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Diversity of summertime thermal and environmental perceptions in residential public spaces: A walking-based assessment in Hong Kong's public housing estates

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ABSTRACT

Increasing excessive urban heat presents world-wide challenges to creating thermally comfortable living environments. Though transient thermal comfort in outdoor spaces is well-observed, the significance of dynamic thermal experience to overall environmental quality, and their multivariate association with the built environment, microclimate condition, and human's physiological responses remains unclear. We conducted 57 twenty-minute guided walking tours in residential public spaces in Hong Kong during summer, with 31 conducted under extreme heat. Dynamic thermal and environmental perceptions were surveyed with simultaneous measurements of microclimate variables and human skin temperatures. Built environment characteristics were extracted from panoramic videos. Results show significant associations among built environment characteristics, microclimate condition, mean skin temperature difference, and thermal and multi-sensory perceptions. Thermal pleasure and scenic beauty are significantly associated with overall environmental quality, with the latter demonstrating greater associations. During summertime outdoor walking, linear regression shows that a 4.29 °C reduction in Universal Thermal Comfort Index between two adjacent spaces leads to a one-level change in thermal pleasure. Significantly greater microclimate variations and more self-reported thermal displeasure are recorded under extreme heat. Higher variation in thermal comfort indices and higher mean wind speed along the walking route are associated with more self-reported thermal *alliesthesia*. A mean lagged response of 58.89s between mean skin temperature and sky exposure is detected. We conclude that dynamic thermal experiences can be created in urban design by considering the space types and morphological diversity, and the sequence and duration of human exposure to these spaces, which ultimately influences the users' perceived environmental quality.

Abbreviations

OTC	outdoor thermal comfort
Ta	air temperature
Rh	relative humidity
Tg	globe temperature
Tmrt	mean radiant temperature
Tsk	skin temperature
Tsk_m	mean skin temperature
v	wind velocity
PET	physiological equivalent temperature
mPET	modified physiological equivalent temperature
UTCI	universal thermal climate index
HKHI	Hong Kong heat index
SVF	sky view factor
GVI	green view index
OEQ	overall environmental quality
TSV	thermal sensation vote
TCV	thermal comfort vote
TPV	thermal pleasure vote
SBV	scenic beauty vote
LSV	loudness sensation vote
VSV	visual sensation vote
AQSV	air quality sensation vote
WSV	walking safety vote

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1. Introduction

Urban liveability requires comfort as its fundamental prerequisite, with outdoor thermal comfort (OTC) playing a crucial role [1,2]. Climate-responsive urban and landscape design has long been promoted to achieve high quality of life [3], yet the continuous urban overheating under the new-normal of heatwaves presents harsher challenges to human health and well-being [4]. With such challenges, OTC enhancement shall remain a critical priority in future planning and design, calling for studies to inform designers and policymakers to create heat-resilient and thermally friendly cities.

1.1. Physio-psychological aspects of thermal comfort

Thermal comfort, referring to the "condition of mind that expresses satisfaction with the thermal environment" [5], is a subjective evaluation affected by multiple direct and indirect factors [6]. The physical thermal environment and its link with the built environment have been most extensively evaluated, with a variety of thermal comfort indices applied [7], and their associations with the built environment characteristics, e.g., sky view factors (SVF), street canyon's height to width ratio, etc., assessed [8]. However, the thermal environment alone cannot independently interpret individual's subjective evaluation of thermal comfort [9], as physio-psychological interactions pose evident effects as well.

Physiologically, parameters of skin surface, e.g., skin temperature (Tsk), are closely associated with subject's thermal perceptions [10], as the skin surface is the interface of heat exchange between the body and environment. Mechanistically, the thermoreceptors beneath skin surface transform thermal stimuli to signals, which are origins of thermal experiences [11]. Evidence from laboratory studies reveals that Tsk and its change rates well reflect individuals' thermal perception change [12,13].

Psychologically, multi-sensory environmental stimuli and perceptions in outdoor environment, e.g., visual, acoustic, aesthetic, etc., interact with the thermal realm in determining human perceptions. Such cross-modal experiences are jointly regarded as crucial components to the overall environmental quality of the built environment [14]. Significant associations exist among thermal and multi-sensory perceptions [15]. Thermal perceptions are mediated by perceived loudness, brightness, air quality, olfactory, and visual quality [16–21]. In different seasons and urban settings, the significance of thermal realm to overall environmental perception varies [18,22,23].

However, among the few studies that investigated the multivariate associations incorporating microclimate conditions, thermal and multi-sensory perceptions [23–25], rarely have physiological signs been incorporated, nor has the extreme-heat conditions been considered. The inclusion of physiological pathway may enhance the understanding of thermal exposure's effects on outdoor experiences. Meanwhile, the cross-sectional surveys adopted by the existing studies also cannot well capture the dynamics of *in-situ* outdoor experiences featuring ever-changing environmental stimuli.

1.2. Transient thermal experience under unsteady state

Through decades of development, the research framework of thermal comfort has undergone a transition from steady to unsteady state, with the latter more suitable for outdoor settings [26], as on one hand the outdoor thermal environment is by nature dynamic and heterogeneous [27], and on the other people are more likely to be under non-static conditions when they are conducting various outdoor activities [28]. Under such transition of research paradigm, the concept of thermal *alliesthesia*, referring to the pleasure or displeasure induced by thermal stimulus with the effect of individuals' internal state, is brought about [29], advocating the pursuit of thermal pleasure instead of a steady state of neutrality. Such phenomenon has been documented in outdoor environments during walking. It is found that thermal perception is influenced by the short-term thermal experience within the past several minutes [30,31]. Greater thermal pleasure can be induced by pre-exposure to slight discomforts [27,31]. Radiation and wind contributes to the understanding of dynamic thermal perceptions [31,32], and the accumulative heat exposure of the walking segment [33,34].

However, though the dynamic thermal perceptions have been linked with the ever-changing thermal environment, their link with the continuous exposure to the built environment remains missing, which is closely relevant to design tasks. And though the dominant effects of wind and solar radiation on outdoor thermal *alliesthesia* have been documented [31,32], if their effects are identical to the two opposing directions, i.e., thermal pleasure and displeasure, still requires investigation. In addition, the association between dynamic thermal perceptions and multi-sensory environmental perceptions during continuous outdoor experiences has rarely been assessed through *in-situ* field surveys [21].

1.3. Objectives

In view of these, aiming to inform practitioners of the dynamic nature of outdoor thermal and environmental perceptions and their link with the built environment, the objectives of this current study are (1) to quantify the multivariate association and influencing pathway among built environment, microclimate condition, and thermal and environmental perceptions during outdoor walking in summer with heat extremes, and (2) to quantify the physio-psychological response of outdoor thermal experience to the diversity of microclimate and built environment.

To reach this goal, five public housing estates (PHEs), representing typical living environment, in Hong Kong are selected as study sites. Recruited participants are guided to experience a series of public spaces along a 20-min walking route, representing daily commutes aligning with the goals for sustainable urban transportation [35]. This subtropical high density city is experiencing growing stress of extreme heat [36], and this study aims to evaluate the current situation and provides references to cities with similar contexts.

2. Method

The workflow of this study is shown in Fig. 1. Field survey and simultaneous measurements were conducted in the selected PHEs with recruited participants, as detailed below.

2.1. Study sites

Located at the southeast coast of China, Hong Kong (22°15′N 114°10′E) features a sub-tropical climate with hot and humid summer. In 2023, the annual mean and the highest air temperature (Ta) was 24.5 °C and 36.1 °C respectively, and a total of 54 days were recorded with daily maximum temperature exceeding 33 °C [37].

After decades of development, PHEs in Hong Kong accommodate 46 % of its population [38], making them an integral living environment. The five selected PHEs, as shown in Fig. 2(a), are deemed typical for their generic building layout and typologies throughout the development history of PHEs in Hong Kong. Situated in Kowloon, one of the most densely built-up areas in Hong Kong, these PHEs face heightened heat risks [39]. Constructed between 1960s and 1990s, they are also prioritized in future urban renewals.

Within and around these PHEs, three types of public spaces are prevalent, i.e., semi-outdoor spaces, open squares, and vegetated spaces. They feature diverse microclimate conditions, with some remaining thermally comfortable even under extreme heat conditions [40]. With a focus on these typological spaces, the walking routes were designed to traverse such areas, where the thermal and environmental perceptions were surveyed. Typical examples of these spaces are illustrated in Fig. 2

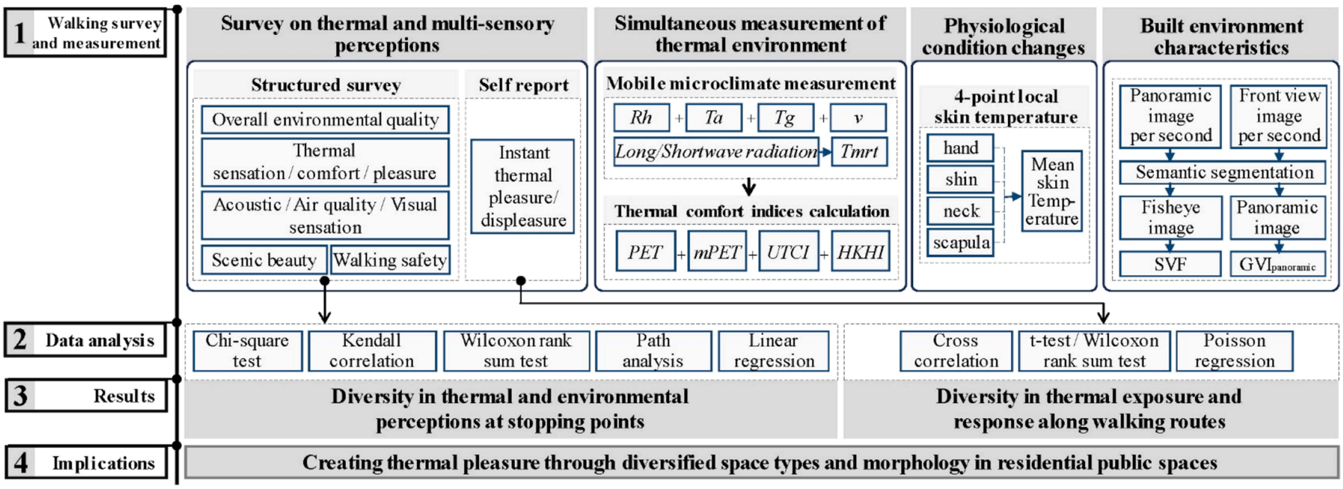

Fig. 1. Workflow of this study.

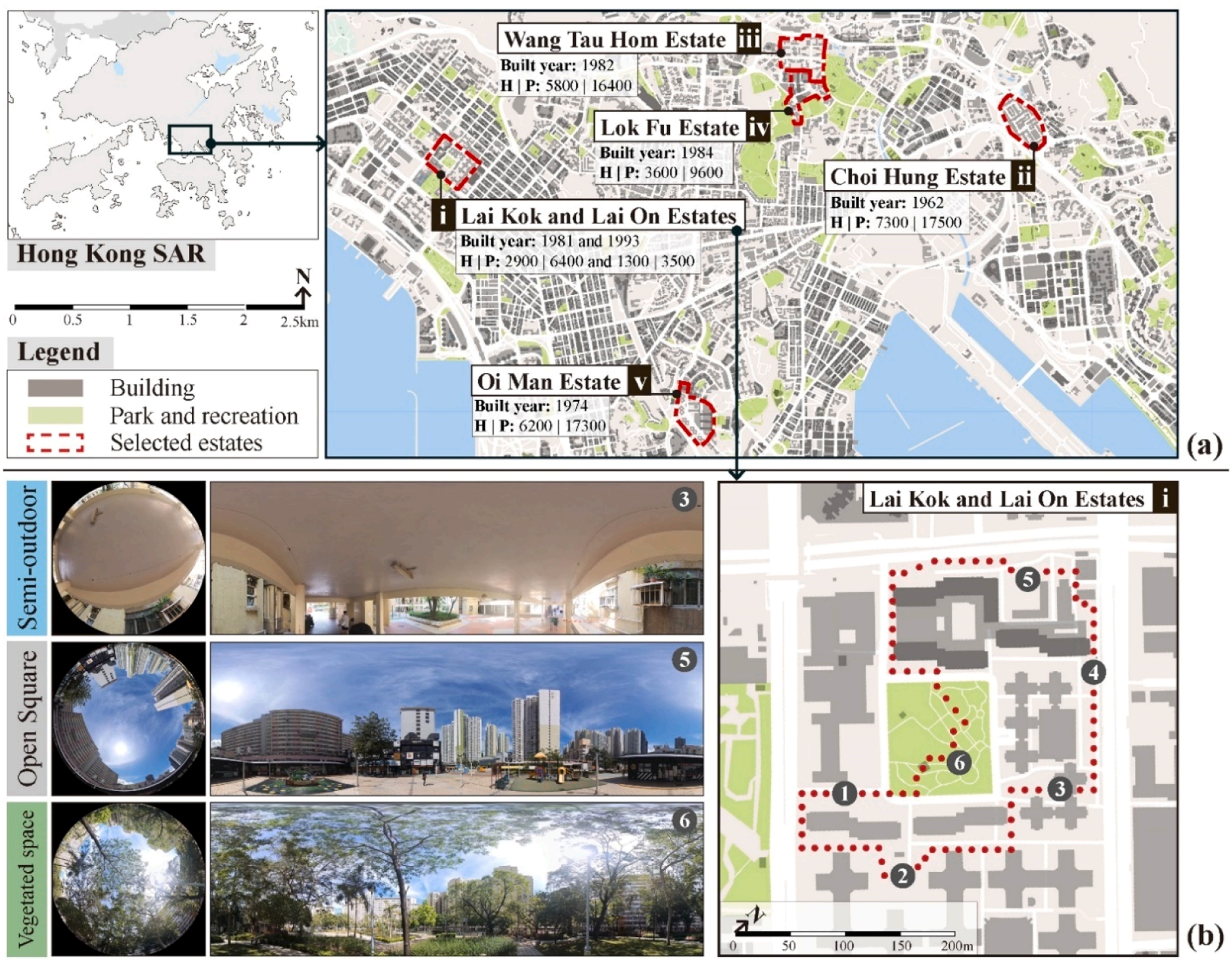

Fig. 2. (a) Locations of selected PHEs, and (b) one example of walking routes and three stopping points belonging to the three types of public spaces. Refer to Appendix C.2 for more examples. (**Note:** "H | P" refers to "households and population". Data source: Hong Kong Housing Authority, by the time of September 30, 2023.).

(b) and Appendix C.2.

2.2. Measurements and surveys

We recruited participants to conduct 20-min walking trips, one participant at a time, from July to September in 2023, which is typical summertime in Hong Kong. Such walking duration aligns with goals for sustainable urban transportation [35]. During walking, we collected the thermal and environmental perceptions of the participants through questionnaire and self-reported responses. Meanwhile, we measured the real-time microclimate variables, Tsk of the participants, and the built environment characteristics.

2.2.1. Mobile measurement of microclimate variables

Microclimate variables, i.e., Ta, relative humidity (Rh), globe temperature (Tg), wind velocity (v), and six-directional longwave and shortwave radiation, were measured along the walking routes with a portable backpack station equipped with calibrated instruments shown in Table 1 and Fig. B1. The accuracy of the sensors meet the requirements of ISO 7726 [41]. Since the measurements were conducted during walking, the measured Tg captures only lagged effects of radiation due to its response time, while the measured six-directional longwave and shortwave radiation depict radiation conditions instantly with a responding time of 1s. Detailed descriptions are provided in Appendix B.1.

2.2.2. Calculation of thermal comfort and heat stress indices

Based on the measured microclimate variables, mean radiant temperature (T_{mrt}), and four thermal comfort and heat stress indices were calculated. T_{mrt} is calculated by using six-directional radiation following Eq. (1) [42].

$$T_{mrt} = \sqrt[4]{\alpha_k \sum_{i=1}^{6} W_i K_i + \varepsilon_p \sum_{i=1}^{6} W_i L_i \Big/ (\varepsilon_p \sigma)} - 273.15 \tag{1}$$

where K_i and L_i are shortwave and longwave radiation fluxes (i=1–6), W_i is the angular factor for six directions (0.22 for lateral, and 0.06 for up-down directions), α_k and ε_p are the absorption coefficients of clothed human body for shortwave and longwave radiations (α_k=0.7, ε_p=0.97), and σ is the Stefan-Bolzmann constant (σ=5.67×10^{-8}W/m^2).

Four thermal comfort and heat stress indices, i.e., physiological equivalent temperature (PET), modified physiological equivalent temperature (mPET), universal thermal climate index (UTCI), and Hong Kong heat index (HKHI), were subsequently calculated due to their wide usage, advanced performance in humid climate, and local warning function. UTCI and PET are most widely used OTC indices worldwide [7], with several local benchmarks available for comparisons [43–45]. Modified based on PET, the multi-node mPET [46] demonstrates enhanced performance in a hot and humid subtropical climate [47]. PET and mPET were calculated by using Biometeo 0.2.9 [48], as detailed in Appendix B.2.1. UTCI was calculated by using the function provided on http://utci.org/. Hong Kong heat index (HKHI), a recalibrated local index reflecting heat stress based on hospitalization, is calculated following Eq. (2) [49].

$$HKHI = 0.8T_{nw} + 0.05T_g + 0.15T_a \tag{2}$$

where T_{nw} is natural wet bulb temperature, T_g is globe temperature, and T_a is air temperature. Detailed calculations are provided in Appendix B.2.2.

2.2.3. Measurement of skin temperature

Tsk and its changes play vital roles in dynamic thermal perception [10,11]. Considering applicability in the field, following ISO 9886 [50], four iButton temperature loggers (DS1922 L) were taped to four body parts, i.e., neck (T_{neck}), right scapula ($T_{scapula}$), left hand (T_{hand}), and right shin (T_{shin}), to measure local Tsk of the participants along the route at a sampling rate of 3s. This combination of local points is selected due to its practicality in outdoor public settings and acceptable accuracy in laboratory settings [51]. Featuring an accuracy of ±0.5 °C, iButton provides accurate and convenient measurements of Tsk [52], without hampering participants' physical activity and influencing their walking experiences. Mean skin temperature (Tsk_m) was calculated following Eq. (3) [50].

$$T_{sk\_m} = 0.28T_{neck} + 0.28T_{scapula} + 0.16T_{hand} + 0.28T_{shin} \tag{3}$$

The mean Tsk_m of the 30 s before the walking survey started, when the participant was surveyed about their basic information at a shaded place, was calculated as baseline. And the difference between the average Tsk_m at each stopping points and the baseline (dTskin) was further calculated to represent the participant's physiological states at each stop.

2.2.4. Survey on thermal and environmental perceptions

Participants aged 18–60 were recruited on-site and through pre-registration. They were required to have lived in Hong Kong for over one consecutive year so that they were acclimated to the climate of Hong Kong, and had not been conducting intense physical activities or exposed to air-conditioned environment within the past 15 min. To ensure a walking experience similar to their daily experience, participants wore their daily costumes without any specific requirements, but were restricted from using parasols or sunglasses.

After obtaining the written consent, the participant was briefed about the walking task, and fitted with the Tsk sensors at a shaded outdoor space, followed by a pre-walk survey to collect the participant's basic information, including biological sex, age, clothing condition, and activity within the past 15 min. The preparations generally took 10–15 min.

The participant was then guided along a preselected route in and around the PHE to conduct the 20-min walking at the participant's preferred walking speed. At each of the six stops of different types of public spaces along the route, as shown in the example in Fig. 2(b), the participant was stopped and verbally asked to respond to nine questions concerning the thermal and environmental perceptions, in the sequence of overall environment quality vote (OEQ), thermal sensation vote (TSV), thermal comfort vote (TCV), thermal pleasure vote (TPV), scenic beauty vote (SBV), loudness sensation vote (LSV), visual sensation vote (VSV), air quality sensation vote (AQSV), perceived walking safety vote

Table 1
Instruments used for microclimate measurement.

Instrument and measured variables		Accuracy	Sampling rate
Testo 480			1s
Temperature/ humidity probe[1]	Ta	0.2 °C/0.5 °C (15 –30 °C/Remaining range)	
	Rh	1.0 %/1.4 % + 0.7 % of mv[#] (0–90 %/90–100 %)	
40 mm black globe[2]	Tg	NA	
Comfort level probe	v	0.03 m/s + 4 % of mv[#]	
Apogee net radiometer (SN-500)[3]	Longwave radiation	0.12 mV per W/m^2	15s
	Shortwave radiation	0.045/0.035 mV per W/m^2 (upward/downward)	
Kestrel 5400 Heat Stress Tracker	Tg	1.4 °C	2s

[#] Measured value.
[1] Shaded with a passive radiation shield.
[2] Made from 40 mm table-tennis ball coated with black matt paint. Data measured with a thermoelectric couple type K, featuring a responding time of 5s.
[3] Data logged with CR1000X. The shortest sampling rate is 15 s under such configuration.

(WSV). Except for TSV, which was a seven-point scale following ASHRAE standard [5], the rest followed a five-point scale. Besides the multisensory dimensions defined in ISO 10,551 [53], visual attractiveness and landscape esthetics were assessed by SBV [54]. Apart from traditional TSV and TCV, we also adopted TPV as a quantification of the hedonic aspect of thermal environment under non-static conditions. Considering that a too-long time spent on surveying would have led to an extended exposure and discontinuous walking experience, we therefore merely asked the multi-dimensional questions covering sensation, comfort and pleasure on thermal but not on all multi-sensory aspects.

Besides the structured questionnaire described above, during walking process, the participant was also asked to self-report instant thermal pleasure or displeasure, i.e., thermal *alliesthesia*, whenever the participant felt so. Such feeling was introduced to the participant in the pre-walk preparation by using examples of daily experiences such as the moment of stepping in an air-conditioned room after walking on a very hot day, and vice versa. After finishing the walking process, a post-walk interview was conducted concerning the participant's walking experience. A 60HKD incentive was provided for finishing each trip. The full questionnaire is presented in Appendix C.1.

2.2.5. Simultaneous measurement of built environment feature

Simultaneous exposure to the built environment was recorded with an Insta360 X3 panorama camera. We extracted the panoramic images every second, and conducted semantic segmentation by using a Mask2Former model trained on Cityscapes with Swin-S as backbone [55]. We further transformed the panoramic images to upper hemisphere sky view images [56], and calculated SVF of every second following the algorithm of Rayman [57,58]. We also calculated green view index (GVI) based on the panoramic images at each stopping point. Detailed descriptions are provided in Appendix D.

2.3. Data analyses

We classify the walking trips as under extreme heat when the maximum mean HKHI at the stopping points exceeds the local benchmark 30.5 °C, which serves as one of the criteria that very hot days warning is considered [49], and describes heat stress on local people instead of comfort. Given the short walking duration and variable weather conditions during summer daytime, we assessed the immediate heat stress at micro-scale by using measured microclimate data rather than city-scale heat stress reported by weather stations.

Votes at different types of public spaces were first examined by using the Chi-square test, before which the responses were aggregated to positive, neutral, and negative responses, as the frequency of some extreme votes were less than five. Kendall's tau-b correlation coefficients were calculated among thermal and environmental perceptions [59]. In addition to using the votes at each stopping points, the differences between two adjacent stopping points were calculated to measure the changes in perceptions along the walking route. Path analysis was conducted to understand the associations among built environment characteristics, microclimate conditions, physiological changes, and thermal and environmental perceptions [60], as detailed in Appendix E1.1. It is a multivariate analysis that enables simultaneous estimation of multiple regression models, and the model fit can be assessed by metrics including Comparative Fit Index (CFI) and Tucker-Lewis Index (TLI). In addition, linear regression models between UTCI, PET and 1 °C binned mean TSV, TCV, or TPV were built to compare with existing local benchmarks.

The means and standard deviations (SD) of microclimate variables along the walking routes were calculated to measure the diversity of the thermal environment. Cross correlations were performed to examine the lag responses among SVF, microclimate variables, and Tsk_m changes, and the time to reach peak and significant coefficient was taken as the lag response duration, detailed in Appendix E.2. In addition, the frequency of self-reported thermal *alliesthesia*, which includes both thermal displeasure and thermal pleasure, was compared between extreme heat and non-extreme heat conditions. When examining the differences between the heat and non-heat condition, we applied *t*-tests for normally distributed data, and non-parametric tests, i.e., Mann-Whitney U tests and Wilcoxon signed-rank tests for non-normally distributed data accordingly [61]. Poisson regression was used to evaluate if the variations of microclimate variables is associated with the frequency of self-reported thermal *alliesthesia*. All data analyses were conducted in R.

3. Results

We conduct 57 walking trips with 35 eligible participants, including 17 males and 18 females with an average age of 31.6 ± 11.0, on 25 days between July 7 to September 23, 2023. Among these participants, 15 conducted 2–3 trips in different PHEs. Considering that their responses were given at different spaces along different routes with diversified thermal and environmental stimuli, their subjective and physiological responses were kept for analysis. Among the 57 eligible trips, 28 were conducted by males and 29 were conducted by females, and 31 were conducted under extreme heat. Due to technical errors, Tsk sensors were loose during eight walking trips, and panoramic videos were missing in seven trips, which were excluded from relevant analyses presented below. The microclimate conditions during each walking trip, as well as the weather conditions of that day, are provided in Table A1. The average duration of all walking trips was 20.29±1.96 min, and the average time spent on conducting the survey at each stop was 55.95 ±14.46s.

3.1. Diversity in thermal and environmental perceptions at stopping points

Fig. 3 demonstrates the thermal and environmental perception votes in different types of spaces under extreme and non-extreme heat conditions. Chi-square tests on all votes cast in different types of spaces reveal that except for WSV, thermal and environmental perceptions are dependent on space types. Values of standardized residual show that more positive votes on OEQ were cast in vegetated spaces (Fig. 3(a)), more hot-biased, discomfort and unpleasant votes were cast on open squares (Fig. 3 (b-d)), and more negative votes on SBV were cast in semi-outdoor spaces (Fig. 3(e)). Concerning VSV, more bright-biased votes were cast on open squares, and more dark-biased votes were cast in semi-outdoor spaces (Fig. 3(h)). Results of Wilcoxon test between extreme-heat and non-extreme-heat conditions show that significant differences in the three aspects of thermal perceptions only exist on open squares (Fig. 3(b-d)). For VSV, significant differences exist for votes cast on open squares and vegetated spaces (Fig. 3(h)), and no significant differences exist in other environmental perception dimensions.

Correlations among thermal and environmental perceptions under extreme-heat and non-extreme-heat conditions are shown in Fig. 4. Significant correlations with OEQ exist in SBV, LSV, AQSV, and WSV, among which the correlations with SBV are the strongest (Fig. 4(a, b), ρ=0.68, 0.55). Among the three aspects of thermal perceptions exist significant correlations, yet their correlations with OEQ are not always significant. For all thermal perception votes cast on non-extreme heat conditions, significant correlations exist (Fig. 4(a), ρ=−0.19, 0.29, 0.33), while for votes cast on extreme-heat conditions, significance only exists between TPV and OEQ (Fig. 4(a), ρ=0.18). Analysis based on the vote differences between two adjacent points reveals that significant correlations with dOEQ exist only under non-extreme heat conditions (Fig. 4(b), ρ=−0.17, 0.27, 0.32). Additionally, dVSV is also significantly correlated with the three aspects of thermal perceptions, with stronger correlations under extreme heat than non-extreme heat condition (Fig. 4 (a, b)).

Pathway models among built environment characteristics, microclimate conditions, environmental perceptions, and the physiological

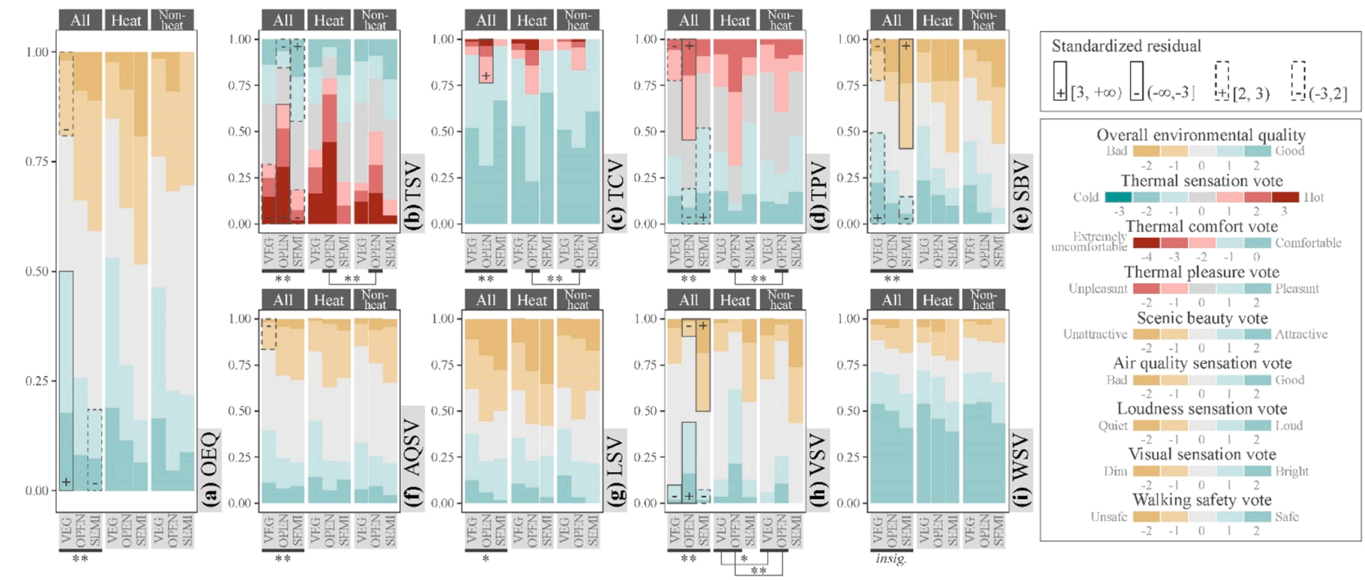

Fig. 3. Percentage of thermal and environmental perception votes in different types of public spaces under extreme-heat, non-extreme-heat, and both conditions (n_{All}=342, n_{Heat}=186, $n_{Non\text{-}heat}$=156). (**Note:** * and ** refer to significance at 0.05 (two-tailed) and 0.01 (two-tailed) respectively. Same below. Pearson standardized residual quantifies the contribution of each category to the overall chi-square statistic, and the contribution can be seen as evident when greater than 2, the more evident, the greater.).

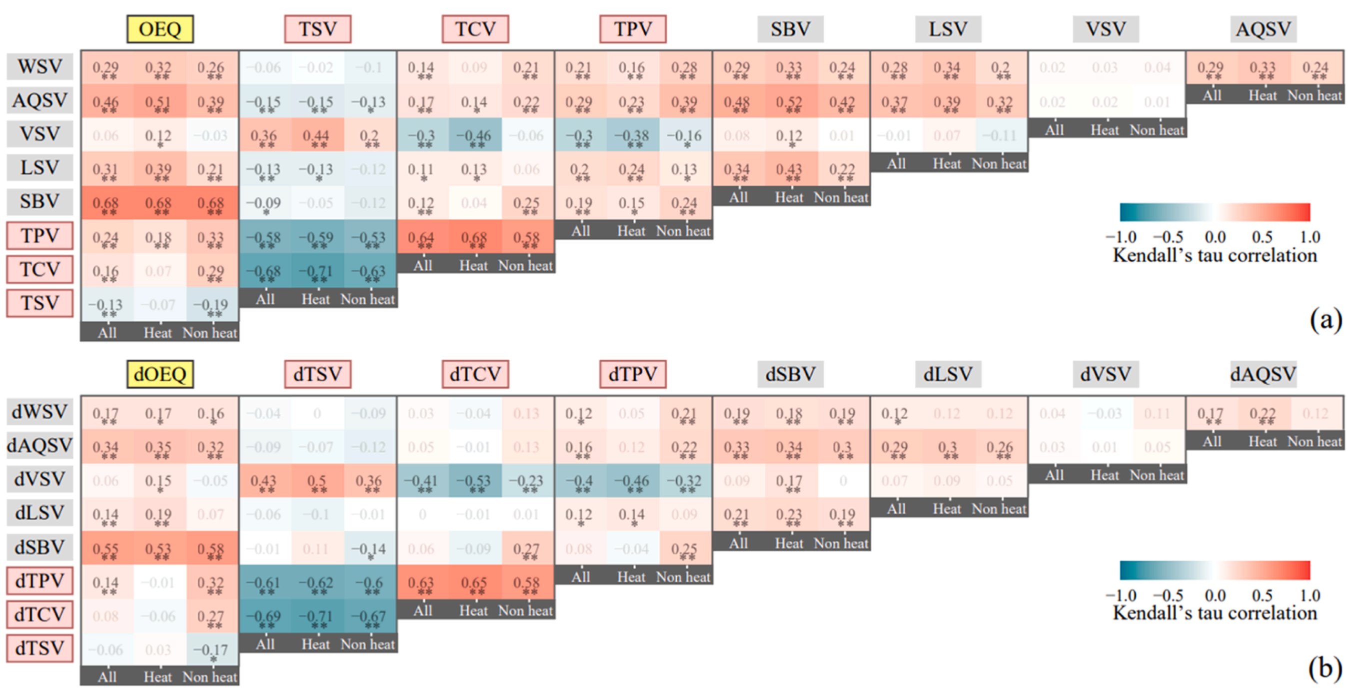

Fig. 4. Kendall's tau correlation coefficients among thermal and environmental perceptions under extreme-heat and non-extreme-heat conditions with **(a)** data at all stopping points (n_{All}=342, n_{Heat}=186, $n_{Non\text{-}heat}$=156), and **(b)** differences between two adjacent stops (n_{All}=285, n_{Heat}=155, $n_{Non\text{-}heat}$=130).

parameter are demonstrated in Fig. 5, and model modification processes are shown in Fig. E2–5. Compared with Tmrt and UTCI, models with mPET demonstrated the best performance (Fig. E2). Among all environmental perceptions, only TPV and SBV were kept after model modification. Both modified models relatively well explain the data collected, with CFI and TLI greater than 0.90.

In the two models shown in Fig. 5, two significant pathways exist between built environment characteristics and OEQ, and the association between SBV and OEQ (0.741, 0.724) is greater than that of TPV (0.116, 0.112). The first pathway links through SBV, which is significantly positively associated with GVI and SVF, with stronger associations with GVI (0.508>0.167, 0.530>0.15). The other pathway links through thermal environment and thermal perceptions. mPET is positively associated with SVF (0.549, 0.557), and higher mPET is linked with higher TSV (0.607, 0.649) and lower TCV (−0.192, −0.268). Higher v, on the other hand, is associated with lower TSV (−0.241, −0.226). The physiological parameter, dTskin, though significantly positively associated with mPET (0.328), is found insignificantly associated with v and all three aspects of thermal perception votes (Fig. 5(b)).

To further quantify the associations between thermal comfort

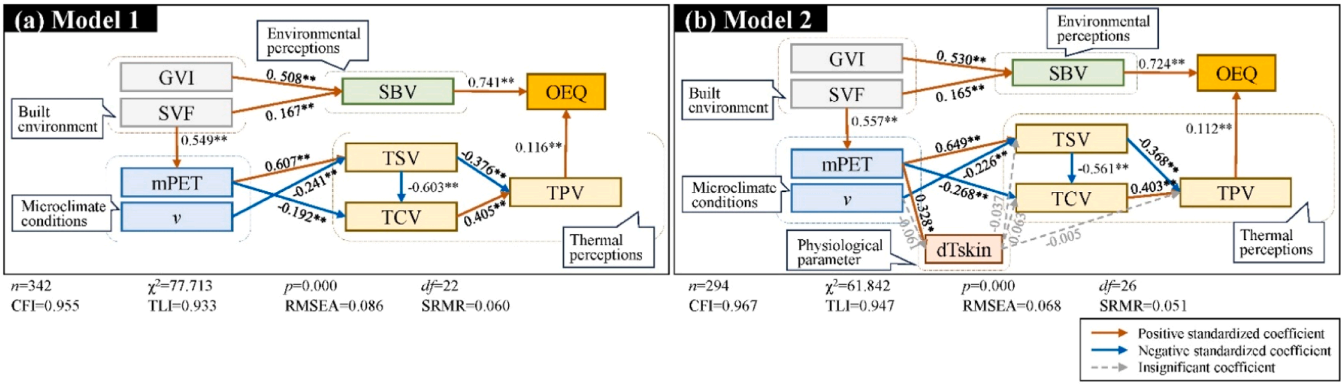

Fig. 5. Pathway models **(a)** among built environment characteristics, microclimate conditions, and thermal and multisensory perceptions, **(b)** with physiological parameter included. (**Note:** *df* degree of freedom, *CFI* Comparative Fit Index, *TLI* Tucker-Lewis Index, *RMSEA* Root Mean Square Error of Approximation, *SRMR* Standardized Root Mean Square Residual.).

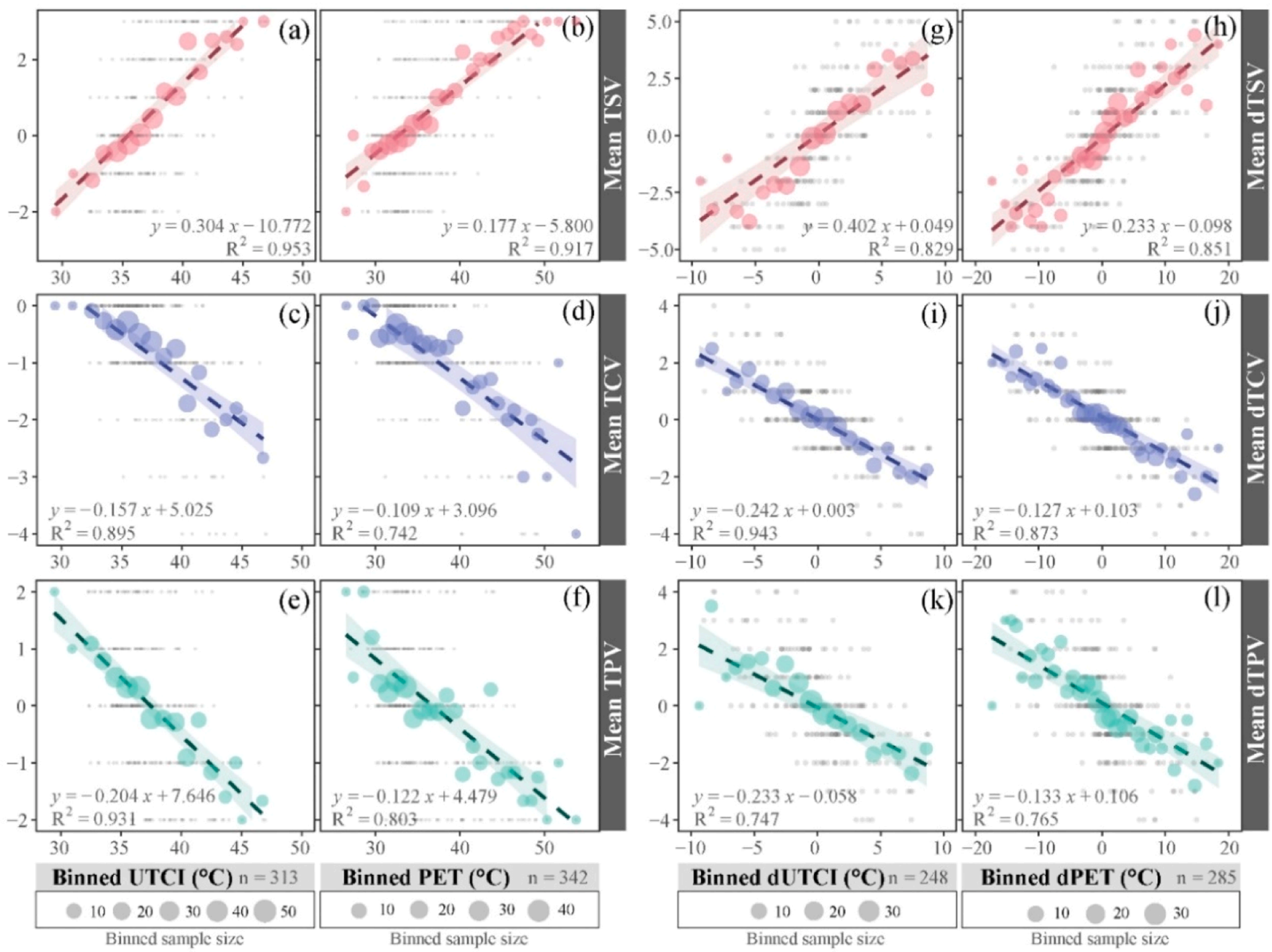

Fig. 6. Linear regression models between binned UTCI, PET and **(a-f)** mean thermal perception votes, **(g-l)** mean difference of thermal perception votes between two adjacent stopping points. (**Note:** Legend shows the binned sample size. Shaded areas refer to 95 % confidence interval.).

condition and perceptions, we conducted linear regression between binned UTCI, PET and the three aspects of thermal perceptions, as shown in Fig. 6. Based on the 7-point TSV, the neutral UTCI and PET are 35.43 °C and 32.77 °C, respectively (Fig. 6(a, b)). With the changes of thermal comfort condition and perceptions in two adjacent spaces considered, one-level change in TSV requires 2.49 °C UTCI or 4.29 °C PET changes (Fig. 6 (g, h)), and one-level enhancement in thermal pleasure requires 4.29 °C UTCI or 7.52 °C PET reduction, respectively (Fig. 6(k), (l)).

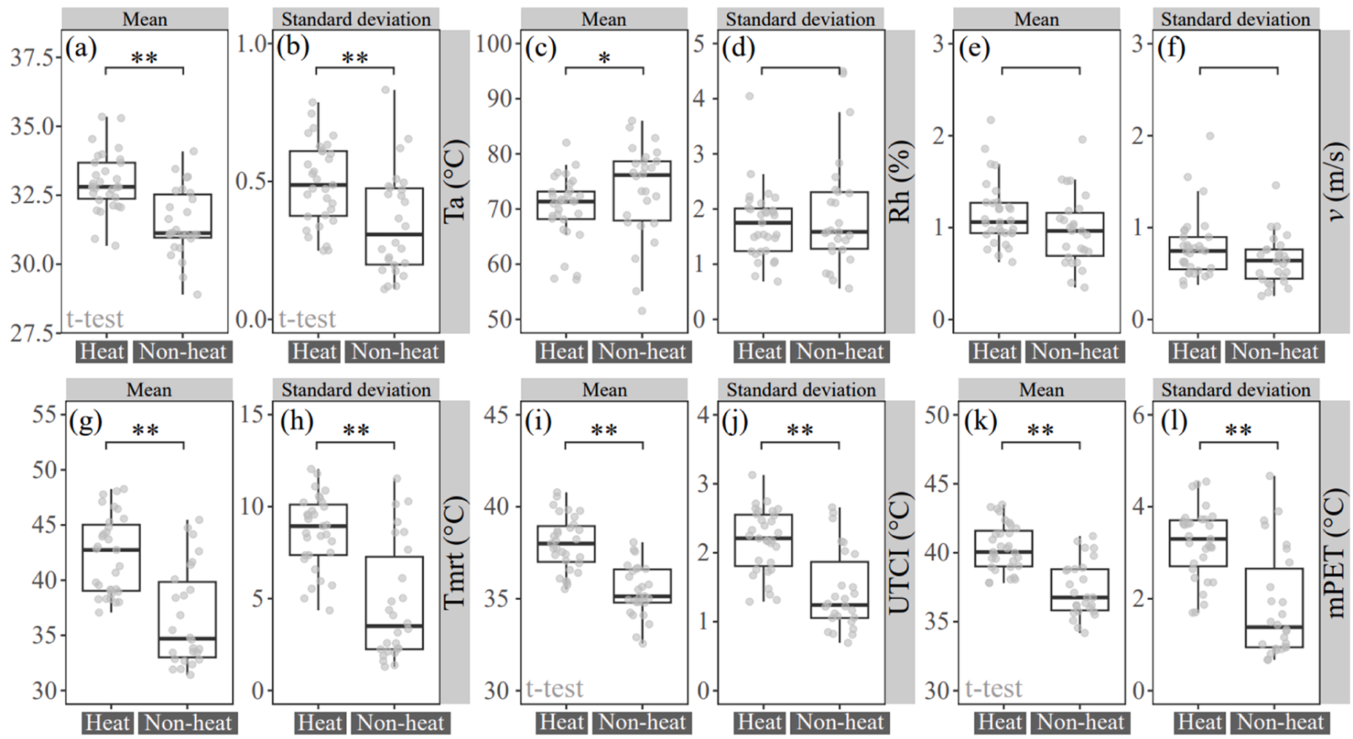

Fig. 7. Means and SDs of microclimate variables along walking routes under extreme heat and non-extreme heat conditions. (**Note:** For data following normal distribution, *t*-tests were conducted and marked, and the rest used Wilcoxon tests.).

3.2. Diversity in thermal exposure and responses along walking routes

To describe the diversity in thermal exposure along walking routes, we calculated and compared the means and SD of microclimate variables and thermal comfort indices under extreme heat and non-extreme heat conditions, as shown in Fig. 7. Results show that significant differences exist for Ta, Tmrt, UTCI, and mPET (Fig. 7(a, b, g-l)), indicating stronger thermal stress, but also significantly greater variations. The SDs of UTCI and mPET under extreme heat condition range 1.29–3.13 °C and 1.70–4.55 °C, respectively, which is found significantly higher than that under non-extreme heat condition (Fig. 7(i-l)).

Fig. 8 demonstrates the lagged responses among built environment

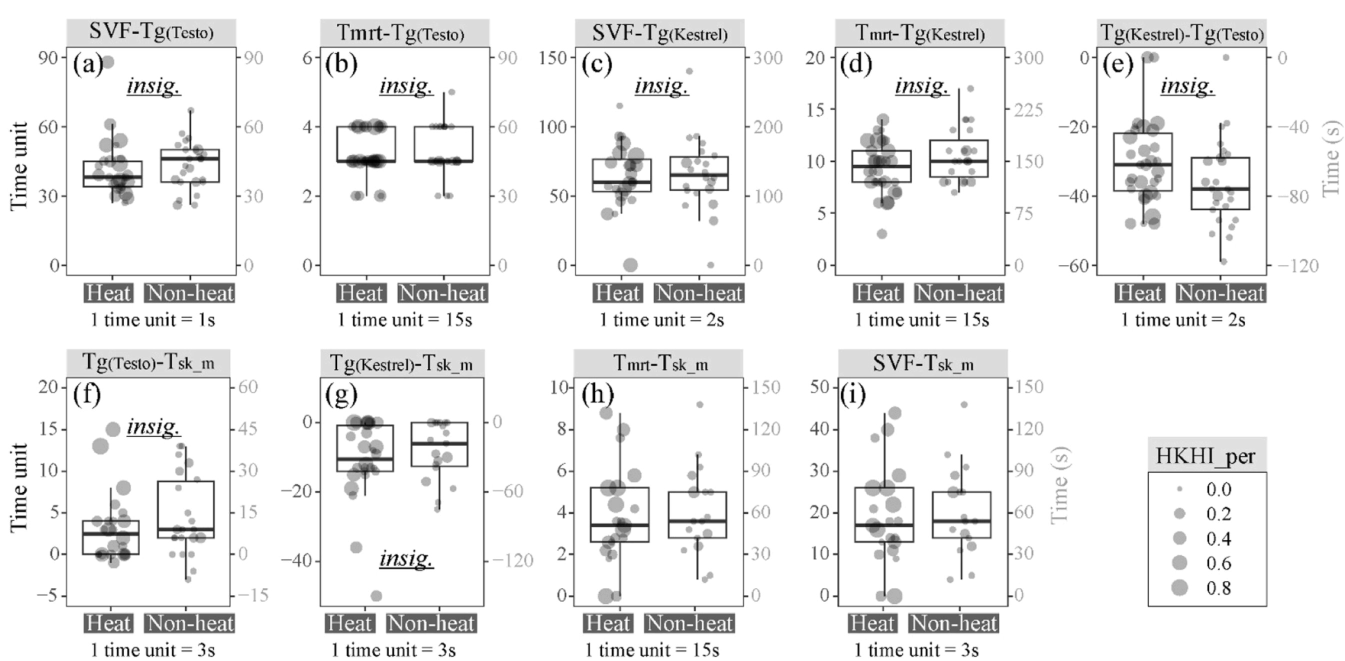

Fig. 8. Lagged response **(a-e)** among built environment characteristics and measured microclimate variables, **(f-i)** among built environment characteristics, measured variables and Tsk_m, along the walking routes under heat stress and non-heat stress conditions. (**Note:** *insig.* refers to insignificant difference between groups. *HKHI_per* refers to the percentage of calculated HKHI higher than 30.5 °C [49] along the walking segments. Different time units applied due to the different sampling rates of the instruments, and the *y*-axis in grey multiplies the duration of each time unit.).

characteristics, microclimate variables and Tsk_m. Wilcoxon tests among extreme heat and non-extreme heat conditions show insignificant differences. Tg measured with the black table-tennis ball is delayed by 42.60±11.52 time units (1s) compared to SVF (Fig. 8(a)), and 3.21 ±0.67 time units (15s, mean=48.15 s) compared to Tmrt measured with six-directional radiation (Fig. 8(b)). Comparatively, Tg measured with copper black globe is delayed by 64.98±24.97 time units (2s, mean=129.96 s) compared to SVF (Fig. 8(c)), and 9.89±2.57 time units (15s, mean=148.35 s) compared to Tmrt measured with six-directional radiation (Fig. 8(d)). The response of the black copper globe is delayed by 33.13±12.56 time units (2s, mean=66.26 s) compared to the black table tennis (Fig. 8(e)).

The lag time of Tsk_m to microclimate variable fluctuates greatly. It is delayed by 4.25±1.83 time units (15s, mean=63.75 s) compared to Tmrt measured with six-directional radiation (Fig. 8(h)), and 19.63 ±11.17 time units (3s, mean=58.89 s) compared to SVF (Fig. 8(i)). Tg measured with copper black globe is delayed by 9.78±10.35 time units (3s, mean=29.34 s) compared to Tsk_m (Fig. 8(g)), while Tg measured with black table tennis is 3.78±4.49 time units (3s, mean=11.34 s) ahead of time (Fig. 8(f)).

Fig. 9 demonstrates the frequency of self-reported thermal *alliesthesia* and its relationship with microclimate conditions. Mann-Whitney U tests reveal that significantly more thermal displeasure was reported under extreme heat condition than non-extreme heat condition (Fig. 9(a)), yet the differences in frequency of thermal pleasure (Fig. 9(b)) and overall thermal *alliesthesia* (Fig. 9(c)) are insignificant. Fig. 9(d-f) shows the summary of Poisson regression between the frequency of thermal *alliesthesia* and microclimate variables that were included in the pathway analyses presented in Fig. 5, and model details are given in Appendix E3. It is shown that the variations of thermal comfort indices are significantly associated with the frequency of thermal displeasure, with greater variations associated with more self-reported thermal displeasure, yet neither the intensity nor the variation of wind was found having a significant effect (Fig. 9(d)). For thermal pleasure, more exposure to thermal stress above the local threshold and stronger wind are associated with more pleasant responses (Fig. 9(e)). Considering both pleasure and displeasure, more exposure to high-level thermal stress and stronger variation of thermal comfort indices, as well as stronger winds, are associated with more experiences of thermal *alliesthesia*.

4. Discussion

4.1. Linkage between dynamic thermal perceptions and overall environmental quality

In this study, we conducted 20-min walking surveys on thermal and environmental perceptions in typical residential public spaces in Hong Kong. Unlike experiments with controlled stimuli in outdoor or climate chamber [18,62], this observation study with *in-situ* exposure utilized dynamic multi-dimensional environmental stimuli in the real world. Though limited in quantity, the number of participants exceeds previous longitudinal thermal comfort studies [30,31].

When surveying thermal perceptions, we applied not only sensation vote but comfort and pleasure votes, which describe the affective and hedonic aspects of thermal stimuli [26]. The pathway between thermal environment and thermal perceptions during outdoor walking is detailed. Noticeably, though the calculation of thermal comfort indices already incorporates the effects of wind, wind velocity remains a significant independent factor relieving hot sensations (Fig. 5), demonstrating its crucial effect in hot summer.

However, we also spotted that thermally comfortable spaces, i.e., semi-outdoor spaces, are not evaluated as spaces of high environmental quality even under extreme heat condition (Fig. 3(a, c)). Correlation among different perceptual dimensions (Fig. 4) and pathway models (Fig. 5) reveal a stronger association between overall environmental quality and scenic beauty rather than thermal pleasure. When without extreme heat stress, the association turns significant as the thermal perception votes are less hot-biased. A similar phenomenon was observed in the cross-sectional survey by Ma et al. during the non-heat season, in which the satisfaction of built environment was found to have the most profound effect [23]. The dominant role of visual stimuli in multi-sensory dimensions recognized in indoor environment [63] can be extended to outdoor environment. Nevertheless, the significance of the thermal realm's contribution varies by contexts. The experiment in climate chamber using virtual reality by Lyu et al. [64] reveals thermal pleasure as the most pronounced factor, though only one scenario was evaluated. The survey conducted by Lai et al. [22] during summer summarizes that thermal comfort is the priority when people selecting places for outdoor activity. Therefore, even if with a weaker contribution, eliminating the negative impact of extreme heat remains crucial in outdoor spaces to enhance the outdoor environmental quality.

4.2. Summertime thermal alliesthesia in outdoor built environment

With a special focus on dynamic thermal perception, we observed

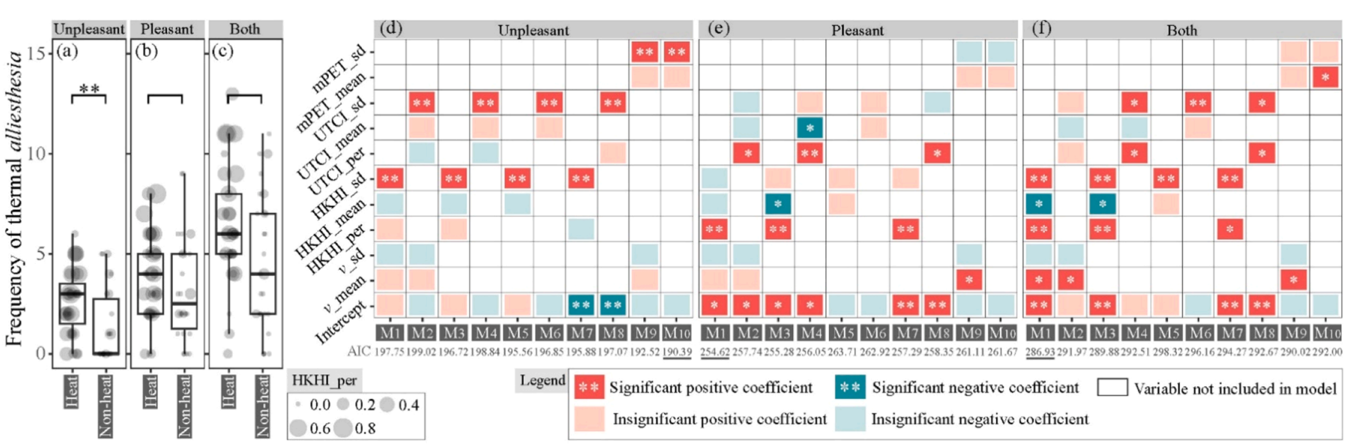

Fig. 9. (a-c) Frequency of self-reported thermal *alliesthesia* under extreme heat and non-extreme heat conditions, and **(d-f)** Poisson regression models between the frequency of self-reported thermal *alliesthesia* and microclimate variables. (Note: *_mean* and *_sd* refer to the mean and SD of microclimate variables along the walking segments. The model with the least AIC is underscored.).

evidence of thermal *alliesthesia* during summertime outdoor walking, as represented by the dramatically higher neutral UTCI and PET, i.e., 35.43 °C and 32.77 °C (Fig. 6), than existing local benchmarks, e.g., 26.16 °C UTCI and 25.16 °C PET [65], 26.01 °C UTCI and 26.48 °C PET [44], and 22.7 °C UTCI and 21.3 °C PET [43]. Such phenomenon originates from the below-neutral votes mostly cast in vegetated and semi-outdoor spaces (Fig. 3(b)) even under extreme-heat conditions, as shown by the value of thermal comfort indices (Fig. 6). Such preferable sensation changes are the source of outdoor thermal pleasure [27], which can be achieved by sequentially experience thermally uncomfortable and comfortable spaces. And based on this, the diversity of thermal experience along walking routes has the potential to serve as a key metric to aid the design process. Quantified by linear regression as 4.29 °C UTCI and 7.52 °C PET difference in adjacent stops to reach one-level enhancement in thermal pleasure (Fig. 6), such pleasantness can be easily sensed in PHEs under extreme heat conditions as the microclimate conditions in different space types varies greatly [40].

However, such quantification cannot be generalized too much, as thermal *alliesthesia* is induced not only by the change in thermal stimuli, but also the physiological condition of the individual [29]. It was found that part of the heat produced by the individual during outdoor walking would be accumulated within the body [45], which poses an impact on an individual's dynamic thermal perceptions. Though Tsk changes are good indicators to evaluate dynamic thermal perception [66], and have been applied to detect *alliesthesia* during outdoor walking [34], the association with thermal perceptions was found insignificant (Fig. 6(b)). One possible explanation is that the measured Tsk baseline prior to the outdoor walking in this study was not under a thermally neutral state, especially considering that under extreme heat condition in subtropical Hong Kong, neutral state is hardly achievable in outdoor environment. Detailed quantification of the heat production and loss during outdoor walking may still be needed to accurately interpret the occurrence of thermal pleasure.

Besides the changes in thermal pleasantness at the stopping points, we took the self-reported responses to capture the instant thermal *alliesthesia* along the walking route, which are mostly induced by instant changes of radiation and wind [31,32]. In this study, we found that besides the average thermal condition [33], the variations quantified by standard deviation also pose significant effects (Fig. 9(d-f)). Moreover, by looking into thermal pleasure and displeasure separately, the effect of wind was found significant to thermal pleasure but not displeasure (Fig. 9(e)). Previous analysis reveals that skin wittedness during outdoor walking affects an individual's preference to heat exposure variance, and greater variance is preferred when skin wittedness is high [45], which describes the same phenomenon that greater variances in wind velocity is more likely to lead to thermal pleasure instead of displeasure.

Accurate measurement of radiation for the calculation of Tmrt and thermal comfort indices is a premise for the above analysis, which was realized by using six-directional longwave and shortwave radiation in this study. Meanwhile, though the black table-tennis ball was deemed inappropriate for outdoor usage [67], its faster responses may better capture the changes along the walking routes and match with the changes of T_{sk_m} (Fig. 8(b, d, e)). Comparatively, the copper black globe, though small in size, cannot rapidly respond to the changes in radiation condition, and therefore should be deemed inappropriate for mobile measurement in outdoor environment.

4.3. Implications for urban and landscape design

Pursuing high urban environmental quality requires comfort as its basis, and OTC is one of the crucial aspects [1]. Existing strategies to improve OTC through built environment elements, e.g., allocating shading, greenery, etc., are effective, yet cannot be applied without limit. Comparatively, adopting the dynamic perspective of thermal *alliesthesia*, OTC can be reached through the provision of diversified thermal environments, which is reaffirmed in our observations. And such diversified thermal environment requires diversity in space types and morphology [68], which can be achieved through design. In the meanwhile, the preferable sequences and duration of exposure to the built environment should also be considered in design interventions.

We conclude that it is a feasible approach for practitioners to create diverse spaces and thermal experiences in a future where heatwaves become the new normal. It allows individuals to sense pleasure in between comfort and discomfort even under extreme heat conditions. However, it must be noted that, despite the continuous creation of pleasure, the potential harmful effects of heat strain on human health under heat exposure are not assessed in the framework presented in this study. In the traditional viewpoint, the sequence of impacts of heat exposure on human subjects is comfort, performance, and health [69]. Yet *alliesthesia* is making use of the undesirable thermal condition including potential stress. Therefore, assessing the proper duration of exposure in urban design proposals would still require relevant evidence and models from the laboratory, especially under extremities and focusing on core temperature, which is the direct indicator of heat stress and health [11]. Assessment of such duration of exposure also requires considering the future climate change scenarios, under which the acceptable duration of exposure for the status quo may become unbearable.

Meanwhile, the benefits of creating diversity in space types and urban morphology extend beyond the thermal realm to other multi-sensory perceptions. The pathway built in this study reveals the compounding effects of built environment on thermal pleasure and aesthetic evaluation. By applying the extended definition of *alliesthesia*, i.e., the hedonistic aspect of any mental processes [70], the dynamic outdoor experience shall co-benefit from the spaces diversity in various multi-sensory dimensions and jointly contribute to the urban environment quality, yet awaiting further systematic assessment.

4.4. Limitations

The below limitations deserve future investigation. First, though sufficient votes were collected for statistical analysis, the limited number of participants and the focus on residential public spaces restrict generalization and further analysis on the effect of participants' socio-demographic background on their dynamic thermal perceptions [34]. Future studies on dynamic thermal comfort may consider different background climates, urban contexts, and social demographic backgrounds, and gradually form comparable results in the way thermal benchmarks are gradually established in different locations [7]. Second, due to the instrument limitation, the sampling frequency of six-directional radiation is limited to 15 s, which is relatively long for outdoor walking with step-change environment. More local points of Tsk can be considered to enhance the accuracy of Tsk_m [51], especially considering the asymmetry radiation condition in outdoor environment [50], and measurement of other physiological responses, e.g., sweating rate, is missing, which restricted detailed analysis of thermal load and heat exchange [45]. Third, the measurement of multi-sensory stimuli along walking is limited to thermal realm. Though the sound level and air quality remained relatively stable in PHEs, the inclusion of the environmental parameters would enhance the comprehensiveness of the pathway models among multisensory perceptions. Additionally, as a physio-psychological response, technologies for more accurate measurement of perception changes can be applied to detect *alliesthesia*, e.g., EEG [71], instead of the traditional subjective voting.

5. Conclusion

In this study, we conducted guided walking tours in residential public spaces in subtropical Hong Kong in summer, with dynamic thermal and environmental perceptions surveyed and simultaneous measurement of built environment characteristics, microclimate conditions, and skin temperature changes. We conclude that,

(1) Significant associations among built environment characteristics, microclimate condition, mean skin temperature difference, and thermal and multi-sensory perceptions exist. Thermal pleasure and scenic beauty are significantly associated with overall environmental quality, with the latter contributing greater effects.
(2) During summertime outdoor walking, 4.29 °C reduction in UTCI in adjacent spaces led to one-level change in thermal pleasantness. Significantly greater variations in microclimate variables and more self-reported thermal displeasure exist under extreme heat condition. Higher variation in thermal comfort indices and mean wind speed along the walking route leads to more self-reported thermal *alliesthesia*. A mean lagged response of 58.89s between mean skin temperature and SVF was detected.
(3) Diversity in space types and morphology, and the sequence and duration of exposure to the built environment should be considered in future urban and landscape design to enhance the dynamic thermal experience.

The evidence of dynamic outdoor thermal and environmental perceptions and their link with the built environment presented in this study are expected to aid future urban and landscape design in creating cities adapting to future extreme heat and of higher environmental quality.

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Ethics approval

This study is approved by Human Research Ethics Committee of The University of Hong Kong (Ref. No: EA230264).

CRediT authorship contribution statement

Yilun Li: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ziming Li:** Writing – review & editing, Software. **Chao Ren:** Writing – review & editing, Supervision, Resources, Project administration, 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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2025.112594.

Data availability

Data will be made available on request.

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