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Assessment of urban physical features on summer thermal perceptions using the local climate zone classification

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ABSTRACT

Urbanisation has changed local meteorological conditions worldwide. The physical features of outdoor spaces are critical in determining outdoor thermal comfort through changes in meteorological parameters. Past studies comparing subjective thermal perception between local climate zones (LCZ) were mainly conducted in humid subtropical regions. This study aims to investigate this relationship using outdoor thermal comfort survey data collected in three research projects in Melbourne, Australia (temperate oceanic climate) ($n = 4717$). The physical features investigated included the sky view factor (SVF) and LCZ classification. During Melbourne's summer, people preferred a higher PET value than neutral PET across all LCZs. People in urban green spaces (LCZs B and C) were more likely to feel 'neutral' when Physiological Equivalent Temperature (PET) was 15.5 °C–24.5 °C and less likely to feel 'slightly warm to hot' when PET was 24.6 °C–55.6 °C. Furthermore, LCZ 6 (LCZ C) reported the highest (lowest) percentage of unacceptable votes. Cluster analysis identified two thermal comfort patterns (neutral and warm groups) representing various thermal sensations and preferences. The thermal comfort patterns proportion differed between built LCZs (5, 6) and land cover LCZs (B, C). Logistic regression revealed that PET values and urban morphology (i.e., LCZ) contributed significantly to people's thermal sensations and acceptability for neutral and warm groups. SVF significantly predicted the thermal sensation and acceptability for the warm group but not the neutral group. Our study approach informs further research to understand the implications of urban design in outdoor spaces using thermal comfort patterns as a benchmark.

1. Introduction

With dense urbanisation worldwide, the need to create thermally comfortable outdoor spaces has become more important than ever [1]. Human thermal comfort is known to be most impacted by four environmental variables (i.e., wind speed, air temperature, solar radiation, and relative humidity) as well as two personal factors (i.e., the level of activity and clothing) [2]. These factors are also used to predict thermal comfort requirements. Environmental factors can influence thermal stress, which is 'the integrated, net thermal load on the body imposed by the external environment' [3, p. 158]. Thermal stress can be evaluated by thermal indices such as the Physiological Equivalent Temperature (PET) [4] and Universal Thermal Climate Index (UTCI) [5]. The physical features of outdoor spaces can moderate these environmental factors, altering human thermal comfort conditions. The previous investigation showed that physical features could determine local meteorological conditions [6–8]. The LCZ classification entails multiple physical features [9], such as vegetation and SVF (Table 1). Table 1 summarises previous thermal comfort research in which these physical features of urban spaces were applied.

It is well documented that replacing vegetation with hard surfaces caused negative consequences, such as urban heat islands [30]. Broadbent et al. [31] reported that the green spaces' cooling effects are underpinned by four mechanisms: evapotranspiration, shading, photosynthesis and trapping longwave radiation. Therefore, green spaces can modify outdoor thermal conditions, particularly during hot spells [32].

The SVF is defined as the fraction of sky that is visible at a given location, ranging from 0 being a fully obstructed sky and 1 being a fully visible sky [6,33]. The SVF represents the level of shading in urban spaces, including trees, buildings and landscape [34]. These urban features modify the visible horizon and incoming radiation [35]. In particular, SVF moderates the ventilation pattern [36] and solar radiation intensity [37], and hence induces variation in shadow pattern (air

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Nomenclature

ATR	Acceptable temperature range
BLR	Binary logistic regression
LCZ	Local climate zone
MTPV	Mean thermal preference vote
MTSV	Mean thermal sensation votes
PET	Physiological Equivalent Temperature (°C)
RH	Relative humidity (%)
SVF	Sky view factor
T_a	Air temperature (°C)
T_g	Globe temperature (°C)
T_{mrt}	Mean radiant temperature (°C)
UTCI	Universal Thermal Climate Index (°C)
v	Wind speed (m/s)
φ_c	Cramer's V

and surface temperature) [38] and PET [13]. The relationship between SVF and outdoor thermal comfort has been identified in various climate zones (Table 1).

The LCZ classification system provides new opportunities to investigate urban form and function concerning the local climate, and classifies urban and natural environments based on various urban morphological characteristics (Fig. 1) [9,39]. It allows for a more detailed spatial understanding of the variability of intra-urban air temperature, instead of a simple description of urban-rural differences comprising critical climate parameters that can categorise zones at a local scale (10^2–10^4 m) [40]. As presented in Table 1, in recent years, this classification system has become an integral part of thermal comfort assessment in outdoor settings [18,41]. It is now the most frequently used descriptor of the physical characteristics of outdoor spaces in thermal comfort research. As a result, more thermal comfort researchers rely on this system to explain the thermal comfort requirements of their study of outdoor users.

Thermal comfort research builds on various thermal perception descriptors. These include thermal acceptability, thermal preferences, thermal sensation, thermal comfort and thermal tolerance [42]. Recently, thermal comfort personality [43], otherwise known as thermal comfort pattern [44], has been used by thermal comfort researchers. This study's thermal comfort pattern is characterised by different thermal sensations and preferences.

1.1. Aim and objectives

Many LCZ studies are related to outdoor thermal comfort worldwide (see Table 1). Das and Das [25] demonstrate that thermal comfort levels can change in various LCZs, so local-based studies are required to identify thermal comfort conditions in various urban configurations. Previous studies have investigated objective thermal comfort indicators (e.g., PET) in different LCZs. However, few studies have compared the subjective thermal comfort in different LCZs using surveys. The few studies that used surveys to investigate subjective thermal perception in LCZs are mostly conducted in tropical [16,26] and subtropical regions [18,22]. Variations of thermal comfort patterns in different LCZs also remain largely unexplored. Thermal comfort requirements would need to be considered carefully by urban planners in designing and building new outdoor spaces, highlighting the immediate need for research in this area. This study aims to compare thermal comfort conditions under three urban configurations: public gardens, university campuses, and public squares. In particular, this study is a compilation of three Australian studies in which various LCZ and SVF values were captured. Our study contributed to the literature by examining the subjective thermal comfort in different LCZs in temperate regions, including the

Table 1
Summary of studies that compared the impact of various physical features on human thermal comfort.

Context of study and year of publication	Climate zone	Main findings	Reference
Vegetation			
Outdoor spaces in Singapore, including urban parks, 2015	Singapore: Tropical rainforest climate (Af)	Field measurements in 10 urban parks of Singapore showed that air temperature could be reduced by 8–12 °C in these parks during the hottest time of year (March–May) and day (1:00 p.m.–3:00 p.m.)	Hwang et al. [10]
Outdoor spaces in Melbourne with various three levels of street tree plantation, 2016	Melbourne (Australia): Temperate oceanic climate (Cfb)	The study found that street trees could modify the level of thermal stress from very strong (UTCI>38 °C) to strong (UTCI>32 °C) by blocking solar radiation	Coutts et al. [11]
Field measurements in an urban park, 2018	Hong Kong: Humid subtropical (Cwa)	Daytime cooling effects of a large tree were 0.6 (air temperature) 3.9 °C (PET[a]) and 2.5 °C (UTCI[a]) which were higher than a concrete shelter at 0.2 °C, 3.8 °C and 2.0 °C respectively.	Cheung and Jim [12]
Sky view factor (SVF)			
Field measurements in a central business district, 2015	Beijing (China): Humid continental climate (Dwa)	Highly shaded areas (SVF <0.3) typically exhibited less frequent hot conditions during summer, while enduring longer periods of cold discomfort in winter than moderately shaded areas (0.3< SVF <0.5) and slightly shaded areas (SVF >0.5), and vice versa.	He et al. [13]
Field experiments on a university campus, 2016	Bucheon (South Korea): Hot continental climate (Dwa)	Thermal stress observed in the study varied with different levels of SVF.	Song and Jeong [14]
Field experiments in a downtown area, 2017	Curitiba (Brazil): Humid subtropical zone (Cfb)	Various SVFs created a different perceptual assessment of thermal conditions in the study area.	Kruger and Drach [15]
Local climate zone (LCZ)			
Field survey in five different zones of a city, 2014	Barranquilla (Colombia(: Tropical savanna climate (Aw)	This study identified the differences in the proportion of thermal, humidity, wind speed and solar radiation sensation across various LCZs.	Villadiego and Velay-Dabat [16]

(*continued on next page*)

Table 1 (*continued*)

Context of study and year of publication	Climate zone	Main findings	Reference
Field surveys in six sites in a city, 2015	Dhaka)Bangladesh (: Tropical Savanna climate (Aw)	This study derived the conditions of the outdoor thermal environment for planned and unplanned residential settlements and other built areas.	Sharmin et al. [17]
Field experiments and surveys in nine local areas in a city, 2018	Shenzhen (China): Humid subtropical climate (Cfa)	Changes in comfort levels among the local areas with different LCZs were identified. The research determined the preferable LCZ for optimized comfort levels for the study areas.	Liu et al. [18]
Simulation and field experiments in an urban area and its vicinity, 2018	Brno (Czech Republic): Temperate oceanic climate (Cfb)	Simulation results showed statistically significant differences in outdoor thermal comfort among different LCZs.	Geletič et al. [19]
Evaluation of LCZs for two desert cities, 2018	Phoenix and Las Vegas (US): (Tropical and subtropical desert climate (Bwh)	Observed LCZ attributes in arid desert environments do not necessarily correspond to the proposed value ranges from the literature, particularly in terms of SVF upper bounds.	Wang et al. [20]
Field experiments in seven built and two land cover LCZ types, 2018	Szeged)Hungary(: Warm Summer continental climate)Dfb)	This study provided insight into the outdoor thermal conditions in various urban and rural environments using the LCZ concept.	Unger et al. [21]
Field surveys in eight sites in a city, 2019	Hong Kong: Humid subtropical (Cwa)	Results demonstrated that the relationship between the level of thermal stress and subjective thermal sensation changed across LCZs.	Lau et al. [22]
Field experiments in a city, 2019	Nagpur)India(: Tropical Savanna Climate (As)	It identified some LCZ features with maximum exposure to discomfort.	Kotharkar et al. [23]
Simulations on a city scale, 2019	Toulouse)France(: Temperate humid subtropical climate (Cfa)	Among the built-up LCZs, the probability of strong heat stress was the highest for open high/midrise and lowest for sparsely built and open low-rise settings	Kwok et al. [24]
Field experiments in urban areas of different cities, 2020	West Bengal) India): Tropical monsoon	A variation in thermal comfort level over LCZs was identified.	Das and Das [25]
Field experiments in urban areas of different cities, 2020	West Bengal) India): Tropical monsoon	Subjective perception of OTC across LCZs varied due to diversified physical landscape settings.	Das et al. [26]
Local climate zone (LCZ)			
Simulations and field experiments in a mixed-use residential neighbourhood, 2021	Chennai)India): Tropical Savanna climate (Aw)	The differences in PET conditions between present conditions and future predicted built geometry were analyzed in three LCZ classes.	Salal Rajan and Amirtham [27]
Simulations for three canopy covers in different urban areas of a city, 2022	Adana (Turkey): Hot-summer Mediterranean climate (Csa)	Suitable green space characteristics were identified in different LCZ classes.	Unal Cilek and Uslu [28]
Field experiments in five sites in an urban neighbourhood park and its surrounding area, 2023	Suwon (South Korea): Hot continental climate (Dwa)	This study quantified the differences in PET and UTCI between land cover types (LCZ D and B_E) and built types (LCZ 2_B, 4 and 5) during summer.	Jo et al. [29]

[a] **Note:** UTCI: Universal Thermal Climate Index, PET: Physiological Equivalent Temperature.

differences in thermal comfort patterns which are generated by cluster analysis. The study builds on the thermal comfort data collected in three PhD research projects performed between 2012 and 2015 in Melbourne with a temperate oceanic climate [45–47]. The study addresses the following research questions.

1) What is the relationship between local climate zones and perceptions of outdoor thermal conditions?
2) To what extent do thermal stress and urban morphology predict individuals' perception of thermal conditions with various thermal comfort patterns?

2. Materials and methods

2.1. Regional climate of the study area

Melbourne is classified as a temperate oceanic climate (Cfb). It experiences a large diurnal temperature range with fluctuating weather conditions in summer [48]. The mean minimum and maximum air temperatures of January and February (1981–2010) are between 15.8 °C and 26.5 °C, and the mean monthly rainfall in January and February is 45.1 mm and 39.9 mm [49]. Between 1981 and 2010, the mean 9 a.m. and 3 p.m. relative humidity of January and February is 65% and 47%, respectively. During the same period, the mean wind speed at 9 a.m. and 3 p.m. are 2.2–2.5 m/s and 3.4–3.5 m/s, respectively. Between 2000 and 2010, the mean daily global radiation in January and February was 280.4 W/m^2 and 242.8 W/m^2, respectively [50]. During summer (December to February), Melbourne sometimes encounters heatwaves because of the occasional hot and dry air flow from inland Australia.

2.2. Site description

Each study site was classified into various LCZ classes according to

Fig. 1. The local climate zone classification schemes (adapted from Demuzere et al. [39]).

the values of geometric and surface cover properties of different LCZs listed in Stewart and Oke [9]. As shown in Table 2 and Fig. 2, the sites are from three studies covering a wide range of LCZ. Fig. 2a shows the LCZ map in Melbourne [51] generated by James Bennie, who used the WUDAPT Level 0 training data for Melbourne submitted to the LCZ generator [52]. The LCZ provides a classification method for various urban spaces to standardise observational urban temperature studies worldwide [2]. This classification method ensures the accuracy and consistency of reporting urban climate studies. The LCZ classification is based on the physical properties of spaces, such as SVF, aspect ratio, building surface fraction, impervious surface fraction, pervious surface fraction, height of roughness elements and terrain roughness class [9].

The SVF represents the level of obstruction to the sky. In the three studies, circumpolar fisheye photographs were taken from digital cameras with a fisheye lens. After that, SVF was calculated by importing fisheye photos into RayMan Pro 2.1 [53]. The first study used Nikon CoolPix 5000 and 5400 Cameras, each calibrated with a fisheye lens. In the second study, we took fisheye photos using Nikon D700 with a fisheye lens (Sigma 4.5 mm f/2.8 EX DC HSM Circular Fisheye Lens) [54]. In the third study, fisheye photos were taken using a Canon EOS 6D SLR camera with a Canon EF 8e15 mm f/4 L Fisheye USM lens [55]. The fisheye photos and sky view factors in different study sites in the three studies are presented in Fig. 3.

In terms of other spatial characteristics parameters, the aspect ratio was determined by the ratio of mean building height to street width (LCZs 1–7) and mean height-to-width ratio of tree spacing (LCZs A – G). The impervious surface fraction was calculated from satellite imageries from Google Earth. In particular, the impervious surface fraction was determined by drawing the corresponding areas on the satellite images, using a radius of 100 m of different survey points. Moreover, the height of roughness elements referred to the average height of buildings (LCZs 1–7) and trees/plants (LCZs A – G). The average building heights were determined from the GIS data of the study sites. The average tree heights were determined by the mean heights of the dominant tree species in different survey sites in the Melbourne and Cranbourne Gardens.

The first study involved two study sites located in the Melbourne

Table 2
Features of study sites and their LCZ classes.

Study sites	Description	Geographical coordinates	Study time	Local climate zone	Major site characteristics	Aspect ratio[a]	Impervious surface fraction (%)[b]	Height of roughness elements (m)[c]	
Study 1	Site 1-A: FS	Federation Square	37°49′4.1" S 144°58′7.3" E	January & February 2012–2014	Open midrise (LCZ 5)	It is situated at the intersection of two main linear paths in the Melbourne CBD. The main plaza is surrounded by key buildings with various cultural and entertaining functions and is mostly paved with cobblestones, with very limited green infrastructure	0.4	42	16
	Site 1-B: BC	Burwood Campus	37°50′52.4" S, 145°6′51.5″ E	January & February 2012–2014	Open low-rise (LCZ 6)	A central courtyard in the campus surrounded by the library, the learning spaces, the food outlet and the student service department. It is characterised by its generous green areas, mainly paved with concrete	0.3	20.7	9
Study 2	Site 2-A: RBGM	Melbourne Gardens	37°50′0.2" S 144°58′49.2" E	February 2014	Scattered trees (LCZ B)	Large urban park, lightly wooded landscape, trees scattered on mostly pervious ground, few roads and buildings	0.27	9	5.7
	Site 2-B: RBGC	Cranbourne Gardens	38°7′42.9" S 145°16′13.0" E	January 2014	Bush, scrub (LCZ C)	Opening spaced shrubs and bushes, woody trees on pervious surface (bare soil or sand), few roads and buildings	0.25	5.1	1.5
Study 3	Site 3-A: RUCC	University Lawn	37°48′30.5" S 144°57′54.2" E	February 2015	Compact midrise (LCZ 2)	A compact recreational space with urban characteristics, including café shading devices, water features, natural green space (a few trees), timber deck and benches, and an artificially turfed area with different microclimates.	1.8	52.1	18.2
	Site 3-B: RUCC	Ellis Court	37°48′32.0" S 144°57′53.2" E	February 2015	Compact high-rise (LCZ 1)	Compact design, surrounded by high-rise buildings and accommodates a range of urban settings, varying shade levels and multiple pervious and impervious surfaces	2	74.7	25.3
	Site 3-C: RUCC	Urban Square	37°48′30.6" S 144°57′42.9" E	February 2015	Compact high-rise (LCZ1)	A large recreation space with surrounding high-rise buildings hosting resting and entertainment areas and includes a modern landscape featured with large planter tubs, apple crate planter boxes and timber decks	2.8	70.5	43

[a] Mean height-to-width ratio of street canyons (LCZs 1,2,5 and 6) and tree spacing (LCZs B and C).
[b] Proportion of impervious plan area to total plan area (%).
[c] Average building heights (LCZs 1,2,5 and 6) and tree/plant heights (LCZs B and C) (m).

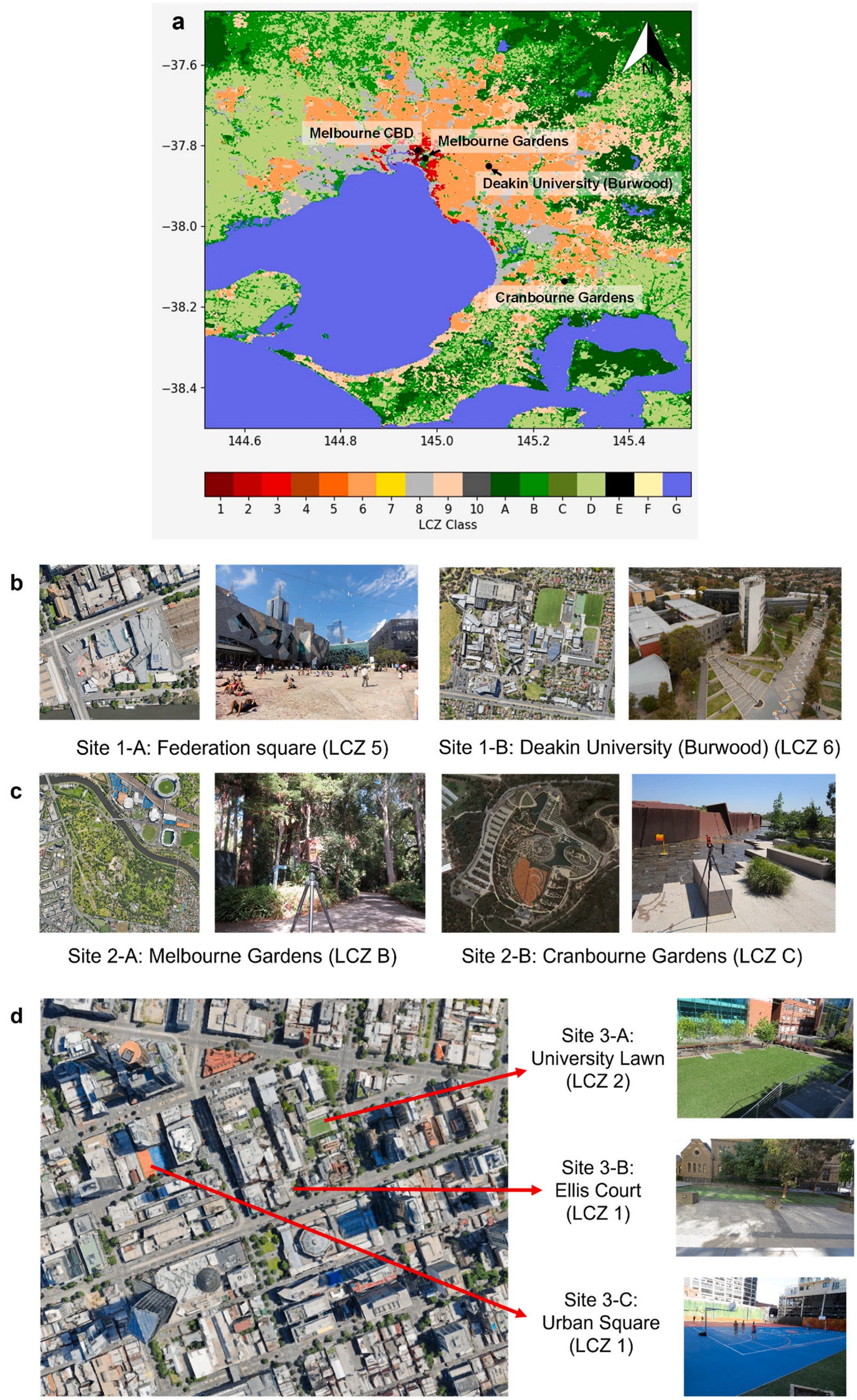

Fig. 2. a) Local climate zone (LCZ) map of Melbourne showing our study sites (source: Bennie [51]). The x-axis and y-axis show the latitude and longitude, respectively. Federation Square and the study sites in study 3 are located in the Melbourne CBD. b) study sites in study 1 (source: Google Earth [56,57]), c) study sites in study 2 (source: Google Earth [58,59]), d) study sites in study 3 (source: Google Earth [60]). The photographs of different study sites were taken by the authors.

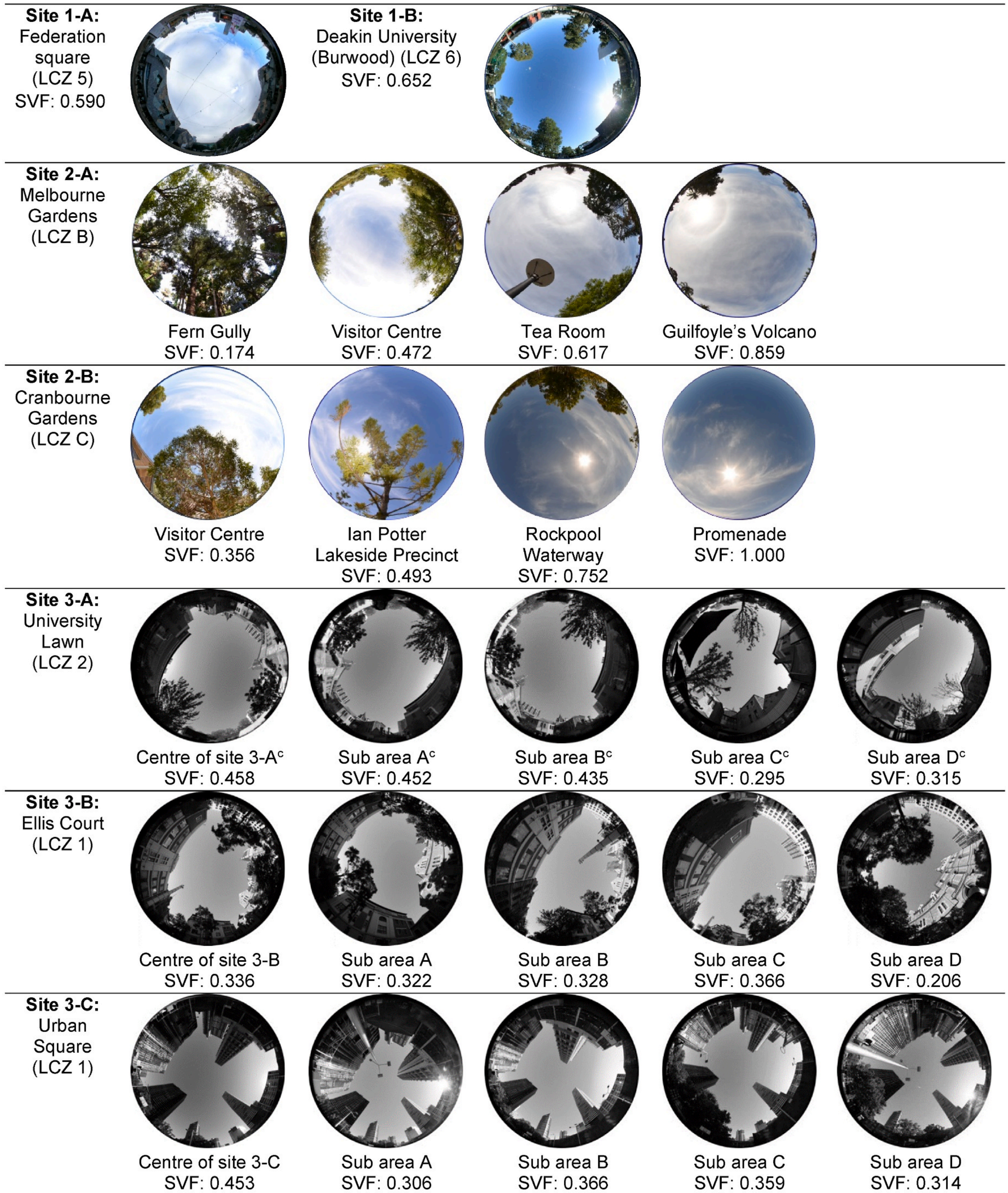

Fig. 3. The sky view factor (SVF) of different survey sites in Melbourne.

central business district (CBD): a university campus (Deakin University Burwood Campus - LCZ 6) and a public square (Federation Square - LCZ 5) (Fig. 2), with SVF ranging from 0.50 to 0.89. The total square area is 3.2 ha adjacent to low-rise buildings (1–3 stories) with an open arrangement. The surface of the Federation Square is cobblestone, partly shadowed with some trees scattered around. The Deakin University Burwood Campus is approximately 15 km away from the Melbourne CBD. The campus's main spine is covered with concrete, features extensive green spaces, and is surrounded by midrise buildings (2-3 stories) in an open arrangement.

The second study focused on two botanic gardens (Fig. 2), namely Melbourne Gardens (established in 1846) and Cranbourne Gardens (established in 2006). The Melbourne Gardens are in South Yarra (a suburb next to the Melbourne CBD) with an N–S orientation. In the Melbourne gardens (LCZ B), there are various varieties of indigenous and introduced vegetation across 38 ha of land. The main surfaces of these gardens are turfed areas, asphalt pavement, and an ornamental lake adjacent to low-rise buildings scattered around the area. The Cranbourne Gardens (LCZ C) is within a 45 km radius of Melbourne CBD with an N–S orientation. These gardens display native Australian vegetation species across 38 ha. The main covers of these gardens are sand, wood mulch, paving stones, scattered lawn areas, shrubs, large trees, and artificial lakes accompanied by low-rise buildings. In the Melbourne Gardens, the SVF levels range from 0.17 to 0.86, whereas these levels are between 0.36 and 1.00 in the Cranbourne Gardens. In brief, these two gardens differ in landscape design and vegetated spaces perspective.

The third study investigated thermal comfort in three open spaces (i.e., Ellis Court, Urban Square, and University Lawn) of a university campus (RMIT University City Campus) located in the heart of Melbourne CBD (Fig. 2). The Ellis Court and Urban Square (both LCZ 1) have a dense mix of tall buildings (>10 stories), whereas the University Lawn (LCZ 2) has closely spaced buildings of 3–9 stories. These sites featured recreational facilities, including seating areas, decks, sports courts, and access pavements. Oriented in NW-SE direction, these open spaces have SVF levels ranging from 0.20 to 0.45. Their main cover is primarily cobblestone, followed by concrete, asphalt, timber deck, artificial turf, multiple green spaces, and exposed concrete aggregate. A summary of study site details is provided in Table 2.

2.3. Meteorological measurements

The specifications and the accuracy of the weather stations used in the different studies are shown in Table 3. The meteorological measurement protocol used complies with ASHRAE [61], ISO 7726 [62] and ISO 7730 [63]. We used portable weather stations for all three studies, and these meteorological measurements were made in the same study sites on various survey days. Although the location of the portable weather station varied slightly on different days, the distance between these portable weather station locations did not exceed 20 m within the same survey location. Two Mobile Architecture and Built Environment Laboratory (Mabel) thermal comfort carts with Campbell Scientific CR23X data logger were used in the first study in order to monitor the micrometeorological variables. These carts are characterised by their high accuracy and being mobile. Each comfort cart measures air temperature (T_a), relative humidity (RH), wind speed (v), and globe temperature (T_g). The measurements were at 1- and 15-min intervals and at various heights which correspond to the ankles, waist, head of a seated person, and the head of a standing person. The MABEL comfort carts are designed to assess thermal environments according to the procedures and protocols prescribed in ASHRAE's thermal comfort standard-ASHRAE 55–92R and ISO 7726 Ergonomics of the thermal environment - Instruments for measuring physical quantities [62,64]. Each cart measures the climatic parameters simultaneously at four heights within the place. These heights are LO (0.1 m above the floor corresponds to the ankles of a seated person), MID (0.6 m above the floor corresponds to the waist of a seated person), HI (1.1 m above the floor corresponds to the head of a seated person), and HEAD (1.7 m above the floor corresponds to the head of a standing person) [46].

In the second study (Melbourne and Cranbourne Gardens), Campbell Scientific CR211X loggers and Kestrel 4400 heat stress trackers were used to measure T_a, RH, v, and T_g. We averaged the data into 1- and 10-min intervals. Black globe thermometers (150 mm and 25 mm for Campbell Scientific stations and Kestrel 4400 heat stress trackers, respectively) were used to measure T_g.

In the third study, the micrometeorological parameters were measured using a portable Testo 480 IAQ Pro Measurement Kit. The kit was placed within a radius of 2 m from the survey respondents. The data were synchronised and recorded at 1-min intervals. The readings were logged by a Testo 480 data logger and H21-002-HOBO Micro Station.

The mean radiant temperature (T_{mrt}) for the different studies was calculated using Eq. (1) [65].

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1 \times 10^8 v^{0.6}}{\varepsilon\, D^{0.4}} \times \left(T_g - T_a\right) \right]^{1/4} - 273.1 \quad (1)$$

Where T_g is the globe temperature (°C); T_a is the air temperature (°C); v is the wind speed (m/s); D is the globe diameter (m), and ε is the globe emissivity (0.95 for black globe).

We calculated the Physiological Equivalent Temperature (PET) using Rayman Pro 2.1. The PET is defined as 'the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed' [66, p.71]. The input data for PET calculation were T_a, RH, v and T_{mrt}, and these meteorological variables were obtained by the automatic weather stations in our three studies. Moreover, the PET was determined based on a standardised person's metabolic rate (80 W) and thermal clothing insulation of 0.9.

2.4. Thermal comfort survey

The thermal comfort surveys were carried out in different summertime (January to February) in Melbourne. During the summers from 2012 to 2015, 4717 surveys were collected in different LCZs across the three studies. For the first study (LCZ 5, $n = 523$ and LCZ 6, $n = 623$), survey data were collected between January and February 2012 and 2014. For the second study (LCZ B, $n = 2182$ and LCZ C, $n = 976$), the data collection was between January and February 2014. Moreover, the surveys were conducted in February 2015 for the third study (LCZ 1, $n = 265$ and LCZ 2, $n = 148$). The data collection for all three studies was conducted during the daytime between 9:00 a.m. and 5:00 p.m. for the first and third studies and between 10:00 a.m. and 3:00 p.m. for the second study. For all three studies, the people who conducted the surveys and survey respondents stood within 2 m of the automatic weather station. In this way, the meteorological measurements of the weather stations could capture the thermal environment experienced by the survey respondents.

The surveys noted respondents' demographic information (see Table A1 in Appendix A). For studies 1 (LCZs 5 and 6) and 2 (LCZs B and C), there were 19.6% and 15.4% more female respondents than male respondents. In contrast, there were 24.4% more male respondents than female respondents in study 3 (LCZs 1 and 2). Respondents between 18 and 45 years old accounted for more than 83% in study 1 (LCZs 5 and 6) and study 3 (LCZs 1 and 2), whereas the proportion for the same age group (48.3%) was lower in study 2 (LCZs B and C). The influence of the demographic characteristics of respondents has been reported in our previous studies [67–70]. However, as this study focused on the effect of urban physical features on outdoor thermal comfort, demographic information was not included in our analysis.

The questions relating to thermal perception were designed following the guidelines of ISO 10551 [42]. Respondents' thermal sensation vote (TSV) in these three studies was assessed according to the 7-point ASHRAE scale. Their thermal preference vote (TPV) was indicated by the 3-point McIntyre scale. The first and third studies also included questions on thermal acceptability (acceptable or unacceptable), which can be used to determine the acceptable temperature range (ATR). However, the second study did not include the thermal acceptability question, so we used an indirect method to determine ATR. This indirect method determines an acceptable vote as people reporting TSV ±1 (slightly cool to slightly warm) and TPV = 0 (prefer no change) [71]. In this way, the survey data were harmonised, allowing a valid comparison between the three studies.

2.5. Statistical analysis

Research question 1 concerns the association between urban morphology and outdoor thermal perception. To address this question, a simple linear regression was conducted to determine the neutral PET (TSV = 0) in different LCZ. We also used probit analysis [72] to define the preferred PET in different LCZs based on respondents' thermal preference votes. The preferred PET refers to those PET values at which respondents preferred neither warmer nor cooler. Responses of 'no change' were split randomly into 'preferred warmer' and 'preferred cooler' so that the probabilities in each PET bin add up to 100% [73]. Moreover, we conducted a chi-square test of association to determine whether there is a significant association between LCZ classifications

Table 3
Specifications of the weather stations used in the three studies.

	Study 1		Study 2			Study 3		
Measured parameter	Logger	Accuracy and resolution	Logger	Measuring range	Accuracy and resolution	Logger	Measuring range	Accuracy and resolution
Air temperature (°C)	3 x OMEGA 44032 linear thermistor composite	- interchangeability ±0.1 °C - time constant 1 s	CR211X: Vaisala HUMICAP® Humidity and Temperature Probe HMP155	−80 °C–60 °C	±0.17 °C [Accuracy with voltage output at 20 °C]	TESTO IAQ probe 0632 1543	0 °C–50 °C	±0.5 °C (at the temperature of 22 °C); 0.1 °C
			Kestrel 4400: Hermetically sealed, precision thermistor mounted externally and thermally isolated for rapid response	−29 °C–70 °C	±1 °C			
Relative humidity (%)	HyCal integrated circuithumidity sensor (IH-3605-B)	- repeatability ± 0.5% rh at 25 °C - total accuracy ± 2% rh at 25 °C - hysteresis ±0.8% of span max - time constant 15 s at 25 °C	CR211X: Vaisala HUMICAP® Humidity and Temperature Probe HMP155	0–100%	±1% (0–90%), ±1.7% (90–100%) [Accuracy at 15 °C–25 °C]	TESTO IAQ probe 0632 1543	0 to +100 %RH (non-condensing)	± (1.8 %RH+0.7% of meas. val.) and ±0.03 % RH/K (based on 25 °C); 0.1 %RH
			Kestrel 4400: Polymer capacitive sensor, mounted externally in thin-walled chamber	5–95%	±3%			
Wind speed (m/s)	3 x Digital TSI omnidirectional anemometers (model number 8475)	- Time constant adjustable 0.2–2 s with default setting 0.2 s. - range = 0.05–2.5 m/s - accuracy = 3% of reading	CR211X: Met One 014A-L Anemometer	0–45 m/s	0.11 m/s or 1.5%	TESTO COMFORT probe 0628 0143	0–5 m s^{-1}	0.5 °C ±(0.03 m/s + 4% of meas. val.); 0.01 m.s-1
			Kestrel 4400: Impeller - Diameter 25 mm, high precision axle and low-friction Zytel® bearings.	0.6–40 m/s	±3% of reading or ±0.1 m/s			
Globe temperature (°C)	3 x OMEGA 44032 linear thermistor	- interchangeability ±0.1 °C - time constant circa 10 min	CR211X: 150 mm black globe thermometer, copper, externally mounted, consisting of a thermocouple wire (44007 Thermistor)	−80 °C–150 °C	±0.2 °C [Accuracy at 0 °C–70 °C]	TESTO Globe thermometer 0602 0743	0 °C to +120 °C	Class 1 (−40 to +1000 °C); 0.1 °C
			Kestrel 4400: 25 mm black globe thermometer, copper, externally mounted. Calibrated to achieve same measurements as standard 150 mm globe	−29 °C–60 °C	±1.4 °C			

and thermal sensation/acceptance under different PET thermal range classifications [74].

The Cramer's V (φ_c) demonstrates the effect size of the chi-square test. Then, a Bonferroni-corrected z test was used to determine whether various categorical groups' column proportions significantly differ from one another [75,76].

Research question 2 is about how well thermal stress and urban morphological features predict people's thermal perception with various thermal comfort patterns (i.e., different clusters) [43]. Each thermal comfort pattern represents a different pattern of thermal sensation and preference. To address this question, two clustering methods were performed. First, this study used the agglomeration schedule and dendrogram from the hierarchical cluster analysis [77] to decide the number of clusters. In particular, agglomerative hierarchical clustering was used. The three studies' clustering input parameters are TSV and TPV, which could summarize the outdoor thermal comfort in the various sites. Second, the clusters were formed by k-means cluster analysis [78], resulting in the thermal comfort patterns in the survey samples. In this case, k-means clustering analysis separated our survey samples into *k* clusters, in which *k* refers to the pre-defined number of clusters resulting from the hierarchical clustering. Previously, outdoor thermal comfort studies have adopted k-means clustering in their analysis [44,79,80].

After the clusters were formed, this study conducted a chi-square test of association to evaluate whether there was an association between LCZ classifications and thermal perception in each cluster (i.e., TSV, thermal acceptability, and thermal comfort patterns). Moreover, binary logistic regression (BLR) was applied to address research question 2. Past outdoor thermal comfort research has adopted BLR [81,82]. The BLR was used to identify which urban morphological and thermal stress indicators significantly predicted respondents' TSV and thermal acceptability in each cluster. The TSV (recoded into a binary variable) and thermal acceptability (a binary variable) are the dependent variables, while the PET, SVF, and LCZ classifications are the independent variables. Unless otherwise stated, the statistical significance was assumed at an alpha value of 0.05. This study used SPSS version 20 for all data analyses.

3. Results

3.1. Biometeorological conditions

Table 4 summarises the biometeorological conditions in different LCZs in Melbourne studies during the survey period. The survey period was from 9:00 a.m. to 5:00 p.m. for the first study (LCZs 5 and 6, January and February 2012–2014) and the third study (LCZs 1 and 2, February 2015). Moreover, the survey period for the second study was from 10:00 a.m. to 3:00 p.m. (LCZs B and C, January and February 2014). The mean air temperature value in LCZ 1, 2, 5, 8, B, and C are 26.6 °C, 23.1 °C, 26.4 °C, 23.1 °C, 28.2 °C, 28.2 °C, respectively. Moreover, the lowest maximum air temperature values were in LCZ 5 (26.8 °C) and 2 (27.3 °C). Heatwave conditions were encountered between 14 and 17 January 2014 and 7 to 9 February 2014 [83]. Therefore, the maximum air temperature (40.6 °C) and PET values (55.6 °C) were highest in the Melbourne botanic gardens (LCZ B and C). The range of air temperature and PET in other LCZs were 18.8 °C–34.6 °C and 15.9 °C to 38.1 °C, respectively. Moreover, the relative humidity ranged from 8.4% to 99.9%, whereas wind speed was between 0 and 4.0 m/s (Beaufort scale: calm to gentle breeze) (Burberry, 1997).

Table 4
Meteorological conditions during the survey period in different local climate zones (LCZ).

LCZ	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	PET (°C)
1	21.3–31.8	32.8–76.7	0.2–4.0	18.5–38.1
2	18.8–27.3	40.2–72.5	0.5–3.9	14.9–30.4
5	19.3–26.8	34.8–82.9	0.2–0.8	17.3–31.0
6	18.2–34.6	8.4–84.5	0.3–2.0	15.9–37.0
B	15.8–40.6	14.6–99.9	0–3.6	11.8–51.5
C	16.9–39.4	18.1–95.1	0–3.7	17.5–55.6

3.2. Neutral PET and preferred PET in different LCZs

The neutral PET and preferred PET values were shown to differ in various LCZs in Melbourne (Table 5). LCZ B had the lowest neutral PET value (14.4 °C), whereas LCZ 6 had the highest neutral PET value (21.0 °C). The preferred PET value across different LCZs was higher than the neutral PET value (mean = 3.3 °C, SD = 2.2 °C). The preferred PET value was the highest in LCZ 2 (26.7 °C) and the lowest in LCZ B (17.3 °C). The results indicate that the neutral PET value was close to 20 °C except for LCZ B, and people generally prefer slightly warmer thermal conditions in Melbourne summer.

3.3. Relationship between LCZ and outdoor thermal comfort

Sections 3.3 and 3.4 address the relationship between urban morphology (indicated by LCZ) and outdoor thermal perception (research question 1). In particular, we explored the relationship between LCZ and various outdoor thermal benchmarks, including TSV, thermal acceptability, and thermal comfort patterns.

3.3.1. LCZ and TSV

The proportion of thermal sensation votes differed across various local climate zones (Fig. 4). Fig. 4a shows the PET ranges of different LCZs in this study. This study divided results into several PET ranges based on the thermal comfort ranges identified in the previous study [74]. Namely, the PET ranges were divided into slightly cool (11.0 °C–15.5 °C), neutral (15.6 °C–20.0 °C), slightly warm (20.1 °C–24.5 °C), warm (24.6 °C–29.0 °C) and hot (>29.0 °C). Respondents in the slightly cool range were limited (n = 74) and only concentrated in LCZ 2 and B, so they were not shown in the results.

For the neutral thermal range, LCZ 6 respondents had the highest proportion of voting slightly cool to cold (57.9%), whereas the lowest proportion of such votes was reported by LCZ 5 respondents (46.8%) (Fig. 4b). Moreover, LCZ C had the highest percentage of people feeling neutral (60.8%), followed by LCZ B (47.8%) (Fig. 4b). When the thermal range was slightly warm, LCZ B respondents had the highest proportion of voting 'slightly warm to hot' (63.3%) (Fig. 4c). The proportion of voting 'neutral' ranged from 17.9% (LCZ 6) to 41.4% (LCZ C). Under the warm thermal range, the highest proportion of respondents voting 'slightly warm to hot' was found in LCZ 2 (87.5%). In contrast, LCZ C respondents had the lowest proportion (45.1%) (Fig. 4d). When the thermal range was hot, all respondents in LCZ 2 felt 'slightly warm to hot', whereas the percentage of LCZ C respondents who felt 'slightly warm to hot' (70.3%) was the lowest among the LCZs in this study (Fig. 4e).

A chi-square test of association indicated a significant association between LCZ and TSV across different thermal ranges. This significant association was applicable to lower PET ranges, such as neutral, χ^2 (10, n = 2212) = 47.1, $p < 0.001$, φ_c = 0.23 (medium effect), and slightly

Table 5
The neutral and preferred PET in different local climate zones (LCZ) in this study.

LCZ	Neutral PET (°C)	Preferred PET (°C)
1	17.9	19.3
2	19.6	26.7
5	20.2	24.5
6	21.0	24.3
B	14.4	17.3
C	20.0	21.0

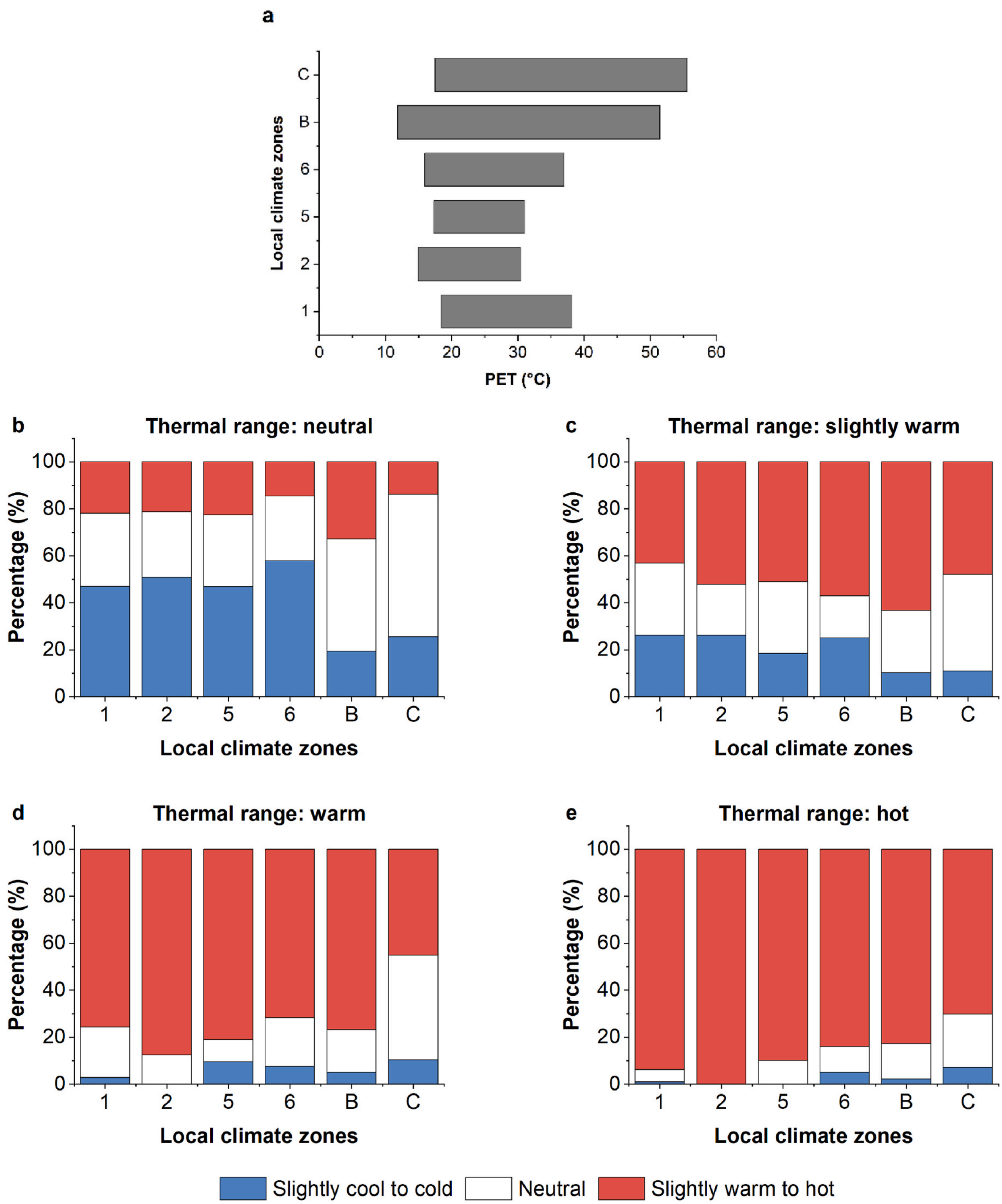

Fig. 4. a) The PET ranges in different local climate zones in Melbourne. The proportion of thermal sensation votes in different local climate zones in this study, stratified into various thermal ranges: b) neutral, c) slightly warm, d) warm and e) hot.

warm, χ^2 (10, $n = 1110$) = 53.9, $p < 0.001$, $\varphi_c = 0.16$ (small effect). The percentage of thermal sensation votes also differed by LCZs under higher PET ranges like warm, χ^2 (10, $n = 916$) = 87.1, $p < 0.001$, $\varphi_c = 0.22$ (medium effect), and hot, χ^2 (10, $n = 2166$) = 67.3, $p < 0.001$, $\varphi_c = 0.13$ (small effect).

Based on the Bonferroni-corrected z test, LCZ B respondents had significantly different proportions in feeling 'neutral' and 'slightly warm to hot' compared with other LCZs under the neutral thermal range (except for LCZ 1) ($p < 0.05$). For the slightly warm thermal range, LCZ C respondents had significantly different proportions of votes on 'neutral' and 'slightly warm to hot' compared with other LCZs (except LCZ 1) ($p < 0.05$). The proportion of votes on 'slightly warm to hot' differed significantly between LCZ 2 respondents and respondents from LCZs 5, 6 and B under the warm thermal range ($p < 0.05$). Under the higher PET range (i.e., hot), the proportions of 'slightly warm to hot' votes significantly differed between LCZ C respondents and other LCZs (except LCZ 2). Among various LCZs, results demonstrate that people in urban green spaces (LCZs B and C) are more likely to feel 'neutral' under lower PET ranges. They are also less likely to feel 'slightly warm to hot' under higher PET ranges.

3.3.2. LCZ and thermal acceptability

Apart from TSV, a chi-square test of association to assess the relationship between LCZ and thermal acceptability was done. An acceptable vote is defined as $-1 \leq$ TSV $\leq +1$ and/or TPV = 'no change'. In contrast, an unacceptable vote is defined as TSV outside the three central categories (i.e. TSV $> +1$ or < -1) and TPV = 'prefer warmer or cooler'.

Across the thermal ranges of neutral to warm, LCZ 6 respondents had the highest percentage of unacceptable votes, whereas LCZ C had the lowest proportion of unacceptable votes (Fig. 5). For the hot thermal range, the proportion of unacceptable votes ranged from 10% (LCZ 5) to 66.7% (LCZ 2) (Fig. 5d). The results suggest that people in open low-rise areas are more likely to find the environment unacceptable than other LCZs, except for the hot thermal range.

There was a significant association between LCZ and thermal acceptability. For example, this association applies to lower PET ranges such as neutral, χ^2 (5, $n = 444$) = 39.7, $p < 0.001$, $\varphi_c = 0.30$ (medium effect), and slightly warm, χ^2 (5, $n = 1110$) = 25.0 $p < 0.001$, $\varphi_c = 0.15$ (small effect). The percentage of acceptable votes also differed among LCZs across the thermal range of warm, χ^2 (5, $n = 911$) = 52.3, $p < 0.001$, $\varphi_c = 0.24$ (small effect), and hot (χ^2 (5, $n = 2163$) = 28.7, $p < 0.001$, $\varphi_c = 0.12$ (small effect). Therefore, the significant relationship between LCZ and thermal acceptability is applicable to different thermal ranges.

The column proportions of thermal acceptability using the Bonferroni-corrected z test were further examined. The percentage of acceptable votes did not differ between LCZ 1 respondents and those from LCZs 2, 5 and 6 across the thermal ranges of neutral to warm ($p > 0.05$). However, LCZs B and C respondents' proportions of acceptable votes were significantly different from respondents from LCZs 2 and 5 under the neutral and slightly warm range ($p < 0.05$). LCZs B and C respondents were significantly different in the percentage of acceptable votes than LCZ 5 and 6 respondents when the thermal range was warm ($p < 0.05$). For the hot thermal range, the proportions of the acceptable vote were similar between respondents from LCZs 1, 2 and 6 ($p < 0.05$). The respondents from LCZ 5 were more likely to find the environment acceptable than those from LCZs 1, B and C when the thermal range was hot ($p < 0.05$). In brief, people from the botanic gardens are more likely to accept the environment than other LCZs across different PET ranges.

3.4. Cluster analysis results of thermal comfort patterns and relationship with LCZ

Observing the agglomeration schedule and dendrogram produced by hierarchical clustering results makes it possible to form two or three clusters. For three clusters, a large sample size ratio (4.18) was noted between the largest and smallest cluster. Accordingly, two clusters were chosen for the k-means cluster analysis, which produced a smaller sample size ratio (<1.88) between the larger and smaller cluster (i.e., the warm and neutral groups). The warm group ($n = 3072$) was characterised by people who generally felt warm (mean thermal sensation vote: MTSV = 2) and preferred cooler (mean thermal preference vote: MTPV = −1). In comparison, people in the neutral group ($n = 1630$) generally felt neutral (MTSV = 0) and preferred no change (MTPV = 0) (Fig. 6). These thermal comfort patterns were used in the subsequent chi-square test of association and logistic regression analysis.

LCZ C had the highest proportion of the neutral group under the

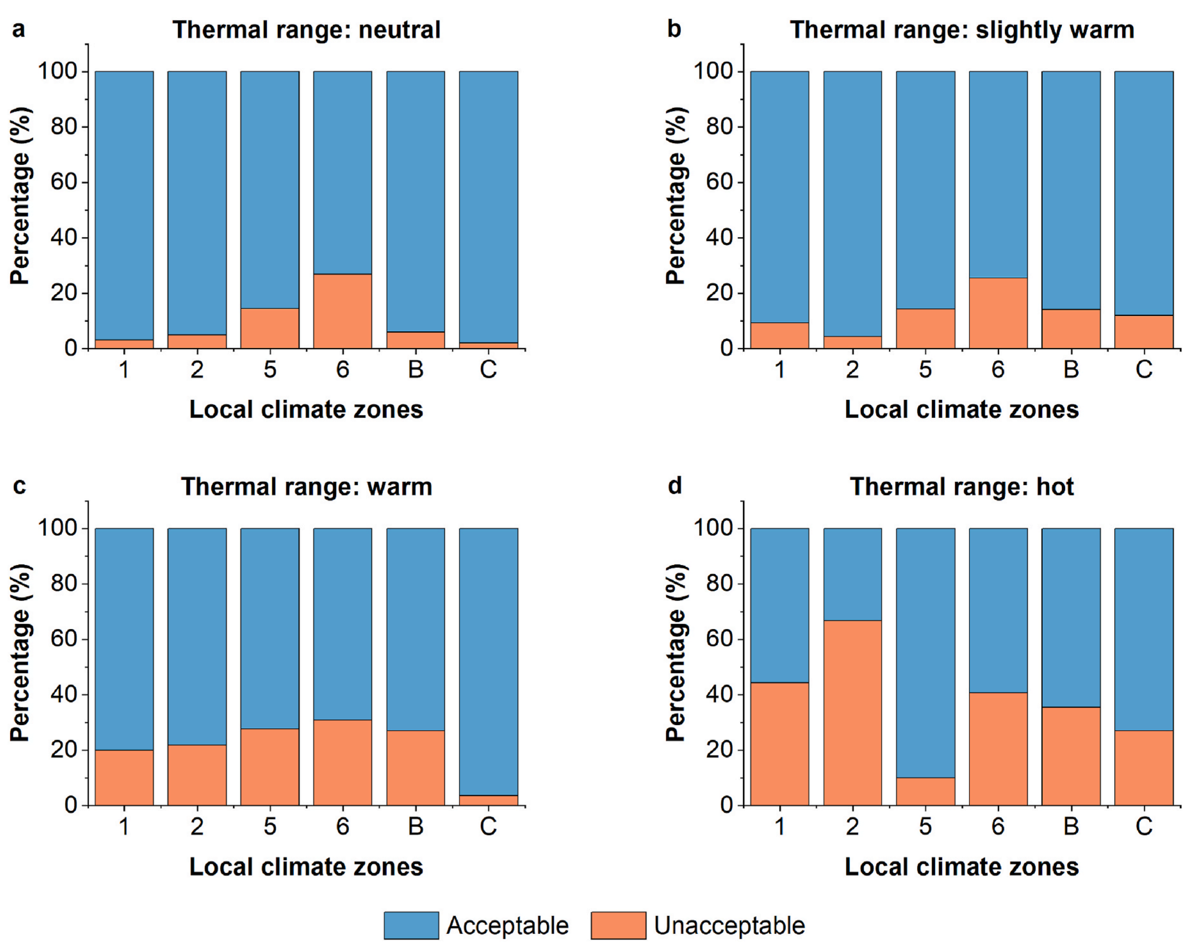

Fig. 5. Proportion of thermal acceptability in different local climate zones in our study, stratified into various thermal ranges: a) neutral, b) slightly warm, c) warm and d) hot.

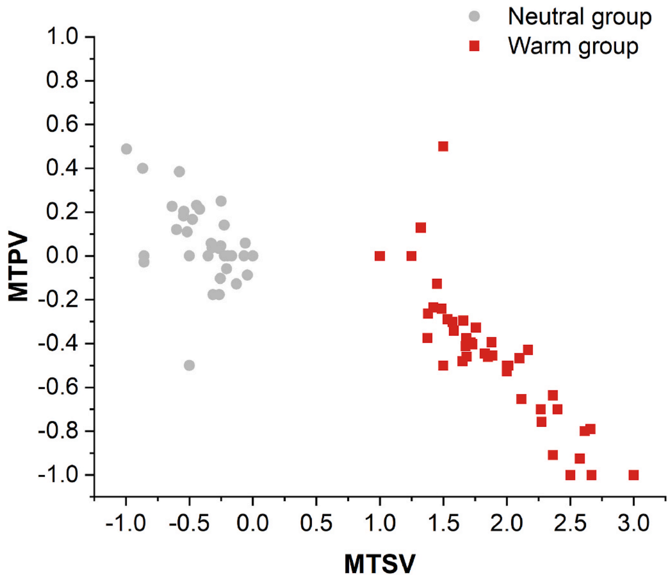

Fig. 6. k-means cluster analysis results, showing the two clusters of thermal comfort patterns characterised by mean thermal sensation vote (MTSV) and mean thermal preference vote (MTPV).

neutral thermal range (86.3%), whereas the percentage of the neutral group was the highest at LCZ 1 under the slightly warm thermal range (56.9%) (Fig. 7a and b). Moreover, LCZ 2 had the highest percentage of the warm group when the thermal ranges were warm (87.5%) and hot (100%) (Fig. 7c and d). Thus, there appears to be an association between LCZ and thermal comfort patterns. This association is subsequently supported statistically by the chi-square test of association. The chi-square test indicated a significant relationship between LCZ and thermal comfort patterns under lower PET thermal ranges such as neutral χ^2 (5, n = 444) = 11.7, p = 0.04, φ_c = 0.16 (small effect), and slightly warm, χ^2 (5, n = 1110) = 17.8, p = 0.003, φ_c = 0.13 (small effect). The same significant relationship also applies to higher PET thermal ranges like warm, χ^2 (5, n = 911) = 76.3, $p < 0.001$, φ_c = 0.29 (small effect), and hot, χ^2 (5, n = 2163) = 55.6, $p < 0.001$, φ_c = 0.16 (small effect). Therefore, the proportion of the thermal comfort patterns was not equally distributed across LCZ in this study.

Bonferroni-corrected z test revealed no significant difference in the proportion of the neutral and warm groups between LCZ 1 and other built-up types (LCZs 2, 5, and 6) across different thermal ranges ($p >$ 0.05). In contrast, LCZs B and C had a significantly different proportion of the neutral and warm groups compared with LCZs 5 and 6 when the thermal range was neutral to hot ($p < 0.05$). In short, the percentage of thermal comfort patterns was different between urban parks and other built-up types (open midrise and open low-rise areas).

3.5. Impact of thermal stress and urban morphology on outdoor thermal comfort

To address research question 2, we applied binary logistic regression (BLR) models to determine to what extent thermal stress (PET) and urban morphology (SVF and LCZ) predict outdoor thermal comfort (TSV

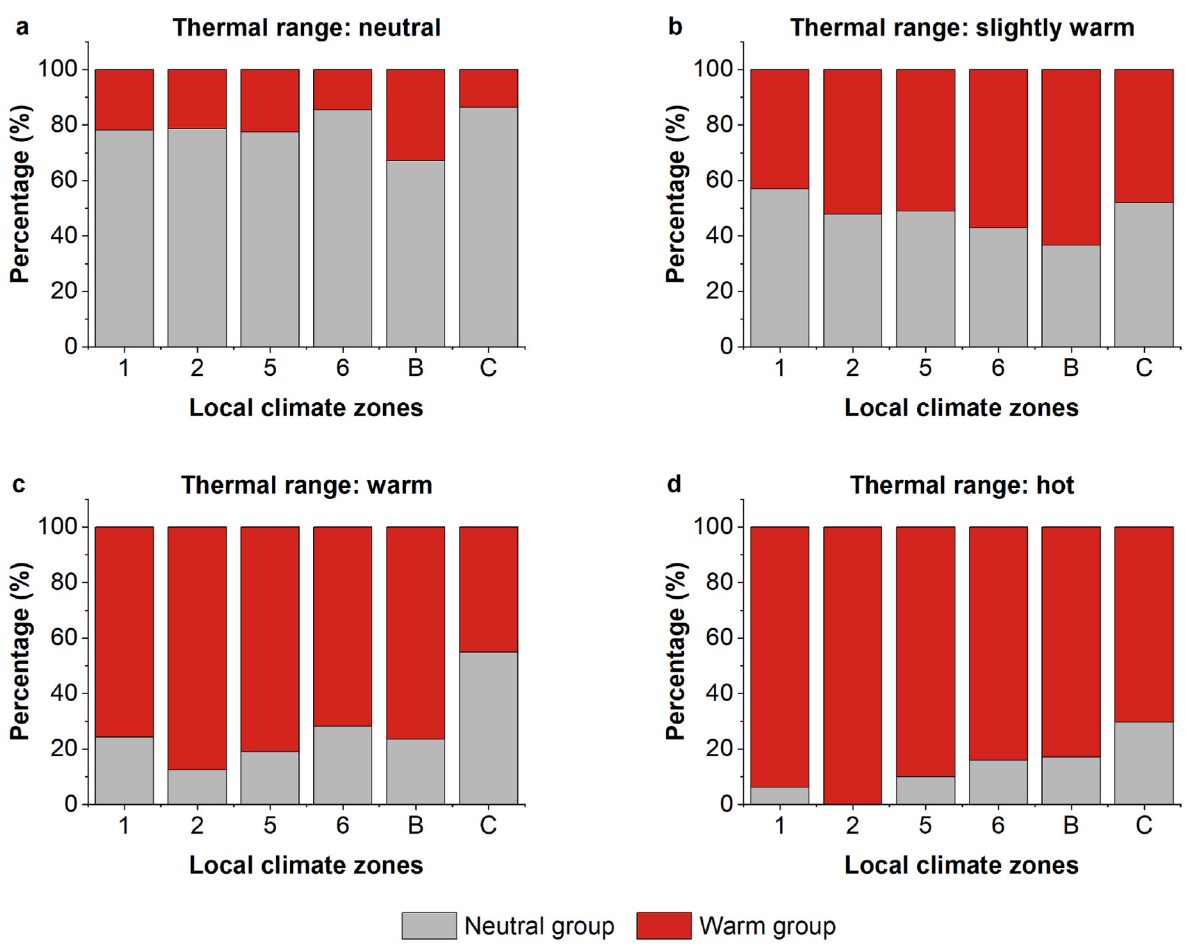

Fig. 7. Proportion of the thermal comfort pattern clusters in different local climate zones in our study, stratified into various thermal ranges: a) neutral, b) slightly warm, c) warm and d) hot.

and thermal acceptability) of different thermal comfort patterns. The BLR model was tested for the multicollinearity assumption. All these models' tolerance values were above 0.1, indicating the absence of multicollinearity. The model regarding PET, SVF, LCZ, and TSV violated the assumption of proportional odds. For the proportional odds model, the proportional odds assumption states that the odds ratio would be the same irrespective of where the outcome categories are dichotomized [84]. Violating this assumption could lead to invalid results, and a separate binary logistic regression (BLR) model can be used instead [85]. Hence, the BLR model was used instead of the ordinal logistic regression model. The results of the BLR analysis were stratified into the two thermal comfort patterns identified in the cluster analysis (i.e., the neutral and warm groups). Certain thermal sensations were not reported in each cluster (i.e., no TSV >0 for the neutral group and no TSV <1 for the warm group). Therefore, different binary TSV variables for the two clusters were used. In particular, the study divided TSV into two classes differently for the neutral group (TSV: cold to slightly cool vs neutral) and the warm group (TSV: slightly warm vs warm and hot). LCZ is a categorical variable, and LCZ 1 was used as the reference category in the BLR model. LCZ 1 is the reference category because previous studies indicate it has the highest thermal load [22,86]. The high thermal load in LCZ 1 is likely due to its urban morphology of compact and high-rise buildings, as well as anthropogenic activities [22].

Of the three predictors in the model, PET and LCZ were significant predictors of TSV of the neutral group (Table 6). The BLR model was statistically significant, $\chi^2(7, n = 1630) = 219.5$, $p < 0.001$, indicating that it could distinguish between respondents who reported TSV <0 (reference sensation) and TSV = 0. The model explained 17.4% (Nagelkerke R^2) of the variance in TSV and correctly classified 71.1% of cases. Increasing PET was associated with an increased likelihood of neutral group respondents reporting neutral (OR = 1.08, $p < 0.001$). These ORs indicated that for every 1 °C increase in PET, neutral group respondents were 1.08 times more likely to feel neutral (compared to feeling cold to slightly cool). Compared with LCZ 1, LCZ 6 respondents were less likely to feel neutral (OR = 0.54, $p = 0.02$), whereas LCZ B respondents were more likely to feel neutral (OR = 1.83, $p = 0.02$). The SVF was not a significant predictor of TSV of the neutral group, showing that shading conditions were not associated with the thermal sensation votes of neutral group respondents.

For the warm group, PET, SVF, and LCZ made a unique statistically significant contribution to the model (Table 6). The BLR model containing the predictor variables was also statistically significant, $\chi^2(7, n = 3072) = 305.1$, $p < 0.001$. The model explained 12.7% (Nagelkerke R^2) of the variance in TSV (with slightly warm as the reference sensation), and it correctly classified 64.5% of cases. Increasing PET was associated with an increased likelihood of reporting warm and hot (OR = 1.10, $p < 0.001$). However, a higher SVF was associated with reducing the likelihood of warm group respondents feeling warm and hot (OR = 0.35, $p < 0.001$). Warm group respondents in LCZ 6 were more likely to feel warm and hot than those in LCZ 1 (OR = 1.80, $p = 0.005$). Compared with LCZ 1, warm group respondents in LCZ B and LCZ C were less likely to feel warm and hot (LCZ B: OR = 0.70, $p = 0.04$; LCZ C: OR = 0.67, $p = 0.04$). These results indicate that urban green spaces were associated with a lower thermal sensation for the warm group.

A similar BLR analysis was performed to ascertain the effects of PET, SVF, and LCZ on respondents' likelihood of feeling unacceptable regarding the thermal conditions (Table 7). For the neutral group, the full model containing all predictors was statistically significant, χ^2 (7, $n = 1630$) = 154.1, $p < 0.001$. This result indicated that the model could distinguish between respondents who found the environment acceptable and those who found it unacceptable. The model explained 23.7% (Nagelkerke R^2) of the variance in thermal acceptability and correctly classified 93.6% of cases. Of the three predictors in the model, only PET and LCZ were statistically significant predictors of the thermal acceptability of the neutral group (Table 7). Based on the odds ratio (OR), respondents were 0.87 times less likely to feel unacceptable for every 1 °C increase in PET, $p < 0.001$. Compared with LCZ 1, respondents in LCZs 6 and 5 were 17.8 times ($p = 0.01$) and 10.5 times ($p = 0.03$) more likely to feel unacceptable. Other LCZ classes did not differ significantly from LCZ 1 regarding thermal acceptability. Moreover, SVF was not a significant predictor of the thermal acceptability of the neutral group.

For the warm group, the logistic regression model was statistically significant, χ^2 (7, $n = 3072$) = 320.9, $p < 0.001$. The model explained 13.7% (Nagelkerke R^2) of the variance in thermal acceptability and correctly classified 69.8% of cases. The PET, SVF, and LCZ made a unique statistically significant contribution to the model (Table 7). Based on the OR, respondents in LCZ 6 were 2.22 times more likely to feel unacceptable compared with LCZ 1 ($p < 0.001$). Other LCZ classes were not significantly different from LCZ 1 in terms of thermal acceptability. For every 1 °C increase in PET, the OR for PET suggested that respondents were 1.10 times more likely to feel unacceptable ($p < 0.001$). The OR of 0.35 for SVF was less than 1, indicating that for every

Table 6
Binary logistic results of thermal sensation vote (TSV), Physiological Equivalent Temperature (PET), sky view factor (SVF) and local climate zone (LCZ) for the warm and neutral groups. The table shows the unstandardized coefficients (*B*), standard error (*SE*), wald statistics (Wald), p-value (*p*), odds ratio (OR), and 95% confidence intervals (95%CI).

Variable	*B*	*SE*	Wald	*p*	OR	95%CI
Neutral group (TSV: cold to slightly cool vs. neutral)						
PET	0.07	0.01	47.24	<0.001*	1.08	[1.05, 1.10]
SVF	0.26	0.30	0.77	0.38	1.30	[0.73, 2.31]
LCZ 1	0[a]					
LCZ 2	−0.58	0.32	3.21	0.07	0.56	[0.30, 1.06]
LCZ 5	−0.12	0.28	0.17	0.68	0.89	[0.52, 1.54]
LCZ 6	−0.61	0.27	5.21	0.02*	0.54	[0.32, 0.92]
LCZ B	0.60	0.25	5.87	0.02*	1.83	[1.12, 2.97]
LCZ C	0.40	0.29	1.93	0.16	1.49	[0.85, 2.63]
Warm group (TSV: slightly warm vs. warm and hot)						
PET	0.10	0.01	208.78	<0.001*	1.10	[1.09, 1.11]
SVF	−1.06	0.18	36.63	<0.001*	0.35	[0.25, 0.49]
LCZ 1	0[a]					
LCZ 2	−0.37	0.30	1.56	0.21	0.69	[0.38, 1.23]
LCZ 5	−0.03	0.21	0.01	0.91	0.98	[0.64, 1.48]
LCZ 6	0.59	0.21	7.96	0.005*	1.80	[1.20, 2.71]
LCZ B	−0.35	0.17	4.25	0.04*	0.70	[0.51, 0.98]
LCZ C	−0.41	0.20	4.29	0.04*	0.67	[0.45, 0.98]

[a] Reference category, *$p < 0.05$.

Table 7
Binary logistic results of thermal acceptability, Physiological Equivalent Temperature (PET), sky view factor (SVF) and local climate zone (LCZ) for the warm and neutral groups. The table shows the unstandardized coefficients (*B*), standard error (*SE*), wald statistics (Wald), p-value (*p*), odds ratio (OR), and 95% confidence intervals (95%CI).

Variable	*B*	*SE*	Wald	*p*	OR	95%CI
Neutral group (thermal acceptability: acceptable vs. unacceptable)						
PET	−0.14	0.03	19.33	<0.001*	0.87	[0.82, 0.93]
SVF	0.12	0.76	0.03	0.87	1.13	[0.26, 4.99]
LCZ 1	0[a]					
LCZ 2	1.11	1.13	0.97	0.33	3.05	[0.33, 28.08]
LCZ 5	2.35	1.06	4.95	0.03*	10.48	[1.32, 83.02]
LCZ 6	2.88	1.04	7.63	0.01*	17.77	[2.31, 136.95]
LCZ B	0.88	1.05	0.70	0.40	2.41	[0.31, 18.87]
LCZ C	0.05	1.21	0.00	0.97	1.05	[0.10, 11.29]
Warm group (thermal acceptability: acceptable vs. unacceptable)						
PET	0.10	0.01	237.05	<0.001*	1.10	[1.09, 1.12]
SVF	−1.05	0.18	33.25	<0.001*	0.35	[0.24, 0.50]
LCZ 1	0[a]					
LCZ 2	−0.45	0.37	1.50	0.22	0.64	[0.31, 1.31]
LCZ 5	0.18	0.23	0.59	0.44	1.19	[0.76, 1.88]
LCZ 6	0.80	0.21	14.14	<0.001*	2.22	[1.46, 3.36]
LCZ B	−0.23	0.17	1.86	0.17	0.79	[0.57, 1.11]
LCZ C	−0.25	0.20	1.56	0.21	0.78	[0.52, 1.15]

[a] Reference category, *$p < 0.05$.

0.1 increase in SVF, respondents were 0.35 times less likely to report feeling unacceptable ($p < 0.001$). Overall, the results suggest that respondents in open low-rise areas (LCZ 6) had a higher likelihood of feeling unacceptable than compact high-rise areas (LCZ 1). This result is consistent for both the neutral and warm groups.

4. Discussion

The effect of physical features of the urban setting and human thermal comfort has been the key aspect of this study. The three main places studied in this study involved different LCZs and SVF values. This variation allowed the investigation to determine the impact of urban physical features on outdoor thermal perceptions.

4.1. Biometeorological conditions in different LCZs

Micrometeorological measurements reveal variations in air temperature in different LCZs in Melbourne. Past studies indicate that the mean temperature in built-up types is 1.98 °C [22] and 2.9 °C [18] higher than in the land cover types. However, these values cannot be compared to the values recorded in this study, given that our biometeorological variables were not measured on the same day. The largest range of air temperature values was found in LCZ B (24.8 °C) and C (22.5 °C), and the smallest range values were in LCZ 5 (7.5 °C) and LCZ 2 (8.5 °C). The small range found in LCZ 2 was explained by Lau et al. [22] by the relatively homogeneous environment, which is dominated by 5–6 storey buildings and a low SVF of 0.37. The lowest minimum air temperature values were found in LCZ B (15.8 °C) and LCZ C (16.9 °C), which could be explained by the shading effect or vegetation, which lowers the exposure to solar intensity [1]. The highest maximum air temperature values were found in LCZ B (40.6 °C) and LCZ C (39.4 °C). The higher maximum RH was found in the land cover types LCZ B (99.9%) and LCZ C (95.1%). These higher air temperature and RH values are due to the more extreme thermal environment encountered during the January 2014 heatwave [87].

Heatwaves could change people's expectations regarding outdoor thermal comfort and lead to different thermal perceptions under similar thermal conditions. For example, Melbourne respondents' thermal sensation votes were higher during a heatwave than during non-heatwave periods under similar UTCI ranges [88]. For the same UTCI range, Melbourne residents also perceived a lower thermal sensation after the heatwave compared with the pre-heatwave period [89]. We acknowledge that expectations and short-term experience during the heatwave could affect our survey results [90,91].

According to Kenawy et al. [74], the neutral PET (NPET) value for Melbourne during summer was calculated to be 16.1 °C. However, in this study, the NPET values ranged from 14.4 °C to 21 °C. The NPET value for the aggregated data is closer to LCZ B (14.4 °C) and LCZ 1 (17.9 °C). However, the neutral PET value for the different places lies between the acceptable temperature for Melbourne city, ranging between 11.3 °C and 20.3 °C except for the LCZ 6 site [74]. This result might be explained by the type of activity on the university campus, in which less quality of physical characteristics is acceptable [92,93].

The difference between the highest and lowest mean PET of our built-up types (LCZs 1,2,5 and 6) was up to 5.7 °C. This result is similar to the range of median PET value among built-up types in Shenzhen (6 °C) [18]. In Melbourne and Shenzhen, LCZ 2 recorded a lower PET value than LCZ 5 and 6. While LCZ 1 had the highest mean PET value in our Melbourne study, Liu et al. [18] found that LCZ 1B had the lowest PET median value in Shenzhen. Their results differ from ours, possibly because of the presence of urban trees in their LCZ 1B, which helps lower PET values by trees' shading effects [94].

4.2. Relationship between LCZ and outdoor thermal perception

As previously stated, the data collection included both objective and subjective monitoring. According to the micrometeorological measurements, the calculated PET values varied from 11.8 °C to 55.6 °C. These values lie between the "slightly cold" and the "hot" comfort range according to the thermal comfort ranges for Melbourne city [74].

Within the neutral range, respondents in LCZ's land cover types reported the highest proportion of the neutral vote, whereas a higher proportion of slight cool to cold sensations was reported in other LCZ's built-up types (Fig. 4). These results are different from other studies [22, 95,96], where cooler thermal sensation votes were observed under hot summer conditions in LCZ's land cover types, due to the extensive vegetation. However, these results could be explained by the duration spent in these two locations (LCZ B and C) in which higher temperature values were recorded.

Thermal sensation differs between LCZ classes in various climate zones. For the warm thermal range in Melbourne, LCZ 1 had the highest percentage of respondents who felt neutral, followed by LCZ 6 (Fig. 4d). Liu et al. [18] also found similar results for LCZ 1 in Shenzhen. Still, they noted that LCZ 6 had the lowest percentage of neutral respondents. The discrepancy between our results and their findings might be due to differences in the PET ranges (Melbourne built-up types: 14.9 °C–38.1 °C vs Shenzhen: 25 °C–50 °C) and climatic zones (Melbourne: temperate oceanic climate vs Shenzhen: subtropical climate). These findings highlight the impact of climatic zones and LCZ classes on people's thermal sensation.

The preferred PET values differed in the different locations varying from 17.3 °C (LCZ B) to 26.7 °C (LCZ 2) (Table 5). No clear distinction was found between the built-up and land cover sites' preferred PET value variations, but LCZ B had the lowest value for preferred PET. This result could be explained by the users' expectation of having cooler temperatures from the shade provided by the deciduous/evergreen trees in this location [97,98]. It is noted that the preferred PET value indicated higher temperature values than the NPET for all studied locations. As per other studies, the discrepancy between neutral and preferred PET values is also explained by different factors, including the users' characteristics, experience, and expectations [99–101].

A significant chi-square was found between LCZ and TSV across different comfort ranges. The effect was more influential in neutral and warm PET ranges. Apart from LCZ 1, the respondents' votes in the land cover types B and C were significantly different from built-up types under the neutral and slightly warm PET ranges (Fig. 4). Similar significances were found between LCZ and thermal acceptability. However, the effect size was larger in the neutral PET range. Within this range, the land cover type LCZ C was found to have the lowest unacceptability votes (Fig. 5). This finding is in line with Klemm et al. [102], who found that within the comfortable PET range (slightly warm to slightly cool), the users within land cover sites are mostly thermally comfortable. These results also confirm the influence of urban morphology through LCZ classification on human thermal perception [15,22,26].

This study reveals that the proportion of thermal comfort patterns differs between LCZ's built-up types and land cover types (Fig. 7), highlighting the influence of the built environment on outdoor thermal comfort. The same significance was also repeated in the chi-square to identify the relationship between LCZ and different thermal comfort patterns. The two tested thermal comfort patterns have been identified from the hierarchical cluster analysis. These are neutral and warm groups, in which MTSV = 0 and 2; and MTPV = 0 and −1, respectively. Past studies have assessed thermal comfort patterns in terms of short-term thermal history and activities [44], as well as air temperature and heart rate [43]. This study extends the evaluation of thermal comfort patterns by considering landscape classification (i.e., LCZ). By combining LCZ and cluster analysis, the study approach evaluates the subjective thermal perception of people with various thermal comfort patterns through thermal stress and urban morphology.

4.3. Predictors of thermal sensation and acceptability of different thermal comfort patterns

Logistic regression is used to predict an ordinal dependent variable given one or more independent variables. In our case, binary logistic regression was used to test the abilities of PET, SVF, and LCZ in predicting the thermal sensation votes of different thermal comfort patterns. The same test was also used for thermal acceptability. Other studies also used this type of logistic regression for various analyses, including locating the biometeorological parameter ranges for thermal neutral and comfort status [82], analysing preference votes [103], and testing the probability of heat stress for a specific LCZ at a given air temperature and relative humidity [104].

PET was a significant predictor of thermal sensation and acceptability for both neutral and warm groups. A higher PET value was associated with a higher TSV of both neutral and warm groups (Tables 6 and 7), which agrees with previous studies on exercising subjects [105]. However, an increased PET value reduced the likelihood of the neutral group reporting unacceptable (Table 7), which could be explained by a higher proportion of the neutral group at the lower PET range (Fig. 7). Other studies have confirmed the significant relationship between TSV and PET and the different biometeorological parameters, including T_a, T_g [106] vapour pressure, T_{mrt} and v [107].

For the neutral and warm groups, LCZ 6 respondents were less likely to feel neutral and more likely to feel warm/hot compared with LCZ 1 respondents (Table 6). This finding could be due to a lower SVF in LCZ 1 than in LCZ 6 (Fig. 3), meaning that there are greater building shade and more green space in the form of tree shade per square meter in LCZ 1 [100]. Our results are supported by Hwang et al. [108], who reported a highly shaded site (low SVF) had a lower percentage of warm hours (PET >30 °C) than slightly shaded sites (high SVF) during summer. For the neutral group, respondents in LCZ B were more likely to feel neutral than in LCZ 1. For the warm group, LCZs B and C respondents were less likely to feel warm/hot than LCZ 1 respondents (Table 6). The cooling effect of green areas could also explain this finding through shading and evapotranspiration [22,109]. The binary logistic regression analysis results complement the previous significant relation between LCZ and TSV across the different thermal ranges in section 3.3.1.

For the warm group, the SVF was also found to be a significant predictor of the TSV. A higher SVF is associated with a lower possibility of reporting warm and hot (Table 6) and a lower likelihood of feeling unacceptable (Table 7). In their study, Krüger and Costa [110] also found that the users' responses in high SVF values skewed towards cooler thermal sensations under moderate heat stress. This finding is also in line with previous studies that reported a significant effect of SVF and thermal conditions and sensation votes [37,111–113]. In brief, SVF is a significant predictor of thermal sensation and acceptability of the warm group but not the neutral group.

5. Conclusions

Dense urbanisation has resulted in a higher temperature value in cities, making outdoor spaces less pleasant for users, especially during summertime. It is often argued that in addition to psychophysiological adaptation, urban physical features have a pivotal role in the perceptions of thermal conditions. The reconfiguration of urban environments has long been practised to improve outdoor thermal comfort and reduce thermal risk in urban areas [94]. Using urban climate-sensitive design and planning principles can help to achieve this goal. Building on three individual research projects, this study aimed to explore the relationship between physical features and individual perceptions of thermal conditions in urban environments. The outcomes of this study can be used to contextualise the application of climate-sensitive urban design principles. Our key findings include the following.

- The neutral PET value in Melbourne was near 20 °C except for LCZ B (14.4 °C). People also mostly prefer slightly warmer thermal conditions across all LCZs during summer.
- People in urban green spaces (LCZs B and C) are more likely to feel 'neutral' under lower PET ranges and less likely to feel 'slightly warm to hot' under higher PET ranges. Among the LCZs, LCZ 6 (LCZ C) reported the highest (lowest) percentage of unacceptable votes.
- The proportion of thermal comfort patterns (derived from cluster analysis) was different between urban parks (LCZ B, C) and other built-up types (LCZ 5: open midrise and LCZ 6: open low-rise areas).
- Thermal stress and urban morphology contribute significantly to people's thermal sensations and acceptability for both neutral and warm groups. PET and LCZ were significant predictors of TSV of the neutral group, whereas PET, SVF and LCZ significantly predicted TSV of the warm group. Furthermore, urban green spaces (LCZs B and C) were associated with a lower thermal sensation for the warm group.
- For both the neutral and warm groups, people in open low-rise areas (LCZ 6) were more likely to feel unacceptable than those in compact high-rise areas (LCZ 1).

The study contributes to the field in two ways. First, it addressed the gap identified in the body of knowledge regarding the extent of the impact of urban physical features on thermal perceptions in urban environments. This study demonstrated that the LCZ classification system could be confidently used to characterise both the physical and thermal environment. Second, this study approach provides a basis for further research that would seek to understand the implications of urban design in the usage of outdoor spaces using thermal comfort patterns as a benchmark. Cluster analysis was used as an unsupervised method to identify thermal comfort patterns in urban populations instead of predefined groups employed in previous studies. Thermal comfort pattern presents a human-centric approach to outdoor thermal comfort, which can tailor to the thermal comfort requirements of distinctive groups.

There are a few limitations to the study. There was a lack of data from certain LCZ classes as we could not include all LCZ classes in Melbourne due to logistic issues. This situation necessitates the inclusion of more study sites in future research to incorporate other LCZ classes. We acknowledge that apart from gender, demographic variables (e.g., age and climatic background) could affect people's outdoor thermal comfort. However, our three studies have different classifications of age group and climatic background, so it is difficult to directly compare these demographic variables in these studies. As this study focuses on the differences in outdoor thermal comfort in various LCZ classes, it is beyond the scope of this study to examine the impact of demographic characteristics on outdoor thermal comfort. This study also utilised the data that was captured in the last decade. Our three studies were conducted in summer in Melbourne in different years. However, our measurements happened at the same time as the survey, allowing the generalisation of our results. We compared people's thermal perception with daytime environmental conditions in Melbourne summer, particularly the effect of outdoor thermal exposure (using PET) on outdoor thermal comfort. As we aimed to achieve more reliable results based on a large sample size of surveys, it was important to use these data in this study. It is also not uncommon to use old thermal comfort survey data for new analysis (e.g., Pantavou et al. [114]).

In terms of future research direction, the relationship between LCZ classes with thermal conditions during other seasons presents new research opportunities. Using sub-classes within the broader LCZ classification could also provide further insights into microclimatic variations [115]. The added value of the present study for the world of practices lies in providing a clear picture of urban morphology and thermal comfort. This study's findings facilitate aligning urban planning and design practices with users' perceptual assessment of outdoor environments.

CRediT authorship contribution statement

Cho Kwong Charlie Lam: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Salman Shooshtarian:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Inji Kenawy:** Writing – review & editing, Writing – original draft, 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 A1
Characteristics of respondents in different studies

Characteristics		Study 1:LCZs 5 and 6			Study 2: LCZs B and C			Study 3: LCZs 1 and 2	
		n	%		*n*	%		*n*	%
Gender	Male	461	40.2	Male	1309	41.4	Male	257	62.2
	Female	685	59.8	Female	1793	56.8	Female	156	37.8
	Missing	0	0	Missing	56	1.8	Missing	0	0
Age	18–24	667	58.2	18–24	312	9.9	<18	20	4.8
	25–34	262	22.9	25–44	1214	38.4	18–30	244	59.1
	35–44	89	7.8	45–64	1029	32.6	31–45	102	24.7
	45–54	58	5.0	>65	583	18.5	46–60	37	9.0
	55–64	36	3.1	Missing	20	0.6	>61	10	2.4
	>65	34	3.0						

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