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Influence of built environment on outdoor thermal comfort: A comparative study of new and old urban blocks in Guangzhou

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ABSTRACT

Urban populations face increasing heat stress in cities. However, the influence of the built environment of new and old urban blocks on pedestrian thermal comfort remains unclear. This study selected typical old (Yongqingfang) and new urban areas (Knowledge City) in Guangzhou, China, as our research sites. Through field monitoring and surveys, we used physiological equivalent temperature (PET) and thermal comfort vote (TCV) to evaluate outdoor thermal comfort by thermal walk experiments. We analyzed the relationships between built environment variables, meteorological variables, and pedestrian thermal comfort at the two sites. Our analysis revealed significant differences in the built environment and meteorological conditions between the new and old urban blocks within the 60-m buffer zone. PET and TCV showed noticeable spatiotemporal variations in both sites, and their correlation was stronger in the morning ($r = 0.87–0.89$) than late afternoon ($r = 0.60–0.70$). Our stepwise regression model indicated that sky view factor and building coverage ratio significantly affected outdoor thermal comfort in old and new urban blocks. Built environment variables explained a higher percentage of the variance in PET (Yongqingfang R^2: 0.59–0.82, Knowledge City R^2: 0.32–0.81) than TCV (Yongqingfang R^2: 0.45–0.57, Knowledge City R^2: 0.48–0.69). In short, built environment variables affected thermal indices more than thermal perception. The impact of built environment variables on TCV is also greater in new urban areas than in old urban blocks. Our findings provide insights into the complex relationship between built environments and outdoor thermal comfort in different urban landscapes, which informs climate-resilient urban design.

1. Introduction

In the context of global climate change and rapid urbanization, urban residents face increasingly severe environmental problems [1,2]. The ubiquitous urban heat island effect and the more frequent and intense heat waves in recent years have reduced outdoor thermal comfort and exacerbated human heat stress [3,4]. In 2003, an extreme heat wave caused more than 70,000 deaths in Europe [5]. Extreme heat events would increase the risk of cardiovascular, cerebrovascular, and respiratory diseases, acute renal failure, diabetes, and other related diseases [6]. Heat-related excess mortality in 161 Chinese districts/counties is projected to increase from 1.9% in the 2010s to 2.4% in the 2030s and 5.5% in the 2090s [7]. Understanding and revealing the complex relationship between the urban thermal environment and urban residents' psychophysiological responses have important theoretical and practical value.

Thermal comfort is a subjective evaluation of people's satisfaction with the surrounding thermal environment and involves three dimensions: physical, physiological, and psychological [8]. Outdoor thermal comfort is closely related to local microclimates, such as air temperature, humidity, wind speed, and mean radiant temperature [9–11]. Researchers typically obtain the subjective thermal perception

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of pedestrians by conducting thermal walk experiments combined with questionnaires [12,13]. Thermal sensation vote (TSV) and thermal comfort vote (TCV) are common subjective indicators that can reflect the thermal sensation of pedestrians and are widely used in thermal comfort surveys [14–16]. However, individual differences (physical and psychological), the combined influence of multiple environmental factors, and the crossed effects between different sensations (e.g., acoustic and visual comfort) make it challenging to clarify the complex relationship between thermal sensations and the surrounding environment [17–19]. In addition to subjective voting, equivalent temperature models are widely used to evaluate environmental thermal comfort. Equivalent temperature refers to the air temperature of a typical indoor room that produces the same physiological response as actual complex conditions. The physiological equivalent temperature (PET) [20] is the most commonly used equivalent temperature model employed in 30.2% of studies [21]. It considers environmental and individual parameters, including air temperature, humidity, wind speed, mean radiant temperature, clothing, and personal activity, to predict thermal sensation. The PET model is usually constructed using relevant meteorological parameters based on mobile field monitoring. Several studies have used portable equipment to obtain objective thermal environmental parameters and subjective thermal perceptions while conducting thermal walk experiments [22–25]. While PET has important theoretical significance, its relationship with thermal comfort requires further exploration in sites with different urban morphologies and landscape parameters [26]. Therefore, the equivalent temperature model and the subjective voting combination can more comprehensively reflect thermal comfort and its relationship with other factors.

Built environments can significantly affect the microclimate and alter local thermal environments. The influence of the geometry of urban buildings and landscapes on thermal comfort has been studied extensively. For example, the effect of building height on thermal comfort varies with the season [27]. Aspect ratio and solar orientation also affect the local thermal comfort of the street [28]. The sky view factor (SVF), building density, and floor area ratio are common urban morphology indicators that affect the thermal environment and thermal comfort [29,30]. As an important part of urban construction, urban green spaces are crucial for regulating the microclimate. Parameters such as greenspace coverage, volume, vegetation composition, and spatial structure can change the thermal environment and thus affect thermal comfort [9,31–33]. However, with the development and renewal of the city, its built environment is diversified. The built environment presented by historical/cultural, commercial, and industrial districts can be quite different. Studying the impact of different blocks of the built environment on pedestrian thermal comfort provides more specific and targeted references for urban designers and planners.

In existing research, the differences in the impact mechanism of the built environment on pedestrian thermal comfort among different blocks have not been fully explored. Moreover, the roles of indicators describing urban morphology (e.g., SVF, canyon aspect ratio), building intensity (e.g., floor area ratio, building coverage ratio), and urban landscape (e.g., the proportion of water body and greening) are still unclear. This situation necessitates comprehensive research combining objective and subjective thermal comfort in different urban forms.

Given this, this study selected typical historical/cultural blocks and newly built urban areas in Guangzhou, China, as our case study. The objectives of this study are as follows.

(1) To compare the differences in the built environment and microclimatic variables between historical blocks and newly built urban areas.
(2) To evaluate the spatiotemporal variations of the thermal index (PET) and subjective thermal indicator (TCV) in these two urban areas.
(3) To examine the impact of different built environment variables on PET and TCV in these two urban areas.

Based on field investigations of architectural elements, mobile monitoring of meteorological variables, and pedestrians' subjective thermal comfort votes, the relationship between urban built-up elements, microclimate, and thermal comfort can be determined from objective and subjective aspects.

2. Materials and methods

2.1. Study area

Guangzhou is located between 22°26′ N–23°56′ N and 112°57' E−114°03 E in the Pearl River Delta of Southern China (Fig. 1a). The city comprises diverse landscapes, with approximately 50% mountainous areas, 40% plains, and 10% waterbodies. Guangzhou has a humid subtropical climate (Koppen climate classification Cfa) with high temperature and high humidity characteristics, and the annual average temperature is approximately 22 °C.

The study was conducted at two sites (Fig. 1b), representing the modern and traditional urban development patterns within Guangzhou. One site is situated in the China-Singapore Knowledge City, a typical new town built in 2010 to create an advanced green and low-carbon district. The site is approximately 30 km from the city center, with modern-style buildings, wide streets, and clear layouts. The mean building height is 40 m, the green coverage rate is 20%, and the development intensity reaches 30%, with a floor area ratio of 9.7 (Fig. 1c).

The other site is in Yongqingfang, an old neighborhood located in a historic core that was first built in 1931. Yongqingfang is approximately 8 km from the city center and has many historical buildings with a rich cultural heritage. It was renovated and repaired after 2016, and most traditional architectural textures and styles have been preserved. The site consists of dense low-rise buildings, narrow streets, and a few greenery. The mean building height is 7.8 m, the green coverage rate is 10%, and the development intensity is approximately 40%, with a floor area ratio of 2.6 (Fig. 1d).

2.2. Experiment design and data collection

2.2.1. The setup of thermal walk experiment

The thermal walk experiment was conducted in Knowledge City on September 25, 2021, and in Yongqingfang on September 29, 2021. The two days were clear and hot, with few clouds, and had similar meteorological conditions. According to the Guangzhou meteorological station, the mean air temperature (9:00-19:00) was 31.77 °C and 32.9 °C, and the mean wind speeds (9:00-19:00) were 1.48 m/s and 1.43 m/s, the relative humidity (9:00-19:00) was 62.5% and 64.2%, respectively, for the experiment duration of two days. The experiment was repeated three times each day: in the morning (9:30–11:00), early afternoon (13:30–15:00), and late afternoon (16:30–18:00).

The thermal experiment was conducted at the two sites. The most common route for pedestrians was taken as the walking experiment route. Each walking route was approximately 1 km long, lasted about 90 min, and was divided into segments according to three built environment criteria (i.e., riverside/main street/inside the block). The Route in Knowledge City consists of four sections, namely the commercial district (segment A), riverside path (segment B), main street sidewalk (segment C), and science park (segment D) (Fig. 2a); 14 stops with typically built contexts were selected on the route for the questionnaire survey (Table 1, and Table A3 in Appendix A). The route in Yongqingfang consists of five sections, namely the Cantonese Opera Museum (segment E), riverside path (segment F), second-phase alley (segment G), main arcade street (segment H), and first-phase alley (segment I) (Fig. 2b); 16 questionnaire survey stops were chosen (Table 1, and Table A3 in Appendix A).

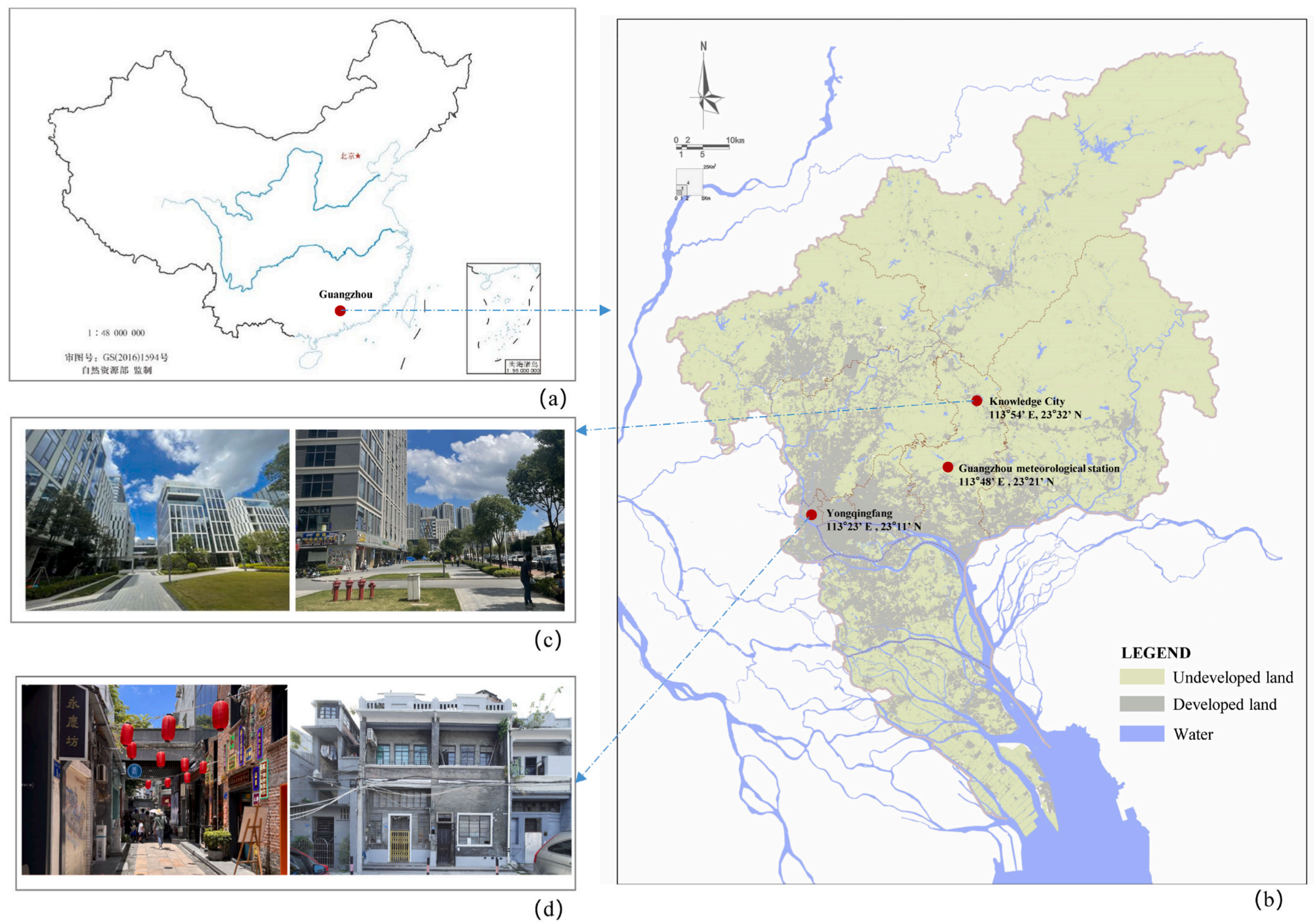


Fig. 1. Location of the study area.
(a) Map of China; (b) Location of study sites; (c) Knowledge City; (d) Yongqingfang.

2.2.2. Urban design measurement

We used a digital camera (Nikon D610) with a fisheye lens (Sigma 8 mm f/3.5 EXDG Circular Fisheye Lens) at each stop to take fisheye photos approximately 1.5 m above the ground. The fisheye photos were then processed and calculated using RayMan Pro 2.1 to obtain sky view factor (SVF) and tree view factor (TVF) indicators.

Based on the building footprint data for 2021, which contains building height attributes, we acquired urban morphology indicators in ArcGIS, such as the canyon aspect ratio and street orientation. We used the coordinates collected by GPS device during the thermal walk experiments as the center point to establish the buffer. Through spatial statistics analysis, development intensity indicators, including the mean building height, building coverage ratio, and floor area ratio, were calculated in the 20-, 40-, and 60-m buffer zones of each survey stop [34]. By visually interpreting the high-resolution aerial image (0.5 m) (according to the characteristics of the target object, such as vegetation coverage and driveway, the land use information was manually identified from high-resolution remote sensing images with an accuracy of more than 85%), landscape parameters, such as the proportion of water/driveway/greenery, were extracted within 20-, 40-, and 60-m buffer zones.

2.2.3. Microclimate measurement

Three researchers wearing instrument backpacks moved synchronously with the subject team in the front, middle, and rear positions to collect the meteorological monitoring indicators. The instrument backpacks included Kestrel 5400, GPS (Garmin Etrex 221x), lux meters (TES1339-R) (Table 2). Thus, air temperature (T_a), globe temperature (T_g), wind speed (WS), relative humidity (RH), illuminance, and GPS coordinates were collected during the thermal walk experiment. The mean values and standard deviations of the six rounds of experiments are shown in Table 3. Considering that the Kestrel 5400 needs to stay for more than 5 min to obtain accurate data [12], two Kestrels with wind blades fixed on a tripod alternately moved to the next stop 5 min earlier than the subject team arrived so that the measurement error can be minimized. Moreover, accurate wind speed/direction information of the survey stops can be collected (Fig. 3b).

The mean radiant temperature (T_{mrt}) was calculated using Eq. (1) [35]:

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

where T_{mrt} represents the mean radiation temperature, T_g is the black-globe temperature (°C), T_a is the air temperature (°C), D is the diameter of the black globe (0.025 m), and WS represents the wind speed (m/s), ε is the globe emissivity (0.95 for black globe).

Based on the above meteorological parameters, including T_a, RH, WS, and T_{mrt}, PET was calculated using RayMan Pro2.1 as an objective index to evaluate human thermal comfort (Matazarakis et al., 2008). PET refers to the air temperature when the Munich energy balance model (MEMI) reaches the thermal equilibrium of the human body, which is often used in outdoor thermal comfort research [20].

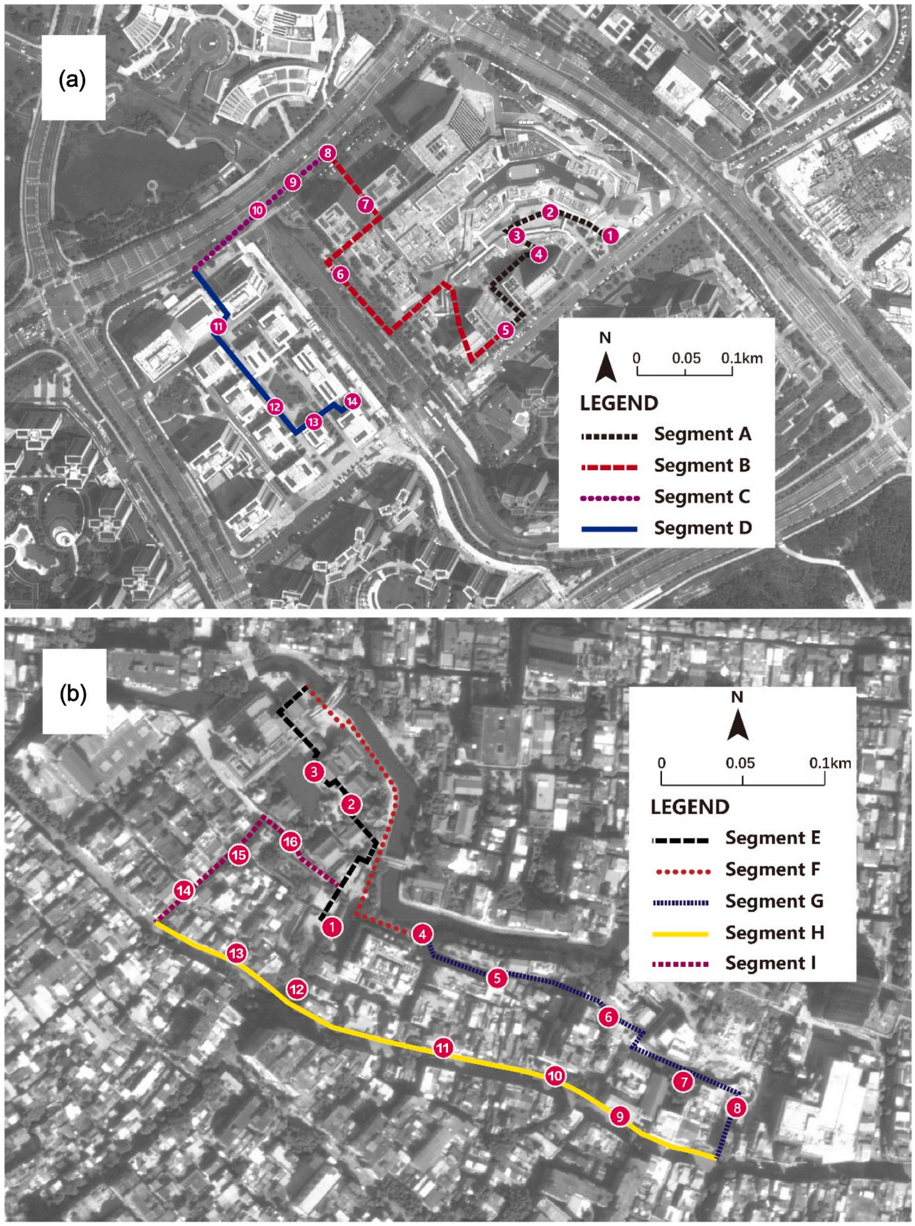


Fig. 2. Walking routes and survey stops. (a) Knowledge City; (b)Yongqingfang.

2.2.4. Survey campaign

The experiment involved 14 subjects (seven males and seven females) from a college in Guangzhou (the number of people limited by the COVID-19 pandemic) who were acclimatized to the local climate in Guangzhou. The average age of the subjects was 20 years, and their weight was between 53 and 75 kg. In the experiment, each subject wore a light-colored short-sleeved shirt, sports trousers, and a peaked cap uniformly. The COVID-19 epidemic was not serious when we conducted the experiment. Considering the accuracy of the outdoor experiment results, all subjects did not wear a mask during the whole experiment. At each stop, the participants were asked to vote on their thermal comfort vote (TCV), emotional state, and perceived fatigue level [36,37]. The TCV was indicated by a five-point scale, ranging from 0 (comfortable) to 4 (extremely uncomfortable) [36]. The subjects were requested to stay for over 3 min at each stop before filling in the questionnaire to account for the time-lag effect of meteorological variables on thermal sensation [22] (Fig. 3c).

2.3. Statistical analysis

First, according to the Pau Ta criterion (if $|X_k - \overline{X}| > 3\sigma$, then X_k is considered an outlier, where X_k is the k_{th} element, $\overline{X}$ is the sample mean, and σ is the standard deviation), the outliers of the meteorological factors at each sampling point were removed. Based on GPS real-time positioning data, ArcGIS was used to draw the diurnal spatial map of the PET and TCV along the sampling path of the two blocks. We used the Wilcoxon rank-sum test to test the differences in built environments within the 20-, 40-, and 60-m buffer zones and meteorological parameters of the sampling sites between Yongqingfang and Knowledge City. Kruskal-Wallis ANOVA with post-hoc Dunn's multiple comparison tests were used to test the differences in meteorological parameters of the two blocks among the three time periods of morning, early afternoon, and late afternoon. The influence of built environment variables on thermal comfort indicators was analyzed using a stepwise regression model. Prior to this, the independent variables were screened according to the variance inflation factor (VIF) to eliminate multicollinearity. After removing variables with a VIF >10, the remaining variables were

Table 1
Context of survey stops.

	Yongqingfang		Knowledge City
Y1	Open square in front of the Cantonese Opera Museum	K1	Open square with canopy
Y2	Shading corridors of the museum	K2	Impervious exposed plaza
Y3	Open platform close to the water	K3	Elevated ground floor, podium overhead passage space
Y4	Riverside walkway with trees	K4	Building enclosed children's square
Y5	Northwest-southeast commercial alley	K5	Exposed activity square facing the street
Y6	Shade Square with two enclosed buildings and a big tree canopy	K6	Riverside walkway
Y7	Pocket square with banyan tree canopy and water features	K7	Pocket square with three sides of buildings facing northwest
Y8	Exposed pocket square	K8	Sidewalk with shading corridor and one side of the building
Y9	Arcade Building	K9	Sidewalk with only shading corridor
Y10	The breakpoint of the continuous arcade building	K10	Sidewalk with no building structure
Y11	Arcade Building	K11	Building enclosure with four sides
Y12	Alley with bamboo green façade.	K12	The green square in the block center
Y13	Enclosed space by buildings	K13	Building setback
Y14	Northeast-southwest alley	K14	Pocket square with three sides of buildings facing northeast
Y15	Pocket square with three sides buildings and water features		
Y16	Northwest-southeast Lane		

Table 2
Specifications of the environmental monitoring equipment used in this study.

Measured parameter	Logger	Measurement range	Accuracy	Measured interval
Air temperature (°C)	Kestrel 5400 Heat Stress Tracker	−29 – 70 °C	±0.5 °C	2 s
Relative humidity (%)		0–100%	±2%	2 s
Wind speed (m/s)		0.6–40 m/s	±3%	2 s
Globe temperature (°C)		−29 – 60 °C	±1.4 °C	2 s
Illuminance (lux)	TES 1339R	0.01–999,900 lux	±3% of readings	1 s

weighted height, building coverage ratio, floor area ratio, street aspect ratio, street orientation, water body proportion, road ratio, SVF, and TVF. All statistical analyses were performed using R 4.2.1.

3. Results

3.1. Built environment and meteorological conditions

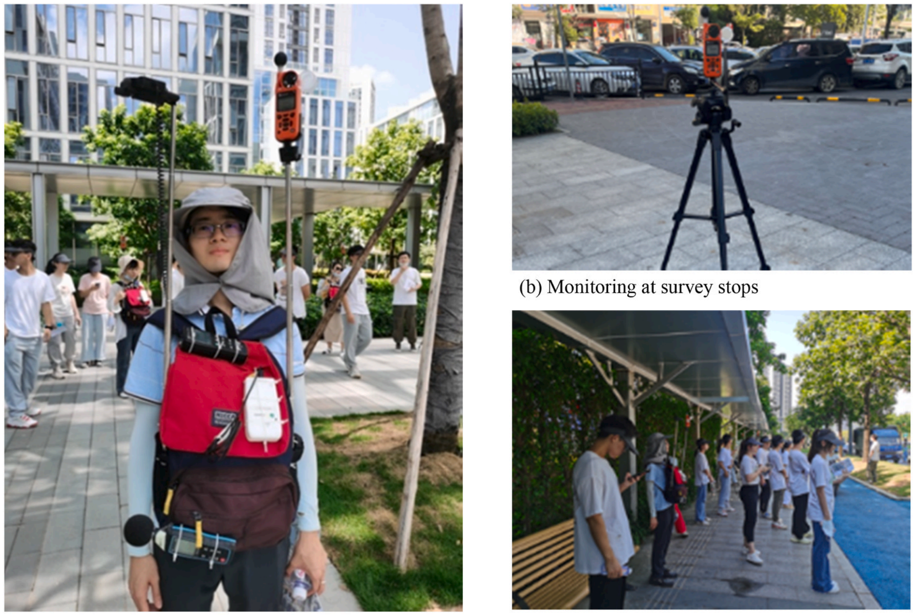
Within the 20-m buffer zone, the built environment difference around the sampling points of Yongqingfang and Knowledge City was insignificant. The built environment difference increased with an increase in the buffer zone. Within the 40-m buffer zone, the mean building height and floor area ratio of Yongqingfang were significantly lower than those of Knowledge City (Table 4). Within the 60-m buffer zone, the mean building height and floor area ratio, green coverage, and proportion of driveways in the Yongqingfang sampling sites were significantly lower than in Knowledge City. The building coverage ratio in Yongqingfang was significantly higher than that in Knowledge City (Table 4).

Compared with Knowledge City, the air temperature of the

Table 3
Data description of meteorological variables in this study.

	T_a (°C)				RH (%)				WS (m/s)				T_g (°C)				Illuminance (lux)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
YQF-M	31.32	2.31	30.67	39.04	68.92	5.83	51.80	77.76	0.22	0.23	0.00	0.85	36.25	5.34	29.11	47.19	20438.58	19417.65	619.89	61101.78
YQF-EA	35.41	1.81	33.52	41.13	55.24	3.92	45.01	62.83	0.21	0.27	0.00	0.64	38.50	4.92	32.31	49.33	21317.83	22608.75	1878.25	73540.94
YQF-LA	35.31	1.16	31.74	37.94	55.50	4.88	47.38	69.16	0.05	0.10	0.00	0.35	34.84	2.74	30.72	40.78	3751.38	5674.83	96.12	21081.56
ZSC-M	29.68	1.35	29.09	35.71	70.29	4.64	58.24	78.77	0.75	0.67	0.00	2.15	36.27	5.46	30.00	46.40	36486.74	37738.48	595.03	98019.67
ZSC-EA	33.68	0.66	32.28	35.64	59.85	1.96	54.81	63.40	0.71	0.49	0.00	1.66	39.28	6.04	33.50	48.79	23745.35	28974.83	2145.18	86123.22
ZSC-LA	31.51	1.68	29.03	34.54	66.54	7.32	57.35	79.34	0.79	0.92	0.00	2.84	35.62	4.12	29.90	46.82	5678.95	8219.63	616.31	34221.72

YQF and ZSC refer to Yongqingfang and Knowledge City, respectively. M, EA, and LA refer to morning, early afternoon, and late afternoon, respectively.



(a) Mobile meteorological station in this study

(b) Monitoring at survey stops

(c) Participants filling in the questionnaire.

Fig. 3. Mobile monitoring equipment and questionnaire survey during the thermal walk experiment.

Table 4
Differences in built environment variables between Yongqingfang and Knowledge City, showing the mean value of Yongqingfang minus that of Knowledge City.

Buffer size	Mean height (m)	Building coverage ratio	Floor area ratio	Canyon aspect ratio	Street orientation	Water body proportion	Greening coverage	Driveway proportion	SVF	TVF
20 m	−7.90	0.14	−4.82	−0.65	0.15	0.01	−0.03	−0.03	−0.01	0.02
40 m	−26.00**	0.14	−5.94***	−0.65	0.15	0.03	−0.05	−0.03	−0.01	0.02
60 m	−25.92***	0.14**	−7.16***	−0.65	0.15	0.01	−0.06*	−0.07***	−0.01	0.02

***: Difference is significant at the 0.001 level (2-tailed).
**: Difference is significant at the 0.01 level (2-tailed).
*: Difference is significant at the 0.05 level (2-tailed).

Yongqingfang sample sites was significantly higher in the morning, early afternoon, and late afternoon. The wind speed was significantly lower in the morning, early afternoon, and late afternoon, and the relative humidity in the early afternoon and late afternoon was significantly lower (Table 5). There was no significant difference in illuminance between the two locations.

3.2. Spatiotemporal variation of outdoor thermal comfort

Fig. 4 shows the spatial variation of PET along the two sites during the three rounds of the thermal walk and the corresponding TCV in the specific questionnaire stops. Subjects generally reported higher TCV values (i.e., more uncomfortable) along routes with high PET values and vice versa (Fig. 5). PET had a strong impact on TCV for both the morning and the early afternoon at both sites. However, this impact weakened in the late afternoon (with decreased slope and R^2) (Fig. 5).

Table 5
Differences in meteorological variables between Yongqingfang and Knowledge City, showing the mean value of Yongqingfang minus that of Knowledge City.

	T_a (°C)	T_g (°C)	WS (m/ s)	RH (%)	Illuminance (lux)
Morning	1.76***	−0.03	−0.53*	−1.36	−16048.16
Early afternoon	2.35***	4.92***	−0.50**	−4.61***	−2427.52
Late afternoon	2.89***	−0.78	−0.75**	−11.04***	−1927.57

***: Difference is significant at the 0.001 level (2-tailed).
**: Difference is significant at the 0.01 level (2-tailed).
*: Difference is significant at the 0.05 level (2-tailed).

The diurnal variation in thermal comfort showed a similar trend between the sites. During the early afternoon, the thermal comfort condition was the worst, with a mean PET value of 36.63 °C in Knowledge City and 37.79 °C in Yongqingfang. The TCV was also highest in the early afternoon, with a mean value of 1.33 and 1.41, respectively, for the two sites. Meanwhile, the PET in the morning and the late afternoon were mostly the same, which diminished to around 33.5 °C in Knowledge City and 35 °C in Yongqingfang. However, the TCV differed more when the subjects voted more comfortable in the late afternoon (mean value: 0.74 Knowledge City; 0.74 Yongqingfang) than in the morning (mean value: 0.78 Knowledge City; 0.93 Yongqingfang). The fluctuation of TCV was most evident during the morning (SD: 3.31 Knowledge City; 3.58 Yongqingfang) and in the early afternoon (SD: 3.38 Knowledge City; 3.24 Yongqingfang), while the fluctuation in the late afternoon was smaller (SD: 3.11 Knowledge City; 2.08 Yongqingfang).

In the Knowledge City, the segment with the highest mean PET (35.58 °C) was along segment A (commercial district). The value was 35.02 °C, 37.6 °C, and 34.13 °C, respectively, for the three rounds. The lowest mean PET (34.66 °C) was observed in segment D (science park) (Fig. 4a–c). The high PET values were concentrated next to stop K12 (exposed open space) in the morning, while they were located around stop K2 (exposed small square) in the early afternoon and the late afternoon. Meanwhile, the low PET values were located near stop K1 (with a big shade canopy) in the morning and the late afternoon, and near stops K4 and K7 (both covered by building shade) in the early afternoon (Fig. 4a−4c). Stop K5 had the largest variation ranging from 29.2 °C to

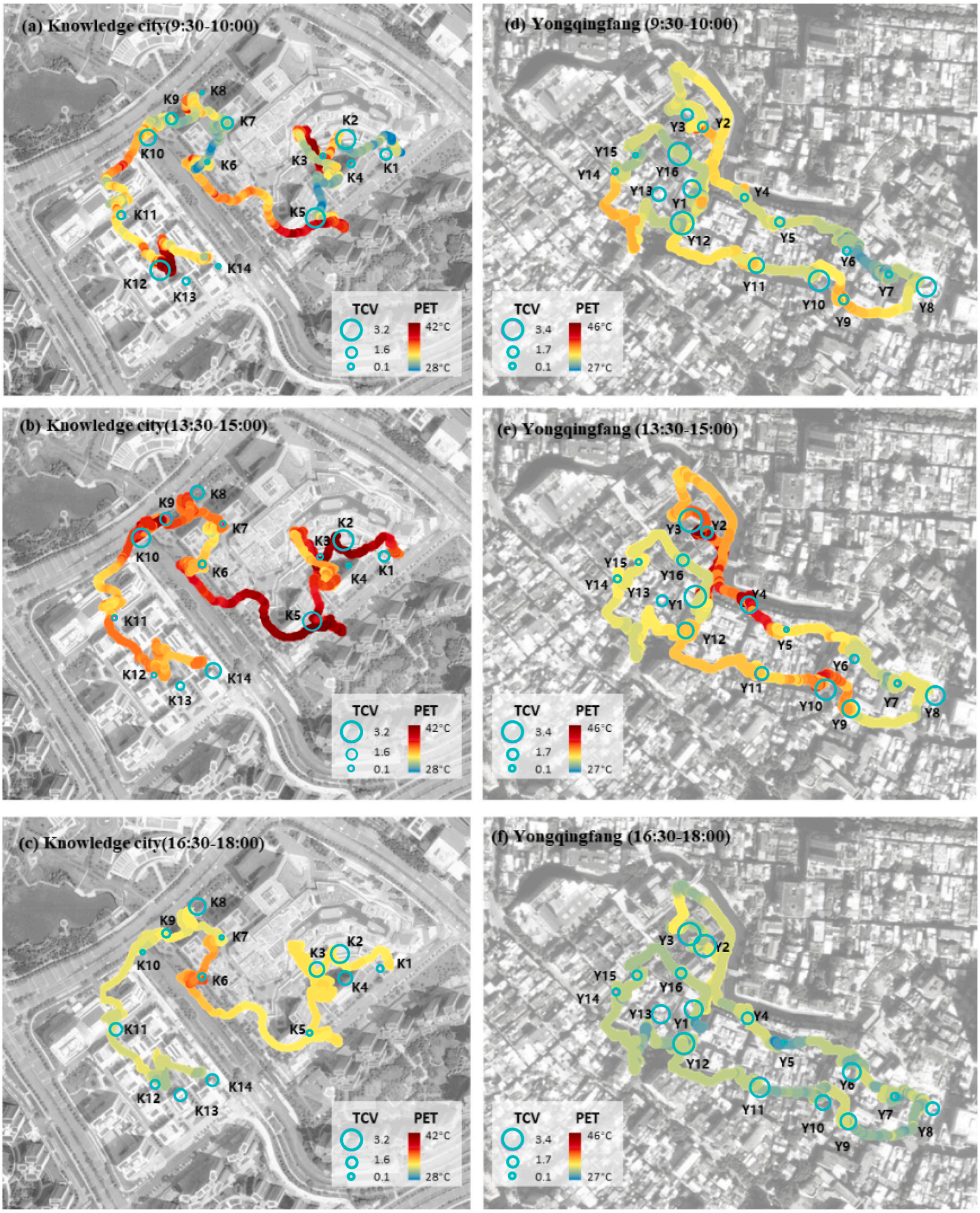


Fig. 4. Spatial distribution of PET for the routes and the corresponding TCV reported by subjects. ((a)–(c) Knowledge City; (d)–(f) Yongqingfang).

40.6 °C; stop K7 had the minimum PET range of less than 2 °C (Fig. 6). Overall, the PET values showed evident spatial heterogeneity, and the spatial pattern changed sharply with time.

In Yongqingfang, the PET values were lowest in segment I (first-phase alley) (mean value 32.53 °C) and also low in segment G (second-phase alley) (mean value 32.56 °C). In contrast, PET was highest in segment F (riverside path) (mean value 37.37 °C), followed by segment E (Cantonese Opera Museum) (mean value 36.5 °C) (Fig. 4d–f). The PET along segment H (main arcade street) had a mean value of 34.02 °C. The high PET values were concentrated in exposed stop Y16 in the morning, while they were located around stop Y3 (exposed small square) in the early afternoon and late afternoon. Meanwhile, the low PET values in the morning were located from stop Y5 to Y6 along a southeast-northwest alley. However, they were next to stops Y14 to Y15 along a southwest-northeast alley in the late afternoon (Fig. 4d–f). Stop Y3 had the largest variation in PET, ranging from 34.2 °C to 46.3 °C, and stop Y15 had a minimum PET range of 1.7 °C (Fig. 6). Overall, the PET values in Yongqingfang showed significant spatial and temporal variations.

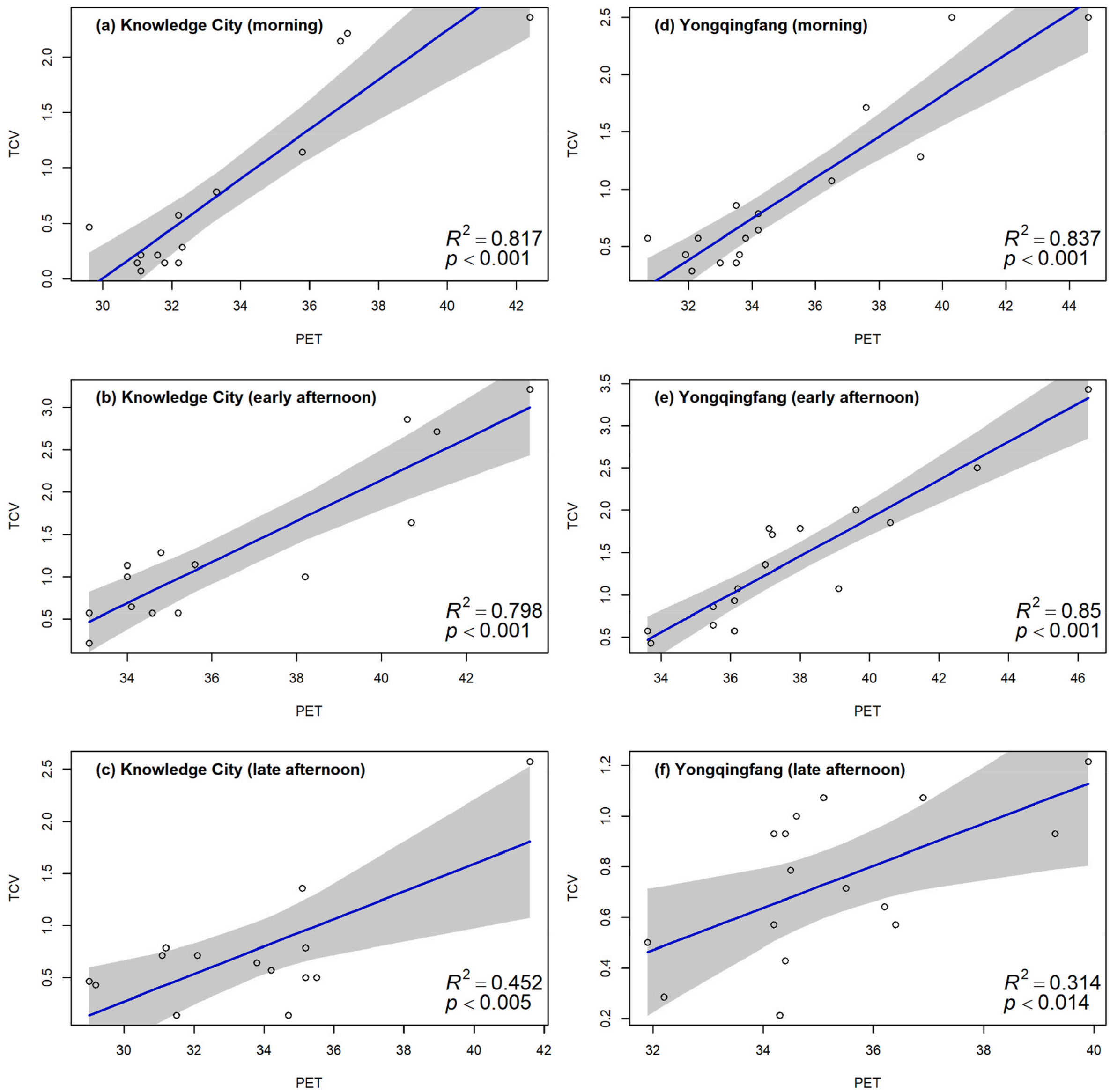


Fig. 5. The linear regression analysis of the association of PET with TCV in Knowledge City (a–c) and Yongqingfang (d–f) at different times.

3.3. Impact of built environment variables on outdoor thermal comfort

The built environment of the Knowledge City sampling sites had a greater impact on thermal comfort in the morning and early afternoon (PET: R^2 was 0.60 and 0.81, respectively; TCV: R^2 was 0.69 and 0.67, respectively). In comparison, the built environment of Yongqingfang was more likely to have a greater impact on thermal comfort in the early afternoon and late afternoon (PET: R^2 were 0.82 and 0.82, respectively; TCV: R^2 were 0.57 and 0.46, respectively) (Table 6).

With a buffer zone of 60 m, the built environment had a greater impact on thermal comfort, and diurnal variation tended to be stable. In the different blocks, the built environment factors that affected thermal comfort were different, and there were diurnal variations in the influencing mechanisms (Table 6). An increase in SVF would lead to a higher PET and TCV (i.e., more uncomfortable). In Yongqingfang, PET was affected by various built environment factors, and relatively few factors significantly impacted TCV. The SVF and mean building height had a significant positive impact on PET, while the building coverage ratio had a significant negative effect on PET in the early and late afternoon. In contrast, the impact of water body proportion and driveway proportion on PET was opposite in the morning and late afternoon. Compared to Yongqingfang, PET and TCV in Knowledge City were affected by fewer built environment factors. In the late afternoon, a higher TVF would lead to a higher PET and TCV (i.e., more uncomfortable). The building coverage ratio also strongly affected thermal comfort in the late afternoon (Table 6). In brief, the built environment had a strong effect on PET and a relatively weak effect on TCV. The diurnal variation in the influence of the built environment of Yongqingfang on thermal comfort was relatively small, whereas that of Knowledge City was relatively large (Table 6).

4. Discussion

4.1. Thermal difference between urban design segments

The relationship between built environment and local microclimate is complex, and it has also become the main carrier to cope with climate change and improve climate resilience [38]. Buildings can change the local microclimate in a variety of ways and then affect people's thermal comfort. In particular, the height, density and arrangement of buildings would affect the wind and thermal environment of the city [39,40]. The energy consumption and carbon emissions of buildings would directly

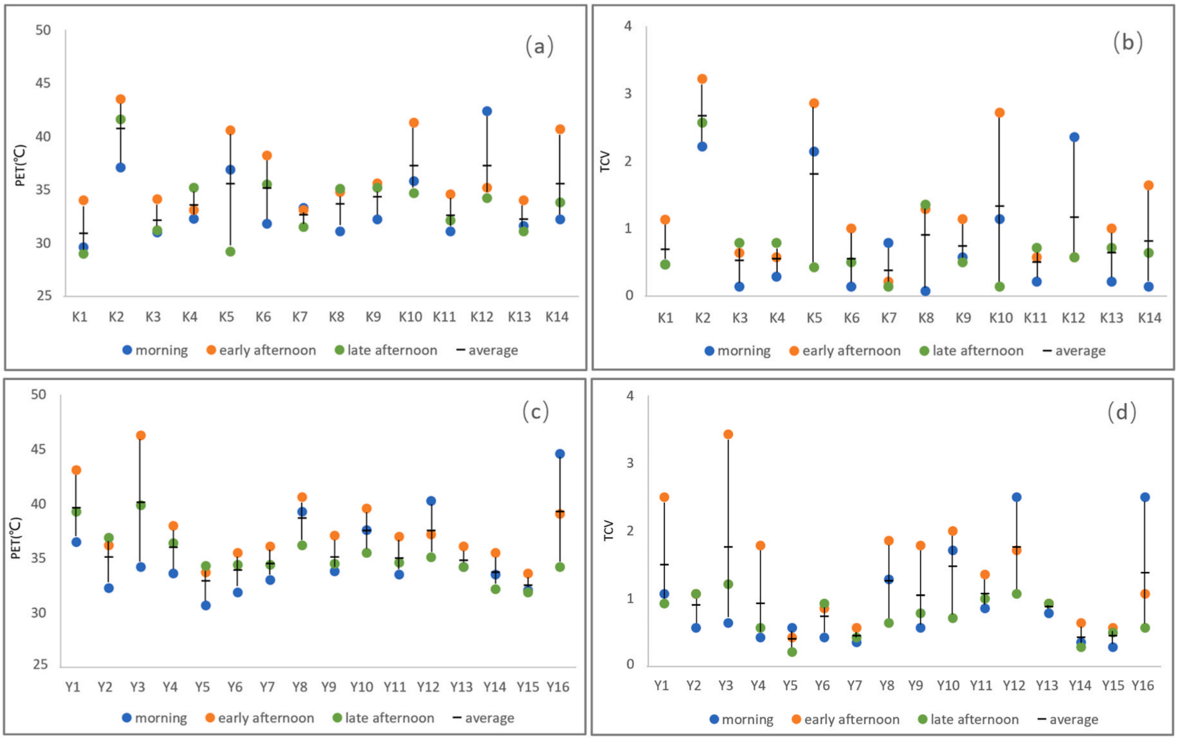


Fig. 6. Thermal comfort conditions at survey locations, showing (a) PET in Knowledge City, (b) TCV in Knowledge City, (c) PET in Yongqingfang, (d) TCV in Yongqingfang.

affect the regional heat balance [41,42]. This study focuses on the impact of building shape, assembly mode, and relevant block-scale urban design on microclimate and pedestrian thermal comfort.

Urban design can alter the solar gain and air circulation in urban blocks. In Knowledge City, segments A and D passed through two adjacent blocks divided by the river; however, segment D had better thermal conditions (Fig. 4). This result is likely due to different urban designs and layouts [43–45]. The commercial block, where segment A is located, is surrounded by high-rise buildings with a large low-rise building mass in the middle. Large-scale commercial buildings block airflow and have less shading effect. Segment D is situated in a science park with medium-high and narrow buildings that form a southeast-northwest layout conforming to the prevailing summer wind. Higher buildings located in the west can produce better shade for the open space in the center.

In old-town regeneration, the strategy of replacing old buildings with open spaces is usually adopted. An example of this is the Cantonese Opera Museum in Yongqingfang. Nevertheless, segment E along the museum had worse thermal conditions than the others, especially in some small squares without tree canopies (Fig. 4). A likely explanation is that the renewed open space did not produce a considerable permeability effect due to the static wind environment in dense old towns and reduced building shade [46]. Moreover, the narrow streets inside the blocks (segments G and I) were cooler than the main arcade street (segment H) (Fig. 4). Three reasons may explain this result. First, a narrow street is better shaded and has a higher aspect ratio [30]. Secondly, water misting facilities installed on the building façade of narrow streets cooled the environment (Fig. A.1 in Appendix A) [47]. Finally, the main street is influenced by anthropogenic heat generated by vehicles [48]. Our results suggest that the urban design in new and old urban blocks affects the outdoor thermal environment differently.

4.2. Difference in PET and TCV between survey locations

Natural and artificial shade provided by trees, buildings, and corridors is crucial for improving pedestrian thermal comfort, and their influence varies over time [49–53]. In our study, high values of TCV (i.e., more uncomfortable) were observed along the more exposed main roads and areas close to large open spaces, except for the late afternoon round when sunlight diminished. Along the arcade street in Yongqingfang, higher PET and TCV values were found at stop Y10, where the continuous arcade interface was broken by a pocket square. The stop had the same built-up environment as stops Y9 and Y11, except for the building shade (Fig. 6). The difference was more evident in the morning, likely due to the shade covering the entire sidewalk at the time, but only half the area during the early afternoon. Moreover, the thermal comfort during the day changed significantly over stops K8–K10 along the main road sidewalk in Knowledge City. The lowest PET and TCV were found at stop K8 (corridor and building shade), the highest value was observed at exposed stop K10, while the mean PET at stop K9 (only corridor shade) was between the PET values of stops K8 and K10. In the late afternoon after sunset, stop K10 had the lowest PET, and the gap between the three stops diminished to less than 0.5 °C (Fig. 6). Furthermore, street orientation changes the shade direction of surrounding buildings [54,55]. The PET of stops K7 and K14 are similar pocket gardens, with roads on one side and buildings on three sides. Nevertheless, the southeast-northwest-oriented stop K7 had better thermal conditions in the late afternoon. In contrast, the southwest-northeast-facing stop K14 was cooler in the morning, highlighting the effects of street orientation on the outdoor thermal environment.

The stops with only one side of the buildings had the largest variation among the three rounds, such as stops K5 and K12 in Knowledge City and stop Y3 in Yongqingfang. In contrast, the stops with more sides of buildings had shade from various directions (Fig. 6). This is primarily due to the sharp change in the building shade directions at different times [56].

Table 6
Regression analysis results of the built environment variables and thermal comfort vote (TCV). A positive beta value means that a higher value of the built environment variables would lead to a higher PET and TCV (i.e. more uncomfortable).

	SVF	Floor area ratio	Canyon aspect ratio	Street orientation	Proportion of waterbody	Proportion of driveway	Mean building height	Building coverage ratio	TVF	R^2	*p*
YQF-PET-M	0.69**	−0.25	−0.45*	0.20	−0.58*	0.50*	–	–	–	0.59	0.0207
YQF-PET-EA	1.09***	−0.52*	–	–	0.39	−0.89**	1.08**	−0.84**	–	0.82	0.0006
YQF-PET-LA	0.80***	–	–	–	0.65**	−0.58*	0.75**	−0.47*	–	0.82	0.0002
YQF-TCV-M	0.43	–	−0.45*	0.29	−0.34	0.73*	–	0.31	–	0.45	0.0637
YQF-TCV-EA	0.94**	−0.38	–	0.24	−0.54	–	0.85*	−0.76	–	0.57	0.0255
YQF-TCV-LA	–	–	–	–	0.80**	–	0.55*	−0.45*	–	0.46	0.0147
ZSC-PET-M	0.84***	–	–	–	−0.24	–	–	–	–	0.60	0.0026
ZSC-PET-EA	0.38*	−0.40	−0.32	−0.41*	0.31	–	−0.33	–	0.38	0.81	0.0086
ZSC-PET-LA	–	0.42	–	−0.37	–	–	–	0.69*	0.63*	0.32	0.1096
ZSC-TCV-M	1.04***	−0.43*	–	0.35	–	–	0.38	–	−0.34	0.69	0.0096
ZSC-TCV-EA	0.49*	−0.27	−0.44*	−0.36	–	0.36	−0.22	–	–	0.67	0.0223
ZSC-TCV-LA	–	–	–	–	−0.54	0.57	–	0.82*	0.74*	0.48	0.0396

YQF and ZSC refer to Yongqingfang and Knowledge City, respectively. M, EA, and LA refer to morning, early afternoon, and late afternoon, respectively. Significance levels of beta values are as follows: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$ (2-tailed). —: the missing value indicates that the parameter is eliminated by the stepwise regression model.

4.3. Difference in urban design features' influence on thermal comfort between new and old urban blocks

Yongqingfang and Knowledge City have typical features of Guangzhou's old and new cities. Old cities tend to have lower building heights, higher density, narrower streets, lower greening rates, and lower wind speeds inside the blocks. New cities tend to have taller buildings, lower densities, wider streets, higher greening rates, and higher wind speeds inside blocks (Tables 4 and 5). In addition to the apparent differences in the built environment (Table 4), the architectural style, culture, and lively atmosphere are also entirely different, affecting the thermal perception of pedestrians.

In this study, urban morphology indicators that significantly impacted thermal comfort included SVF, TVF, canyon aspect ratio, and street orientation (Table 6). SVF strongly affects thermal comfort, which has been confirmed in many other studies [57,58]. The SVF is closely related to the shading effect of buildings. A higher SVF tends to correspond to a weaker shading effect. Thus, a higher SVF would lead to higher PET and thermal discomfort [59,60]. The wind speed in Knowledge City was higher (Table 5), which made the ventilation effect in the street canyon obvious, and the impact of street orientation on thermal comfort was reflected. In this study, southeast-oriented streets would be more favorable for urban ventilation because the prevailing wind direction of Knowledge City was southeasterly (Table A2 in Appendix A). Therefore, the southeast orientation coefficient of streets in Knowledge City would lead to a lower PET and TCV (i.e., more uncomfortable) (Table 6). In Yongqingfang, the dominant wind direction was northerly (Table A2 in Appendix A). However, street orientation had no significant effect on thermal comfort because of the low wind speed (mean wind speed between 9 a.m. and 7 p.m. was 1.08 m/s on our study day). The canyon aspect ratio is an important parameter that affects the total amount of solar radiation. The larger the aspect ratio, the smaller the total radiation in the street canyon [54,56]. This situation enhanced thermal comfort for pedestrians in the morning and early afternoon (Table 6). In the late afternoon, the thermal comfort for pedestrians was no longer affected by solar radiation, the shading effect of buildings, or vegetation but mainly by the wind [61]. The presence of vegetation could affect the ventilation effect of the block [62,63] and thus affect thermal comfort. Therefore, the TVF of Knowledge City, but not the SVF, strongly positively affected thermal comfort indicators in the late afternoon. The lack of greening facilities and low greening rate of Yongqingfang might explain why the TVF had a limited impact on the thermal comfort of pedestrians.

The development intensity indicators that affected thermal comfort included the floor area ratio, building coverage ratio, and mean building height (Table 6). Among these, the building coverage ratio played the most important role. Building height is often closely related to shading effects [50,64]. However, in this study, the mean building height strongly affected thermal comfort indicators in the early afternoon and late afternoon (Table 6). This result might be due to changes in solar angles and the projection of the building, so the shading effect did not significantly affect the thermal comfort of pedestrians in the morning. In contrast, the height of the building affects ventilation in the block [65]. Tall buildings tend to be detrimental to the heat dissipation of the block, so the thermal discomfort of pedestrians would be more intense.

Owing to the poor ventilation in Yongqingfang, the impact of building height on heat dissipation was more evident than that in Knowledge City (Table 6). As the building coverage ratio in Yongqingfang increased, there was more building shade, which lowered both PET and TCV. However, as a new commercial block, Knowledge City had a better ventilation effect (Table 5). The increase in building coverage ratio hindered the ventilation effect of the street canyon and affected heat dissipation [66,67], which was reflected as a positive effect on thermal comfort indicators in Knowledge City in the late afternoon (Table 6). The floor area ratio comprehensively represents the building coverage ratio and height [29]. Because the building height was relatively uniform, the floor area ratio of Yongqingfang was more influenced by the building coverage ratio; therefore, it reflected the same impact as the building coverage ratio in the early afternoon. However, the building height of Knowledge City varied significantly, making a major contribution to the floor area ratio. Consequently, in the morning, owing to the shading effect of high buildings, the floor area ratio significantly negatively affected TCV (Table 6).

In terms of landscape parameters, the water body proportion had opposite effects on thermal comfort in the morning (beta value of YQF-PET-M: −0.58, i.e., the higher the proportion, the more comfortable people felt) and late afternoon (beta value of YQF-PET-LA: 0.65, i.e., the higher the proportion, the more uncomfortable people felt) (Table 6). Moreover, as the driveway proportion increased, people felt more uncomfortable in the morning (beta value of YQF-PET-M: 0.5) and more comfortable in the afternoon (YQF-PET-LA: −0.58) (Table 6). The reason for this phenomenon might be that the water body had a higher specific heat capacity than the impervious surface, and the rate of warming and cooling was relatively slower [68]. Therefore, it would appear as an endothermic and humidification effect in the morning, whereas in the late afternoon, it was weakened and might appear as a negative effect of heat dissipation [69].

Overall, in Knowledge City, because of the shading effect of the building and the influence on the amount of solar radiation, the built environment had a greater impact on the local microclimate in the morning and early afternoon, thus affecting the thermal perception of pedestrians. In particular, the built environment variables of Knowledge City explained a greater proportion of variations in PET and TCV in the morning and early afternoon (i.e., higher R^2 value) (Table 6). In the late afternoon, this effect weakened, as indicated by a lower R^2 value. In addition, the influence of the built environment on meteorological conditions was weakened in the late afternoon, which influenced thermal comfort through psychological and other aspects. Therefore, compared with PET, Knowledge City's built environment had a greater effect on the TCV in the late afternoon (Table 6).

The influence of the built environment of Yongqingfang on thermal comfort was different from that of Knowledge City. The buildings in Yongqingfang are generally low, and the streets are narrow and compact. Therefore, the shading effect of the buildings would be lower accordingly. The built environment variables in Yongqingfang explained a higher proportion of variation in PET in the early and late afternoon ($R^2 = 0.82$) than in the morning ($R^2 = 0.59$) (Table 6). Due to the cultural and historical significance of Yongqingfang, the psychological state of pedestrians could be affected by factors including architectural style and cultural history, which resulted in a relatively weak built environment impact on TCV [70–72], as indicated by a lower R^2 value (0.45–0.57) (Table 6).

4.4. Implication for practice and research

Our findings provide evidence of the difference between old and new urban blocks in terms of how urban design elements affect thermal comfort. The old city has been in a static wind environment for a long time. Therefore, the shading effect should be the primary concern. It is worth noting that the shading effect of the tree canopy is often offset by the shade produced by surrounding high-density buildings, so creating tree shade in relatively exposed spaces with sparse buildings is crucial. For the new town, the influence of urban design on thermal comfort is more complex and has dual effects on wind speed and radiation. Paying attention to coordinating the two objectives of maximizing wind speed and shading area during summer is necessary.

This study demonstrated that the influence of urban design elements on subjective and objective thermal comfort is different, and its effects vary at various times of the day. Urban design has a smaller effect on subjective thermal comfort because thermal comfort is affected by both urban morphology and psychological factors. Therefore, future urban planning should focus on the impact of architectural style and landscape features on the subjective psychology of pedestrians, which can enhance pedestrian thermal comfort. Owing to the change in the solar elevation and orientation, the shading effect caused by the variations in urban design presents significant differences for different times of the day, which inspires urban planners to design a combination of buildings and open spaces rationally. It is recommended that higher buildings be placed in the west to minimize strong solar heat gain in the afternoon, and open spaces should be placed at the center to take advantage of the shade the surrounding buildings provide.

In addition, a thermal walk experiment can simultaneously collect subjective thermal comfort and objective meteorological indicators, which can effectively record the actual experience of the human body when moving in an outdoor thermal environment. Staying at the survey stops for 3–5 min can account for the time-lag effect of thermal sensation to a certain extent, which meets the aim of studying the link between the built environment and thermal comfort and can be applied in future research.

4.5. Limitations of the study

We chose PET as the outdoor heat stress indication for two reasons. First, PET requires wind speed to be measured at pedestrian height, while UTCI requires wind speed to be measured at 10 m. Second, although PET does have the problem of overestimation, PET has been widely used in many outdoor experiments [22,23,73]. Furthermore, the PET unit is easily understandable as it is presented as an equivalent temperature (°C). Therefore, we chose PET as the thermal index in our study. In selecting the subjects, because of the need to control for social background and individual differences, college students were selected as the representative population group in our experiment, which might differ from the conditions of other age groups. The effects of diurnal temperature change during the 90 min experiment were not excluded, as we addressed both subjective thermal perception and objective thermal indices. In addition, in this study, we did not consider the possible effects of metabolism. During walking, the changes in metabolic rate would affect thermal sensation until a steady-state is reached [25,74]. Although TCV data at each point were collected after a 3-min stay in our study, this may not be enough to keep the metabolic rate stable. In the future, the effect of metabolic rate is worth further study.

5. Conclusions

Based on field monitoring and questionnaire surveys, this study compared the built environment and microclimate variables of typical new and old areas in Guangzhou. In particular, we examined the impact of different built environment variables on thermal comfort and its spatiotemporal variations in these two urban areas at the objective (PET) and subjective (TCV) levels. Within the 60-m buffer zone, the built environment and microclimate conditions of the two areas differed significantly. PET and TCV showed apparent spatiotemporal variations in both areas, and their correlation was stronger in the morning than in the late afternoon. Different parameters of the built environment affect pedestrian thermal comfort. In particular, SVF, TVF, canyon aspect ratio, street orientation, floor area ratio, building coverage ratio, mean building height, water body proportion, and driveway proportion all had significant effects. Among them, SVF and building coverage ratio were important influencing parameters. Under the coupling effect of meteorological conditions and cultural/historical significance, the influence mechanisms of the built environment on outdoor thermal comfort were different in the new and old urban areas and showed diurnal variations. In the new urban area, the impact of the built environment on thermal comfort was greater in the morning and early afternoon, while in the old urban area, it was stronger in the afternoon. The built environment variables had a greater impact on PET than on TCV because pedestrians' subjective thermal perception was also affected by physiological and psychological factors.

This study helps clarify the complex relationship between the built environment and pedestrian thermal comfort, as well as the subjective and objective thermal comfort indicators, providing a reference for subsequent related research. In addition, this study highlights the differences in the impact of the built environment on pedestrian thermal comfort between new and old blocks, indicating the diversity of the thermal environment inside the city. The findings of this study would inform strategies for urban planners and architects to build climate-resilient cities, and can provide a reliable reference for the regulation of built environmental factors in the renewal of old cities to better cope with climate change and the design of new urban areas facing future climate risks.

CRediT authorship contribution statement

Xingdong Deng: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Weixiao Nie:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Xiaohui Li:** Writing – review & editing, Supervision, Project administration. **Jie Wu:** Writing – review & editing, Supervision, Project administration. **Zhe Yin:** Writing – original draft, Formal analysis, Data curation. **Jiejie Han:** Writing – original draft, Investigation, Formal analysis, Data curation. **Haonan Pan:** Investigation, Formal analysis, Data curation. **Cho Kwong Charlie Lam:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Table A.1
Hourly mean data of the Guangzhou meteorological station during our study period.

Date	Hour	T_a (°C)	WS (m/s)	Wind Direction (°)	RH (%)
September 25	09	29.4	1.5	64	74
	10	29.6	1.9	4	74
	11	31.3	1.6	97	65
	12	32.5	1.3	109	61
	13	32.6	1.6	100	56
	14	33.4	1.3	121	53
	15	33.8	1.4	130	51
	16	33.5	1.9	57	53
	17	33.1	0.9	60	56
	18	32	1.0	360	63
	19	28.3	1.9	348	81
September 29	09	29.7	1.3	224	75
	10	30.9	1.5	263	69
	11	32.3	1.5	198	67
	12	33.1	1.1	262	63
	13	33.2	2.5	315	61
	14	34.5	1.9	258	57
	15	35.2	1.7	343	54
	16	35.7	1.4	305	55
	17	35.3	0.9	319	54
	18	32.3	0.5	351	72
	19	29.7	1.4	350	79

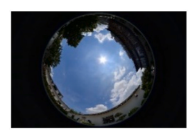
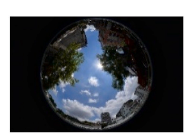
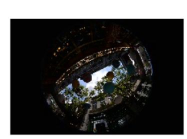
WS refers to wind speed at 10 m height.

Table A.2
Mean hourly data of two meteorological stations close to our study sites during our study period.

Sites	Hour	T_a (°C)	WS (m/s)	Wind Direction (°)	RH (%)
Knowledge City (September 25)	09	28.4	1.7	286	–
	10	29.9	1	68	–
	11	31.5	1.6	72	–
	12	32.3	1.9	127	–
	13	33.2	1.1	150	–
	14	33.4	1.2	177	–
	15	33.6	2.3	133	–
	16	33.5	1.7	28	–
	17	32.9	2.1	149	–
	18	31.8	1.3	172	–
	19	29.5	1.4	260	–
Yongqingfang (September 29)	09	30.4	0.8	39	72
	10	31.8	0.9	263	68
	11	32.9	1.2	324	61
	12	33.9	1.2	357	57
	13	34.4	2.1	17	52
	14	35.5	1.1	100	50
	15	35.6	1.1	30	51
	16	36.3	0.8	299	46
	17	35.5	1.3	25	47
	18	34	0.9	326	54
	19	33.7	0.5	98	54

WS refers to wind speed at 10 m height. RH refers to relative humidity.
Note: : there are missing RH values because the station close to Knowledge City had no RH sensor.

Table A.3
The pictures and fisheye photos of the survey locations at our two study sites. Y1 to Y16 are at Yongqingfang, whereas stops K1 to K14 are at Knowledge City.

ID	Description	Fisheye photos	Scenes
Y1	Open square in front of the Cantonese Opera Museum		
Y2	Shading corridors of the museum		
Y3	Open platform close to the water		
Y4	Riverside walkway with trees		
Y5	Northwest-southeast commercial alley		

(continued on next page)

Table A.3 (*continued*)

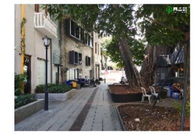
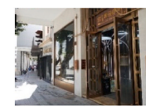
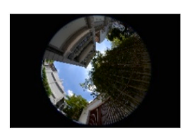
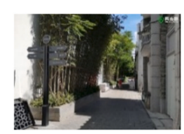
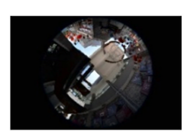
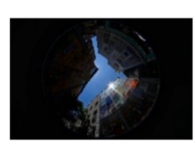
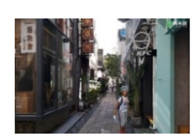
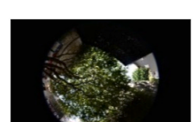
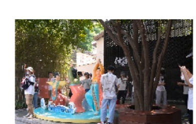
ID	Description	Fisheye photos	Scenes
Y6	Shade Square with two enclosed buildings and a big tree canopy		
Y7	Pocket square with banyan tree canopy and water features		
Y8	Exposed pocket square		
Y9	Arcade Building		
Y10	The breakpoint of the continuous arcade building		
Y11	Arcade Building		
Y12	Alley with bamboo green façade		
Y13	Enclosed space by buildings		
Y14	Northeast-southwest alley		
Y15	Pocket square with three sides buildings and water features		

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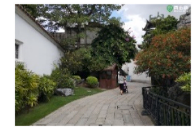
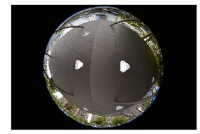
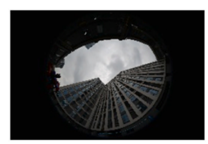
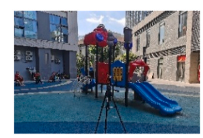
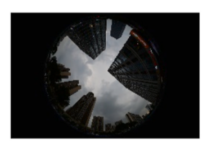
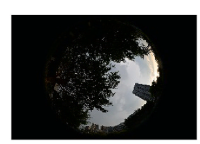
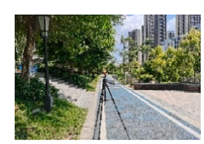
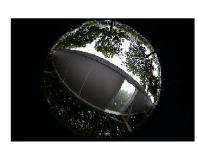
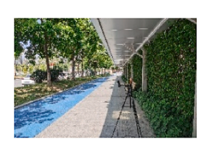
Table A.3 (*continued*)

ID	Description	Fisheye photos	Scenes
Y16	Northwest-southeast Lane		
K1	Open square with canopy		
K2	Impervious exposed plaza		
K3	Elevated ground floor, podium overhead passage space		
K4	Building enclosed children's square		
K5	Exposed activity square facing the street		
K6	Riverside walkway		
K7	Pocket square with three sides of buildings facing northwest		
K8	Sidewalk with shading corridor and one side of the building		

(*continued on next page*)

Table A.3 (*continued*)

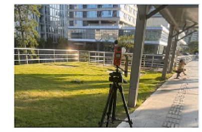
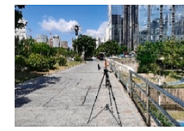
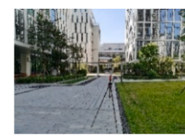
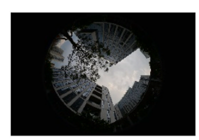
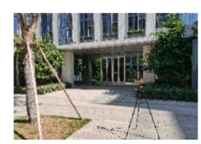
ID	Description	Fisheye photos	Scenes
K9	Sidewalk with only shading corridor		
K10	Sidewalk with no building structure		
K11	Building enclosure with four sides		
K12	The green square in the block center		
K13	Building setback		
K14	Pocket square with three sides of buildings facing northeast		

Fig. A.1. Water Misting Facilities on building facades on Yongqingfang's narrow streets.

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