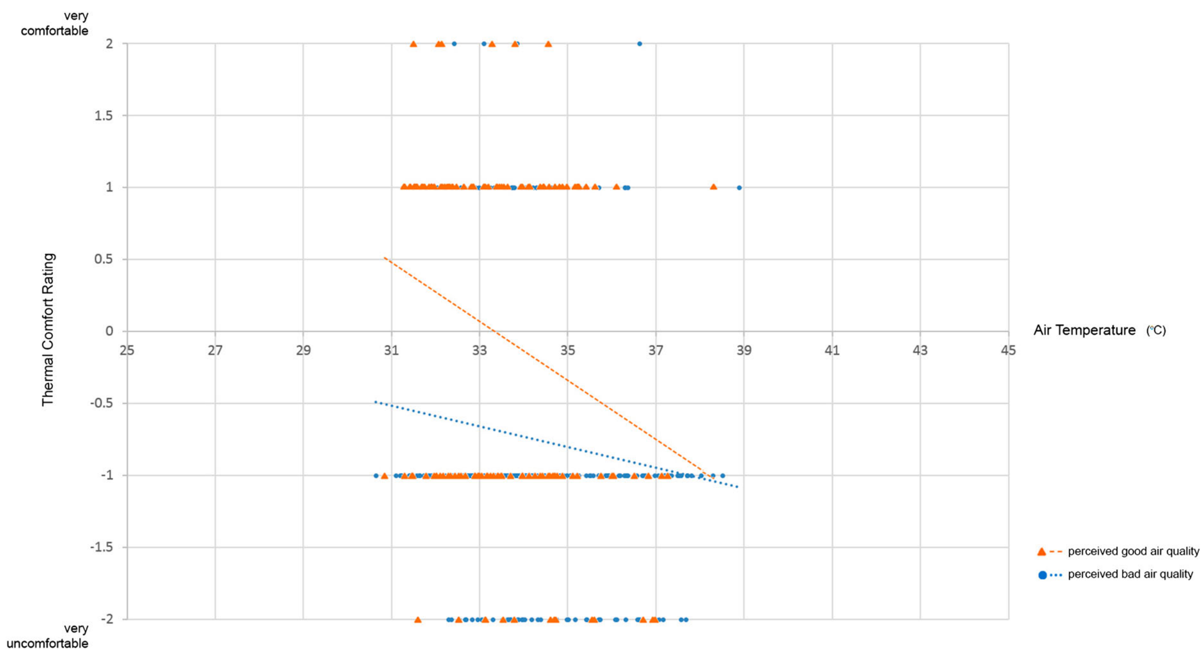

Figure 5. Moderating effect of perceived air quality on the relationship between air temperature and thermal comfort rating.

measured wind speeds, subjective assessments of wind, and rating of thermal comfort. Test results showed that although the direct effect of wind speed on thermal comfort was not statistically significant ($p = .174$), the indirect effect of wind speed on rating of thermal comfort was positive and statistically different from zero, as evidenced by a 95% bias corrected bootstrap confidence interval that is entirely above zero (0.058 to 0.142). According to recent studies, the only requirement for mediation is that the indirect effect ($a \times b$) is significant (Hayes 2009; Zhao, Lynch, and Chen 2010). Individual pathways analysis showed that a unit increase in wind speed positively increased subjective assessment by $a = 0.473$ ($p < .001$) units, and a unit increase in subjective assessment of wind increased thermal comfort rating by $b = 0.203$ ($p < .001$) units. Hence, with a unit increase in wind speed, participants tend to rate thermal comfort 0.473(0.203) = 0.096 unit more positively on a 4-point scale, as a result of improvements in the subjective assessment of wind.

3.2.4. Effects of past thermal experience and perceived environmental quality on thermal sensation and comfort

Potential influences of individual acclimatization, immediate past thermal experience, and environmental quality on thermal sensation and comfort were tested with moderated regression analyses and associated subgroup analyses. Neither the number of hours spent outdoors daily nor whether the participant stayed in an air-conditioned room in the past 15 mins was found to have significant effects as moderators of meteorological condition–thermal sensation relations. Specific interaction effects of perceived accessibility, aesthetic quality, acoustic environment, air quality, and perceived safety on the relationships between microclimate variables, thermal sensation and thermal comfort were evaluated by the model (Nikolopoulou and Lykoudis 2006; Hayes and Rockwood 2017). The results (Figure 5) indicated that under unshaded conditions, the effects of air temperature on outdoor thermal comfort were positively moderated by perceived air quality on site (F (1,857) = 3.99, $p = 0.021$). Subgroup analyses found a stronger relationship between air temperature and thermal comfort rating among participants who thought the air in the environment was good to very good ($p < .001$), compared to those who rated the air quality as bad and very bad ($p = .284$). Also, the subgroup with higher ratings on air quality tended to have higher ratings on thermal comfort under the same air temperature. Meanwhile, both perception of the acoustic environment (F (1,857) = 9.39, $p = .002$) and perception of air quality (F (1,857) = 10.67, $p = .001$) were found to be significant moderators of the relationship between wind speed and subjective assessment on wind environment. The model showed that when participants perceived the acoustic environment as good and very good, their subjective assessment on wind environment was significantly related to wind speed ($p < .001$) and had a much higher rate of increase with the increase of wind speed (Figure 6). When participants perceived the acoustic environment as bad and very bad, on the other hand, their subjective

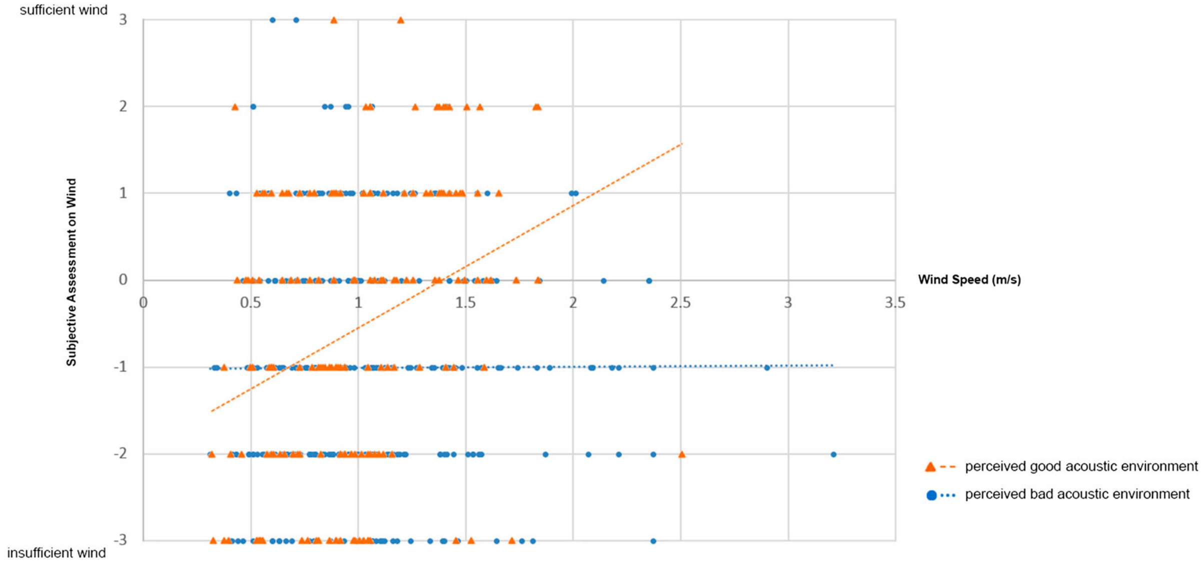

Figure 6. Moderating effect of perceived acoustic environment on the association between wind speed and subjective assessment on wind.

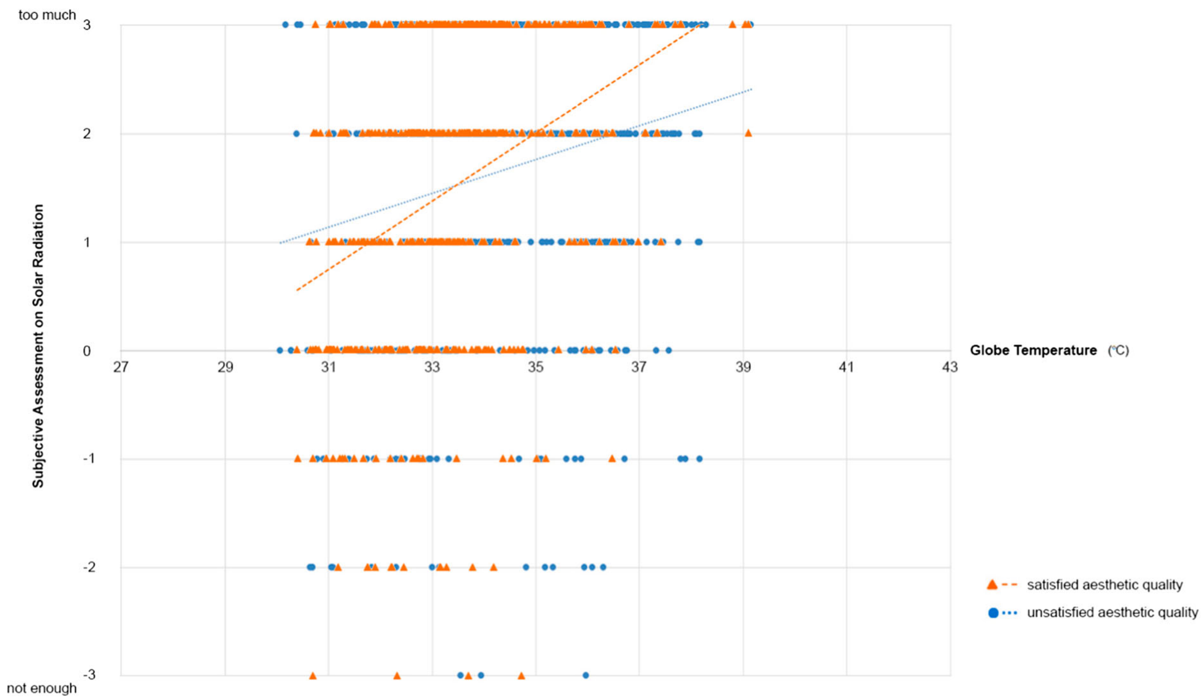

Figure 7. Moderating effect of satisfaction on aesthetic quality on the relationship between globe temperature and subjective assessment on radiation.

assessment on wind did not correlate with the actual wind speeds ($p = .512$), i.e. increasing wind speeds did not lead to positive changes in subjective assessment when the acoustic environment was found unsatisfactory. The same holds true for the moderating influence of perceived air quality.

For shaded conditions, a similar pattern was found for the moderating effects of perception on air quality in the association between wind speed and subjective assessment on wind. Moreover, the test results demonstrated significant, positive moderating influences of satisfaction of site accessibility (F (1,1141) = 11.59, $p < .001$) and aesthetic quality (F (1,1141) = 10.45, $p < .001$) on the relationship between globe temperature and subjective assessment on radiation in shaded conditions (Figure 7). The subgroup analyses found a stronger correlation ($r_s = 0.39$, $p < .001$) for participants satisfied with the aesthetic quality of the site than the ones who were not. When the recorded globe temperatures were below 34°C (accounting for approximately 60% cases), those who were satisfied with the aesthetic quality of the landscape showed higher tolerance to solar radiation than those who were not. Perceived safety, on the other hand, did not have a significant moderating influence on the effects of microclimate variables.

4. Discussion

PET and T_{mrt} obtained in the study sites with various urban settings demonstrated that with extensive vegetation cover and high permeability for ventilation, open spaces such as parks and water front areas provide cooler environments for pedestrians in Hong Kong. Type B setting with SVF values ranging between 0.6 and 0.7, however, presented a comparable T_{mrt} value to that recorded in Type E (very compact building volume), and a PET value that was nearly 1°C higher. This can be explained by the high SVF formed in relatively lower density building geometry, and the large amount solar heat entering the environment during day time (Giridharan, Ganesan, and Lau 2004). Meanwhile, Type C setting with SVF reduced to 0.4–05 had PET and T_{mrt} which were 1.3 and 0.9°C lower than Type B, respectively. Such results suggest optimum urban morphology in hot-humid regions should be further studied to mitigate both daytime and nigh time urban heat island effects. Apart from differences in urban microclimate conditions, comfort evaluation in the five types of urban settings presents different correlations to PET. Nikolopoulou and Lykoudis (2006) pointed out that there were multiple determinants of outdoor thermal comfort. The diverse patterns of PET – comfort ratings relationship shown in this study reveals that apart from the biometeorological index PET, there are other factors that affect outdoor thermal comfort in the urban environments of Hong Kong.

The results indicated air temperature is the strongest determinant microclimate variable of thermal sensation, echoing Nikolopoulou, Baker, and Steemers (2001). The data also showed that subjective assessments of radiation intensity and wind environment are strongly correlated to outdoor thermal sensation, whether the person is in shaded or unshaded conditions. Rating of thermal comfort is significantly related to subjective assessment of wind but not actual measured wind speeds. Combining both unshaded and shaded conditions, the mean of wind speeds under which participants considered there was sufficient wind was approximately 1.0 m/s. The finding is comparable to the results of a previous study (Ng, Cheng, and Chan 2008; Ng 2009).

Previous studies in both hot-humid and hot-dry areas concluded that wind speed has profound effects on human outdoor thermal, given air movement above 1.5 m/s in the urban areas (Ali-Toudert and Mayer 2006; Johansson and Emmanuel 2006). In our study, no significant relationship was found between rating of thermal comfort and actual wind speeds. It can be explained by the weak wind conditions and small fluctuation in wind speed in the ultra-dense urban environments in Hong Kong (Ng 2009). On the other hand, due to acclimatization, Hong Kong people show high sensitivity to relatively small changes in wind speeds, especially during hot weathers (Xie et al. 2018). This study has provided further evidence that through influencing subjective assessment on wind, wind speed has a significant indirect effect on thermal comfort in the urban environments of Hong Kong. Such finding has great implications for designing for outdoor comfort in highly developed urban areas. It demonstrates that relatively small improvements on wind in the urban areas can be detected by local people and hence their thermal levels can be enhanced during critical periods in summer. The results highlight the necessity and feasibility of promoting good practices that improve pedestrian wind environment in high-density cities (Alcoforado et al. 2009; Ng 2009; Reiter 2010).

It has been pointed out that thermal sensation is influenced by both short- and long-term experience (Nikolopoulou and Steemers 2003), and thermal experience and expectations play a major role in comfort rating in mild seasons (Nikolopoulou and Lykoudis 2006). This study reveals that in hot summer months, however, one's immediate thermal experience does not have significant moderating effect on the relationship between meteorological condition and comfort sensation, and the same is true for individual adaptation established from past exposure. A different pattern of results may be expected with different weather conditions and urban settings, and further study would be needed to provide better understanding on acclimatization.

Perceived environmental quality including air quality, acoustic environment, site accessibility and aesthetic quality showed significant, positive moderating effects on the associations between microclimate variables and subjective assessment / thermal comfort. Positive perception of environmental quality of the mentioned aspects strengthens the contribution of microclimate variables to outdoor thermal comfort or subjective assessment on thermal environment, i.e. high sensitivity to microclimate determinant was shown. This could be explained by the influence of environmental stressors (air pollution, noise, unsatisfying urban landscape, inconvenient commute) when a person has negative perception of the environmental quality (McHale et al. 2017; Li et al. 2018). Psychological effects associated with such negative perceptions of other environmental aspects would suppress the roles of co-existing microclimate attributors, whether on a positive scale (contributed by high wind speed) or negative (contributed by high temperature and radiation level). Relatively negative influence on perceived thermal comfort in general will then be shown (Santos Nouri et al. 2018). Such finding provides further evidence on the complementary interaction between physical environmental and psychological effects in regards of outdoor thermal comfort (Nikolopoulou and Steemers 2003). Hence, to design for climate resilience and outdoor thermal comfort in urban areas, attention should be paid to different environmental aspects and improve urban environmental quality in a synergistic way.

5. Conclusion

With a sample of 1998 respondents on 13 urban sites, we show that thermal comfort is influenced by both environmental and psychological factors. While objective measurements of environmental variables showed that thermal comfort is related to air temperature, we found that it is also dependent on subjective perceptions of wind speed and radiant heat. These subjective perceptions are moderated by seemingly unrelated parameters, such as the acoustic environment, air quality and appreciation of urban landscape. Designers need to take these factors into account, especially in ultra-dense cities where wind speed is limited by urban morphology. This study offers new evidence on the complexity of influential factors on outdoor thermal comfort in summer in high density cities. To obtain a more comprehensive understanding and better consider psychological influences in designing for climate resilience, further research on personal parameters, adaptation and expectation, as well as detailed urban design approaches, is urgently required.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Research Grants Council (RGC) of Hong Kong under Grant No-14603617.

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