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ORIGINAL PAPER

How 'hot' is too hot? Evaluating acceptable outdoor thermal comfort ranges in an equatorial urban park

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Abstract

Urban green spaces offer vital ecosystem services such as regulating elevated temperatures in cities. Less information exists, however, on how urban green spaces influence outdoor thermal comfort (OTC), which is dependent on people's perceptions of the complex interactions amongst ambient humidity, wind and both air and radiant temperatures. In this study, we analysed an existing OTC dataset compiled within a large Singapore urban park and calibrated OTC thresholds for physiological equivalent temperatures (PET) by analysing PET against thermal perception survey responses from the park visitors ($n = 1508$). We examined OTC according to (i) neutral, (ii) acceptable and (iii) preferred temperatures, where respondents felt 'comfortable' outdoors in the park. We estimated that neutral temperature, when all respondents experience neither heat nor cold stress, is 26.2 °C; acceptable temperatures, when only slight heat or cold stress is experienced, range between 21.6 and 31.6 °C; and preferred ('ideal') temperature for all respondents is 24.2 °C. Respondents residing for more than 6 months in Singapore achieved thermal neutrality, suggesting that a greater degree of thermal adaptation likely developed during acclimatisation to local climate through a combination of physiological, behavioural and psychological circumstances. Comparisons with other OTC studies showed differences in synoptic climates are linked to variations in the magnitude and ranges of perceived PET. Lastly, respondents in this study perceived lower neutral and preferred temperatures compared to respondents surveyed over a variety of urban land use categories in another local study. The differences in neutral and preferred temperatures between studies suggest that lower park temperatures and different environmental attitudes influence perceived OTC.

Keywords Physiological equivalent temperature · Outdoor thermal comfort · Urban greenery · Acclimatisation

Introduction

Urban greenery and outdoor thermal comfort

Urban greenery, e.g. street trees, parks and rooftop gardens, offer important provisional, support, cultural and regulatory ecosystem services (Gómez-Baggethun et al. 2013). The latter service manifests through regulation of the urban heat island (UHI), a phenomenon where enhanced heat within cities is caused by the alterations to the aerodynamic, thermal and hydrological characteristics of non-urban landscapes (Oke 1982; Oke et al. 2017). This regulation occurs across multiple scales (Bowler et al. 2010). For instance, enhanced tree shade reduces radiation fluxes and lowers microscale surface temperatures in urban areas; enhanced urban greenery partitions more turbulent urban energy balance terms towards evapotranspirative/latent heat than sensible heat fluxes, and lowers local-scale ambient temperatures (Spronken-Smith et al. 2000; Chow and Brazel 2012). As such, tropical cities and cities with seasonal hot summers utilise urban greenery to manage exposure to additional warmth from both UHI and climate change (Emmanuel 2016), as increased health risks by mortality events ensuing from outdoor thermal discomfort and heat stress caused by UHI or climate change (e.g. Chuang et al. 2013; Mora et al. 2017).

Local- and regional-scale impacts of urban greenery on surrounding climates are well-documented (e.g. Bowler

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et al. 2010), but research on microscale impacts of urban greenery on surrounding climate is scarce. Specifically, research on individual outdoor thermal comfort (OTC) occurs less compared to city-wide UHI impacts or its mitigation (Johansson et al. 2014). This disparity exists despite acknowledgement amongst scientists and policymakers that achieving appropriate conditions for urban OTC is beneficial. Some of these benefits include the enhancement of outdoor space utility (Lin 2009; Lin et al. 2013) and heat resilience during extreme weather (Sharifi et al. 2016); increasing visitor numbers to tourist attractions (Lin and Matzarakis 2008) and improving urban pedestrian comfort (Hirashima et al. 2016; Middel et al. 2016). The scarcity of microscale OTC studies of urban greenery may be attributed to uncertainties in current methods and instrumentation for OTC assessments (Johansson et al. 2014). These uncertainties arise from the understanding of what thermal comfort is, and from the array of methodological approaches to assess OTC in various contexts.

A comprehensive understanding of OTC stems from the definition of thermal comfort, which refers to 'the condition of mind that expresses satisfaction with the thermal environment' (ASHRAE Standard 2001), or the state in which the individual is not compelled to correct his or her environment (Djongyang et al. 2010). Thermal comfort assessment requires understanding complex interactions between the physical environment, physiology, psychology and behaviour (McGregor 2012). By extension, OTC research should consider an individual's physical condition, and of his or her mental perception and sensation of outdoor climate exposure. The complexities are evidenced by studies which found that about half of the variance in OTC evaluation can be explained by physical parameters (Nikolopoulou and Steemers 2003), and the remainder is attributed to a dynamic human parameter comprised of anthropometric characteristics, physiological activities, psychological factors and behaviours affecting acclimatisation of an individual to the local climate (Chen and Ng 2012). Further, we can also assess OTC and appropriate outdoor conditions in and across different cultural and/or climate zones (Hirashima et al. 2016; Krüger et al. 2017), by modifying and calibrating an appropriate OTC metric accounting for psychological processes and cultural characteristics affecting thermal (dis)comfort.

OTC assessments have traditionally been developed in temperate cities (Johansson et al. 2014), but research in tropical or equatorial cities have been increasing (Emmanuel 2016). As much future urbanisation occurs in these low-latitude areas (Georgescu et al. 2015), insights on OTC can be useful information for stakeholders residing in these rapidly developing settlements. Alongside rapid urban transformation, these settlements are also enhancing their development and management of urban greenery, which thus bolster the demand to assess the impacts of these urban green spaces on OTC.

Common indices for OTC assessment

OTC can be assessed through simple and rational indices. The former is based on measurement of basic environmental variables, while the latter integrate both environmental and physiological parameters (Epstein and Moran 2006). Simple indices are more appropriate for daily weather monitoring since these are based on readily available and accessible environmental data. Some of these include (i) Thom's (1959) temperature-humidity discomfort index (THI), (ii) Steadman's (1979) apparent temperature (AT) and (iii) derived heat indices from AT (Anderson et al. 2013). Both THI and AT are simple indices calculated from measurements of atmospheric moisture and air temperature (Thom 1959; Steadman 1979). THI thresholds were originally developed in mid-latitude cities; for instance, 100% of human subjects from these climates will experience discomfort when THI > 26 °C (cited from Chow et al. 2016). For equatorial climates, Mohd Din et al. (2014) suggested increasing thresholds to > 31 °C as residents of such climates have higher heat tolerance levels. AT values can be derived using air temperature and relative humidity tables (Steadman 1979), or from algorithms that calculate AT and corresponding a heat index; Anderson et al. (2013) identified at least 21 algorithms (and corresponding heat indices) used in environmental health research. For instance, heat advisories are specified according to thresholds of AT by the National Oceanic and Atmospheric Administration (National Weather Service 2017).

Rational indices are preferred for personal-scale or individual OTC assessments, where less accessible physiological and environmental data are actively measured. These indices used in OTC assessments include (iv) standard effective temperature for outdoor (OUT_SET) (Pickup and de Dear 2000); (v) universal thermal climate index (UTCI) (Jendritzky et al. 2012; Lam et al. 2018) and (vi.) physiological equivalent temperature (PET) (Matzarakis et al. 2010). These indices are based on thermal exchanges of the human body with the atmosphere and are calculated from body thermal equations (Sarebanzadeh et al. 2018). OUT_SET adapts an indoor thermal comfort index, the standard effective temperature (SET), to outdoor conditions. SET accounts for both environmental (e.g. climate measurements) and physiological (e.g. skin temperature and wettedness) variables (Sarebanzadeh et al. 2018). OUT_SET incorporates outdoor mean radiant temperature calculated from a separate model —OUT_MRT (Pickup and de Dear 2000). UTCI is the air temperature of a reference environment producing the same strain index value compared with the reference individual's response to the real environment. It is based on an advanced multi-node model of thermoregulation, which refers to an organisms' capability to retain its body temperature within a particular limit even when the surrounding temperature is different (Jendritzky et al. 2012). Lastly, PET is 'the equivalent (air) temperature of an isothermal reference environment with a water vapour pressure of 12 hPa (50% at 20 °C) and light air (0.1 m s^{-1}), at which the heat balance of a reference person is maintained with core and skin temperature equal to those under the conditions being assessed' (Matzarakis et al. 2007).

Applications of PET in OTC assessments

While some consensus exists on the difficulty in achieving a universal system for OTC assessment (Epstein and Moran 2006), some indices, e.g. PET have been widely applied over different climate contexts to this end (e.g. Kampmann et al. 2012; Matzarakis and Fröhlich 2015; Hirashima et al. 2016; Provençal et al. 2016; Ndetto and Matzarakis 2017; Cheung and Jim 2018). The extensive use of PET as a rational OTC index is possible for several reasons. It uses Celsius as a unit, enabling an easy understanding by people without specialised knowledge in human biometeorology (Matzarakis and Fröhlich 2015). PET also enables the development of local OTC thresholds or a PET assessment scale, when subjective perceptions of OTC are analysed in conjunction with objective OTC measurements. A PET assessment scale related to thermal sensation was first proposed by Matzarakis and Mayer (1996), where subjective perceived thermal comfort from Fanger's (1970) predicted mean vote (PMV) was related to PET and applied to temperate Central European regions. 'Comfortable' conditions were experienced when PET ranges 18–23 °C. PET thresholds can also be calibrated for subjects in different climates; comfortable thermal perceptions for visitors to Sun Moon Lake in subtropical Taiwan occurred when PET ranges 26–30 °C (Lin and Matzarakis 2008). However, perceptions of extreme heat stress conditions for PET vary across different climates; apart from > 41 °C for a Central European city, hot desert cities such as in Doha, Qatar, have proposed extreme thermal stress conditions occur > 50 °C (Matzarakis and Fröhlich 2015).

OTC studies utilising PET rely on field measurements of the physical environment and subjective microclimate perceptions from survey respondents (Johansson et al. 2014). PET data can be analysed in isolation to examine respondent exposure to environmental conditions, or concomitantly with subjective OTC survey responses to investigate the relationships between thermal perceptions and PET. The latter approach calibrates PET for the specific local climate context perceived by survey respondents and can derive the thermal neutrality, thermal acceptance and thermal preferences of respondents towards the studied sites. These three expressions have been explored using probit analysis (Hirashima et al. 2016; Salata et al. 2016), or via regression analysis (Lin and Matzarakis 2008; Hirashima et al. 2016; Middel et al. 2016; Krüger et al. 2017). PET calibration to local climate contexts can also be done by matching percentages of thermal votes to each level of PET increment (da Silva and de Alvarez 2015; Lucchese et al. 2016). Given the absence of a common strategy for PET calibration, Krüger et al. (2017) pointed to careful comparisons of PET calibration methods, results and research contexts (sites, climate, time) by Salata et al. (2016) as an alternative to facilitate PET comparisons across different studies.

OTC assessment and calibration in the low-latitude cities using PET

To assess OTC, Hirashima et al. (2016) analysed differences in daytime thermal comfort experienced by users in two public squares in Belo Horizonte, Brazil. This examination across tropical summer and winter seasons used field surveys and PET calibration against their subjective microclimate data. Respondents in this study were acclimatised (i.e. the adaptation to different climates through behavioural, physiological, or psychological factors) to their local conditions, which is warmer than the typical comfortable ranges of PET for a city located in a mid-latitude climate. The study found that under the same thermal conditions, individuals were more tolerant concerning their thermal comfort and sensation (i) in winter, (ii) in the public square characterised with low-rise buildings, green areas, wide sky view factor, permeable surfaces and water features.

Makaremi et al. (2012) applied PET to assess shade impacts on OTC within two outdoor spaces at a college campus near Kuala Lumpur, in equatorial Malaysia. Significant differences in PET occurred between shaded vs. unshaded spaces, with largest variations occurring at noon. An evaluation of acceptable thermal comfort ranges was also attempted; rather than calibrating PET against local microclimate survey data, their calibration applied existing thresholds developed by Lin and Matzarakis (2008) for a tourist location in Taiwan.

In Singapore, OTC assessments relying on both subjective microclimate votes and measurements of microclimate data took place in urban parks (Yang and Wong 2013; Chow et al. 2016) and over indoor and semi-outdoor spaces (Yang et al. 2013a, b). In their papers, Yang et al. (2013a) and Yang and Wong (2013) assessed OTC through field surveys of microclimate votes and microclimate data. Survey votes were calibrated against an OTC index derived from microclimate station data. Instead of PET, both studies opted for operative temperatures (OT) as the selected index. Neutral and acceptable temperatures were derived from the analysis of the relationship between thermal sensation and acceptance against OT. While these calibrations enabled a situated understanding of the thermal comfort in the study sites, the results cannot be directly compared to other OTC studies in Singapore and elsewhere, because their OT calculations were ambiguous (for examples of clearly stated OT calculations, see Gagge 1981 and Bakken 1992). In addition, OT is understood as 'a direct measure of the environmental heat stress on a human subject due to sensible heat exchange alone' (Gagge 1981, p. 82). The exclusion of latent heat exchange effects in OT precludes an understanding of how evapotranspiration affects heat stress and thermal comfort. Given the high ambient humidity and latent heat flux exchanges in Singapore, the role of evapotranspiration on OTC should be examined.

In contrast, Yang et al. (2013b) applied PET in estimating neutral (28.1 °C), acceptable (24–30 °C) and preferred temperatures (25.2 °C) from ~ 2000 surveys in 13 urban locations in Singapore (six park space and seven urban land use sites). While no investigation of local vs. visitor acclimatisation towards climate was reported in Singapore, a comparative analysis of these data was made against results from urban locations in subtropical Changsha, China. As per other studies, Yang et al. (2013b) found significantly different threshold ranges of OTC sensation between these cities with different climatic conditions, with evidence that both sets of respondents showed high levels of acclimatisation to their city's warm environment.

In their paper, Chow et al. (2016) compared the seasonal and site variations in OTC within a single urban park. Alongside wet-bulb globe temperatures (WBGT) and THI, they applied PET to assess OTC in their four study sites objectively. Comparisons between the objective and subjective thermal comfort data were also correlated, but only between WBGT and the microclimate sensation votes. There was no calibration of PET (and other indices) against the microclimate votes, thereby impeding comparisons of OTC to other studies in tropical parks.

Study objectives

In lieu of the research reviewed, we aim to examine OTC conditions of an urban park located in a low- and humid tropical climate through evaluating neutral, acceptable and preferred temperatures for park users, by calibrating PET against subjective microclimate perceptions data. We also aim to compare these results with studies from other cities reporting similar PET thresholds. We seek to answer the following questions:

1. What is the range of microclimate conditions providing thermal comfort for park-users in Singapore?; and,
2. How do these ranges of thermal comfort within this equatorial urban green space compare with other urban OTC studies?

Methodology

Study area—synoptic climatology

We conducted our study in a large urban park located in Singapore—the Singapore Botanic Gardens (SBG). The SBG is a popular tourist attraction with ~ 4.4 million visitors per annum (Feng 2013). The SBG is located within a tropical rainforest climate largely due to Singapore's low latitude (1° N) and maritime location. Mean daily temperatures in Singapore are ~ 27 °C, with a diurnal range of ~ 7 °C. Total annual precipitation is ~ 2400 mm, and consistently high dew point temperatures with generally low hourly wind speeds throughout the year are documented (Meteorological Services Singapore 2018). Although Singapore is subject to the East Asian Monsoon system which can be discerned from the higher-than-normal total precipitation over the months of November–January, there is little seasonality in terms of marked wet/dry periods for its synoptic climate. Singapore's consistently hot and humid climate, especially in the summer monsoon, is linked to uncomfortable microclimate conditions perceived by visitors from other climates (Chow et al. 2016). A large UHI with intensities in excess of 7 °C exacerbates this discomfort (Roth and Chow 2012).

Data collection

Fieldwork consisting of concurrent microclimate measurements and survey questionnaires spanned across 8 days during the winter and summer monsoon seasons of 2013/2014. Objective in situ microclimate data were collected using the Kestrel 4400 heat stress integrated sensor-logger (Nielsen-Kellerman; Pennsylvania, USA). Each sensor-logger was set on a tripod at 1.3 m above ground level, approximating to an average adult's core height of 1.1 m used in biometeorological research (Mayer and Höppe 1987). The sensor-loggers measured both air and globe temperatures, relative humidity, and horizontal wind velocity every 60 s. The measurements were first utilised to calculate corresponding mean radiant temperatures using the equation proposed by Thorsson et al. (2007) (for more details, please refer to Chow et al. 2016). Subsequently, these microclimate and mean radiant temperature data were input into the RayMan model to obtain PET. RayMan is a one-dimensional numerical biometeorological model enabling users to calculate PET with high temporal resolution for various climate contexts, such as for this analysis (Matzarakis et al. 2007).

Subjective microclimate perception data were collected via survey questionnaires. The survey consisted of two separate components. First, general and demographic information (i.e. time of survey, age group, gender, clothing, activity, acclimatisation) were queried. Second, questions related to each site's thermal comfort perception were asked—specifically, microclimate sensation, preference and acceptance at the time of their survey. We used the ASHRAE 7-point scale to gauge the thermal sensation vote (TSV), and a 5-point scale to gauge humidity, wind and sun sensation vote (HSV, WSV, SSV respectively) (Table 1).

Table 1 Description of sensation votes for each microclimate variable. Positive point scales corresponded with higher or stronger microclimate variables (i.e. high sun, wind, humidity and temperature conditions). Negative values corresponded with weaker microclimate variables perceived

Sun sensation vote (SSV)	Wind sensation vote (WSV)	Humidity sensation vote (HSV)	Thermal sensation vote (TSV)	7/5-point scale
			Hot	3
Too strong	Too much wind	Too humid	Warm	2
Little strong	Windy	Humid	Slightly warm	1
Neutral				0
Little weak	Little wind	Dry	Slightly cool	− 1
Too weak	No wind	Very dry	Cool	− 2
			Cold	− 3

We also surveyed questions on microclimate preference and acceptance. Preferences were voted on a 3-point McIntyre preference scale to reflect the user's ideal comfort levels for the site; (+ 1) corresponded with the preference of a stronger microclimate condition; (0) corresponded with a preference of 'no change' to the current microclimate variable and (− 1) corresponded with the preference for a weaker microclimate condition (i.e. weaker sun/wind/humidity/thermal conditions). Acceptance for the condition of a microclimate variable was asked via a binary scale—either acceptable or unacceptable.

Data validity and treatment

A potential issue affecting PET accuracy is that this index is defined and based on indoor clothing and moderate activity, which may be unsuitable if the respondent's activity level is too high. To minimise potential inaccuracies, the fieldwork excluded surveying park users actively jogging or running. Further, only park users within a 5-m radius of the sensor-loggers were asked to participate to ensure consistent perceived microclimate within the sensor-logger measurements (Chow et al. 2016). A total of 1573 surveys were collected over the eight survey days; after omitting incomplete surveys, we had a quality-controlled dataset of $n = 1508$ to analyse in this study. Table 2 summarises the general demographic profile of the park users whom we surveyed.

Using the same dataset, Chow et al. (2016) examined the physical heat stress of the park users derived from microclimate measurements via WBGT and THI and investigated subjective thermal comfort through (i) sensation and preference votes of temperature, humidity, sunlight, and wind; as well as (ii) overall comfort through acceptability of each microclimate variable. Of particular importance was the significant differences in correlations between acclimatised (residence time of more than 6 months enabling adaptation to Singapore's climate) and non-acclimatised respondent (residence time of less than 6 months) sensations with WBGT. The distinction was a result of the SBG being a popular location for tourists and short-term visitors to Singapore that may not have acclimatised to Singapore's hot and humid environment. In lieu of the distinction, we examined three relevant temperature metrics derived from the relationship between PET and the microclimate perception votes—neutral, acceptable and preferred temperatures, with respect to acclimatised vs. non-acclimatised differences. Due to sample size limitations, we calculated these temperatures by combining all eight fieldwork days in both seasonal periods.

The first metric, neutral temperature, refers to the temperature at which people neither feel cold or warm, but neutral (Nikolopoulou and Lykoudis 2006). Neutral temperature is the PET when mean thermal sensation vote (MTSV) equals to zero. Neutral temperature is ascertained by examining the ordinal regression of the surveyed TSV and the corresponding PET values. The latter is binned into 1 °C intervals, and the corresponding TSV are averaged within each PET bins to get arithmetic MTSV (Middel et al. 2016). Kántor et al. (2016) recommended using median TSV over arithmetic MTSV to minimise the

Table 2 Selected survey results and the demographic profile of survey respondents at SBG. Incomplete answers for the demographic profiles were not included in the summary table, thus responses will not tally with total valid surveys $n = 1508$

Survey respondents' demographics	Number of responses
Age	
18–20	164
21–40	936
41–60	348
> 60	76
Gender	
Female (Male)	764 (760)
Frequency of visits to SBG	
> 2 times a week	102
1–2 times a week	229
1–2 times a month	323
1–2 times a year	488
1st visit	349
Residence time in Singapore	
More than 6 months (less than 6 months)	1196 (326)

influence of potential outliers, but the central tendencies of our mean and median PET data were relatively aligned (33.8 °C and 31.9 °C, respectively); thus both arithmetic mean and median TSV binning were suitable for this analysis. As numerous other studies also used arithmetic MTSV, we also utilised this variable in this paper to facilitate cross-study comparisons.

Second, acceptable temperatures are derived when PET ranges between slight cold and slight thermal stress, i.e. between ± 0.5 MTSV, which corresponds to the three central categories of respondent predicted mean votes encompassing slight cold, neutral and slight heat physiological stresses (e.g. Matzarakis and Mayer 1996; Lin 2009). This resulting range of PET defines conditions in which park visitors will generally feel comfortable with their environment. Third, we examine preferred temperature, which is the 'ideal' PET based on the arithmetic mean preference votes for cooler or warmer temperatures at a given PET (e.g. Spagnolo and de Dear 2003). Usually, this variable is obtained through probit analysis of the binary preference votes (e.g. 'prefer warmer' or 'prefer cooler') with binned PET (e.g. Hirashima et al. 2016) and the intersection of probit curves indicate the preferred temperature.

Results

Neutral and acceptable temperatures

Although neutral temperatures can be estimated by probit analysis of sensation votes (e.g. Spagnolo and de Dear 2003; Kántor et al. 2016), most other studies estimate neutral temperatures from linear regression of MTSV vs. PET (e.g. Lin 2009; Middel et al. 2016; Krüger et al. 2017). For our initial analyses, we adopted a similar method for both acclimatised and non-acclimatised visitors. We plotted linear ordinal regression curves for all, acclimatised, and non-acclimatised respondents, together with the corresponding lower and upper 95% confidence intervals (CI) (Fig. 1). The models for each respondent category were

$$\mathrm{MTSV}_{(\mathrm{all})} = 0.099\ \mathrm{PET}{-}2.645;\ R^2 = 0.68\ (F = 67.0;\ \text{significant at}\ p = 0.05) \quad (1)$$

$$\mathrm{MTSV}_{(\mathrm{acclimatised})} = 0.928\ \mathrm{PET}{-}2.527;\ R^2 = 0.61\ (F = 50.6;\ \text{significant at}\ p = 0.05) \quad (2)$$

$$\mathrm{MTSV}_{(\mathrm{non-acclimatised})} = 0.043\ \mathrm{PET} + 0.142;\ R^2 = 0.35\ (F = 14.83;\ \text{significant at}\ p = 0.05) \quad (3)$$

Based on the different modelled slope/gradients (β) and significant R^2 values, our results indicate clear and significant variations in MTSV between acclimatised and non-acclimatised respondents when visiting urban green spaces. Thermal neutrality for all survey respondents is achieved when PET = 26.6 °C (95% CI = 21.5 °C, 29.5 °C), while acclimatised respondents achieve thermal neutrality at 27.2 °C (95% CI = 21.5 °C, 31.1 °C). In contrast, non-acclimatised respondents failed to achieve thermal neutrality; i.e. the regressed curve does not approach MTSV = 0 with the dataset. This result could be due to the relatively smaller sample size of non-acclimatised (n = 325) vs. acclimatised (n = 1183) survey respondents, but non-achievement of thermal neutrality was also reported in another study based within another hot and humid tropical city (Rio de Janeiro) with a similar methodology (Krüger et al. 2017). The neutral temperatures for all and acclimatised respondents reported here are similar to Singapore's mean monthly air temperatures that vary between 26 and 27 °C.

The significantly higher modelled β for acclimatised vs. non-acclimatised respondents (0.928 and 0.043, respectively) illustrates distinct thermal sensitivities of respondents. The values suggest acclimatised respondents are likely to perceive changes in their thermal sensations with every 1 °C change in PET. This sensitivity could emerge from acclimatised respondents' familiarity with Singapore's tropical climate and with the SBG's microclimate conditions. According to Humphreys et al. (2007), there may also be a tendency for respondents to adjust their TSV to accommodate the sensation scale range (7-point in this case) to the range of prior experienced microclimate conditions. Consequently, acclimatised respondents may be more sensitive to microclimatic changes compared to those accustomed to larger microclimatic variations.

R^2 values for acclimatised and non-acclimatised respondents also differ (0.61 and 0.35, respectively). This suggest that for acclimatised respondents, 61% of the variability in their thermal sensations can be explained by microclimatic and physiological conditions, while only 35% of the variability is explained for the case of non-acclimatised respondents. These values are discordant with findings by Nikolopoulou and Steemers (2003), where environmental conditions can explain ~ 50% of the variance. Differences in the accounted variability between acclimatised and non-acclimatised respondents also suggests that anthropometric factors such as psychology and behaviour (Chen and Ng 2012), may have greater influences on non-acclimatised subjective thermal sensations vs. acclimatised.

The sub-optimal fit of models in Fig. 1 imply that linear regression models may not be the most appropriate approach in estimating neutral temperatures. While standardised residuals for non-acclimatised model were distributed randomly (Fig. 2), residual plots for both (i) all and (ii) acclimatised model are non-random. It may be appropriate to use a linear

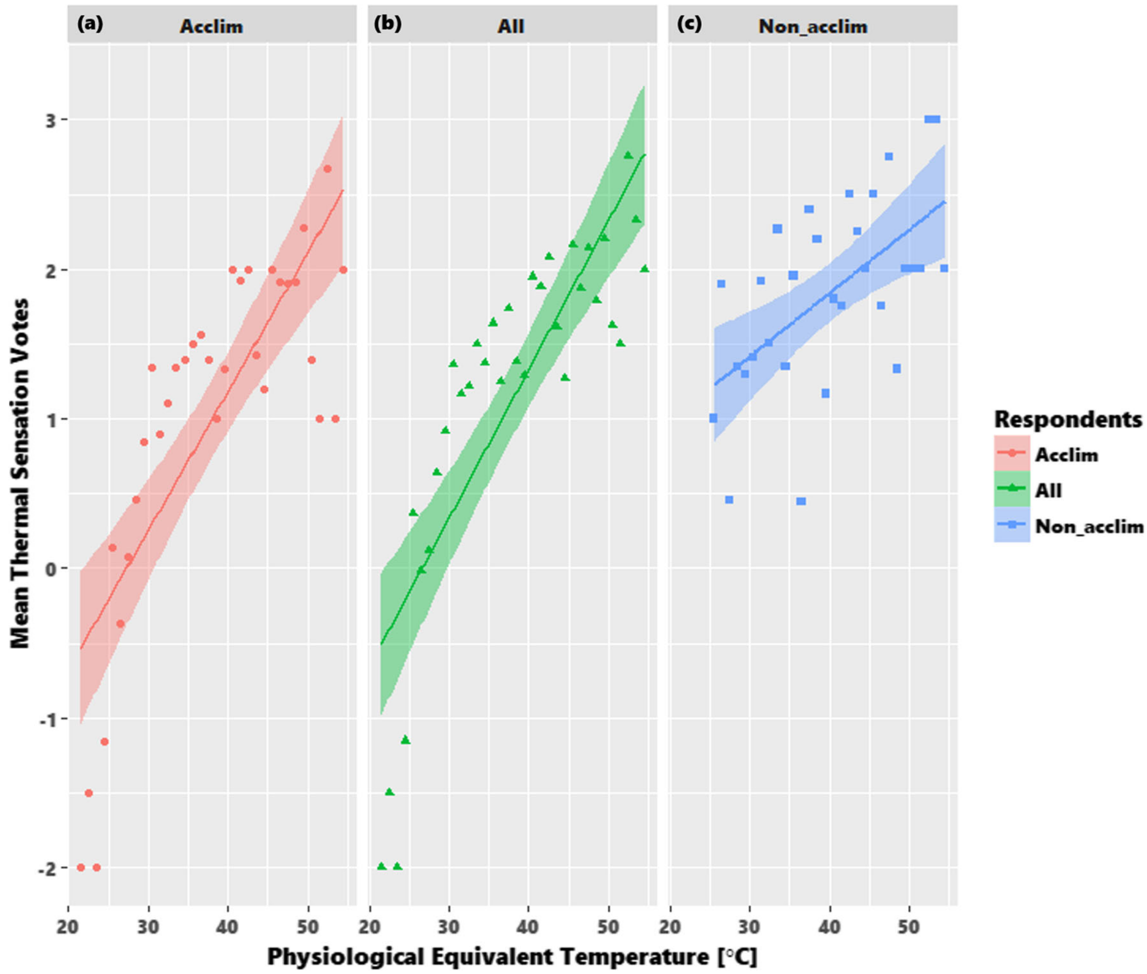

Fig. 1 Ordinal least-squares regression curves (with corresponding 95% confidence intervals) of mean thermal sensation vote (MTSV) vs. PET for **a** acclimatised ($n = 1183$, best fitted model in red); **b** all ($n = 1508$, best fitted model in green) and **c** non-acclimatised ($n = 325$, best fitted model in blue) respondents in SBG database

regression model to estimate neutral temperatures for non-acclimatised respondents, but a revised regression approach for acclimatised respondents for a more robust predictive model could be applied. Kántor et al. (2016) and Hirashima et al. (da Hirashima et al. 2018) noted the ordinal nature of the thermal perception data and suggest using ordinal logistic regression model to analyse relationships between thermal perception and PET. As per Kántor et al. (2016), we found that a more robust fit occurs for both all and acclimatised respondents with the following logarithmic models:

$$\mathrm{MTSV}_{(\mathrm{all\_log})} = 3.81 \times \ln(\mathrm{PET}) - 12.59; R^2 = 0.76 \ (\mathrm{Wald} = 25.94; \text{significant at } p = 0.05) \quad (4)$$

$$\mathrm{MTSV}_{(\mathrm{acclimatised\_log})} = 3.597 \times \ln(\mathrm{PET}) - 11.96; R^2 = 0.70 \ (\mathrm{Wald} = 27.7; \text{significant at } p = 0.05) \quad (5)$$

The resulting neutral temperature when MTSV = 0 slightly increases from models (1) and (2) for both all and acclimatised respondents (Table 3), and there still is substantial overlap in the respective 95% confidence intervals even though the range decreases with the change in model type. R^2 values for all and acclimatised respondents increased by 0.08 and 0.35, respectively. For both respondent groups, at least 70% of the variability in their thermal sensations can be explained by microclimatic and physiological conditions, whilst the remainder are explained by anthropometric factors.

To complement assessment of neutral temperatures, we also examined proportions of (dis)satisfied respondents to SBG's thermal conditions according to the grouping of thermal sensation votes: cold discomfort (MTSV = − 3 and − 2) and heat discomfort (MTSV = + 2 and + 3) for binned PET data at 1 °C intervals were classed as dissatisfied votes. Conversely, binned PET data that corresponded with MTSV ranging from − 1 to + 1 reflects SBG respondents' satisfaction with their experienced thermal conditions. As per Krüger et al. (2017), a polynomial fit curve model was adopted for this analysis of percentage of satisfied/dissatisfied votes. Results indicate that 55.2% of all respondents were dissatisfied with the thermal conditions at the neutral temperature, i.e. when

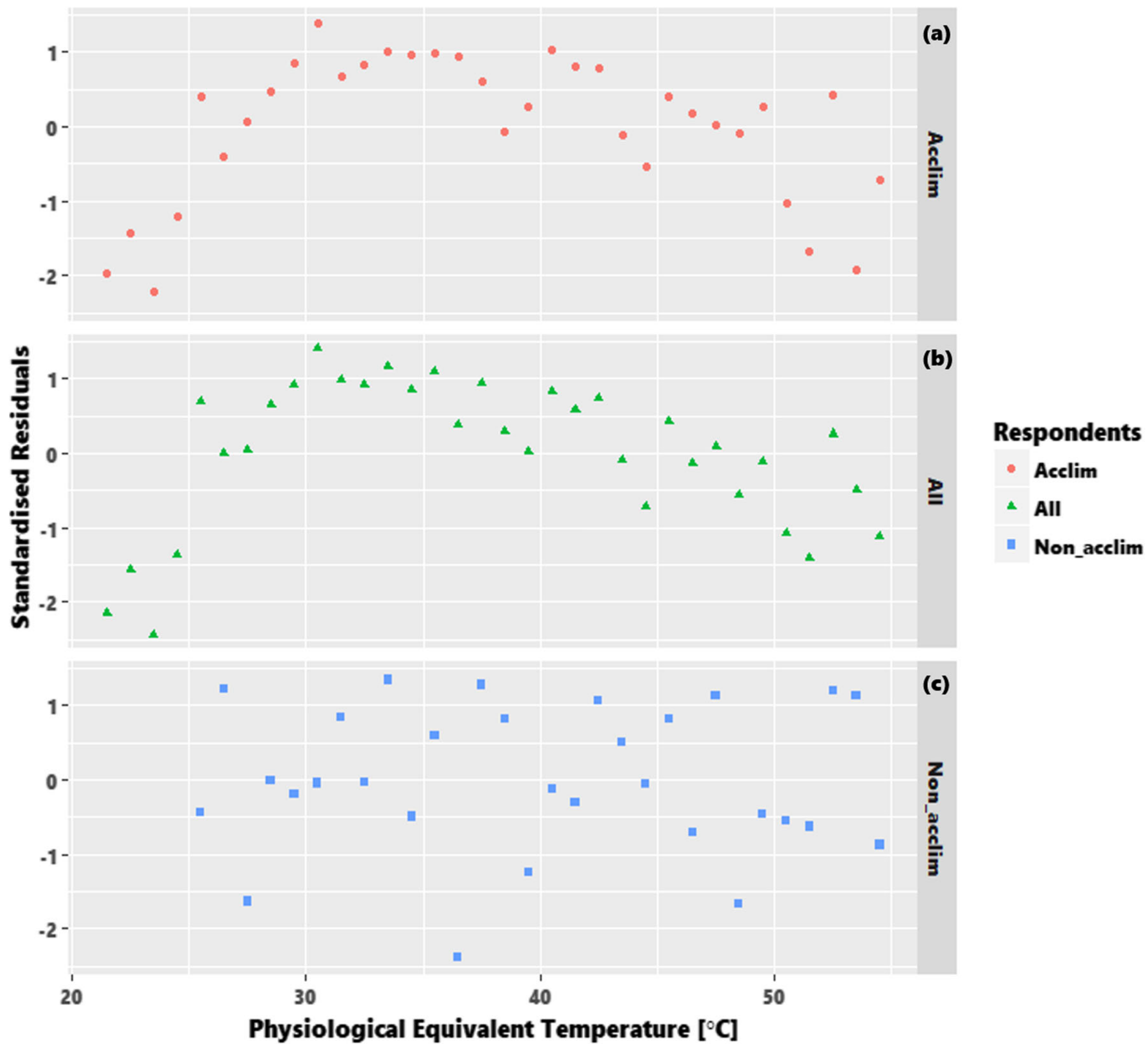

Fig. 2 Standardised residual plots based on linear regressions of **a** acclimatised (red), **b** all (green) and **c** non-acclimatised (blue) respondents at the SBG

MTSV = 0 (Fig. 3). Conversely, the contrasting polynomial plots indicate that 45.1% (52.0%) of acclimatised (non-acclimated) respondents are dissatisfied; further indicating that each group had significant contrasting levels of heat tolerance even at neutral temperatures within an urban park.

To compare our results with other urban OTC studies across different climates categorised by Köppen-Geiger regions, we report both (i) neutral temperatures and (ii) thermal comfort or stress classes (e.g. Spagnolo and De Dear 2003; Lin and Matzarakis 2008; Lin 2009; Yang et al. 2013b; Lai et al. 2014; Middel et al. 2016; Salata et al. 2016; Krüger et al. 2017; Ndetto and Matzarakis 2017) (Table 4). Our neutral temperature results are consistently lower than those found in tropical climates (*A* climate). However, when compared to neutral temperatures calculated in both temperate (*C* climate) and continental (*D* climate) climates, the results are mixed. Our neutral temperature results are lower than that in Changsha (China), Sun Moon Lake (central Taiwan), and in the warm season in Rome, Italy, and Belo Horizonte, Brazil, but higher neutral temperature results occur in other investigations done in *C* and *D* climates. Neutral temperatures in the SBG are also lower than neutral temperatures obtained from

Table 3 Neutral temperatures and respective 95% CI for all and acclimatised respondents. NB: Thermal neutrality for non-acclimatised respondents was unachieved in both models

	Regression fit	All (°C)	Acclimatised (°C)
Neutral temperature	Linear ordinal	26.6	27.2
	Logarithmic	27.3	27.8
Upper and lower bounds of 95% confidence intervals	Linear ordinal	21.5; 29.5	21.5; 31.1
	Logarithmic	24.5; 30.5	24.6; 31.4

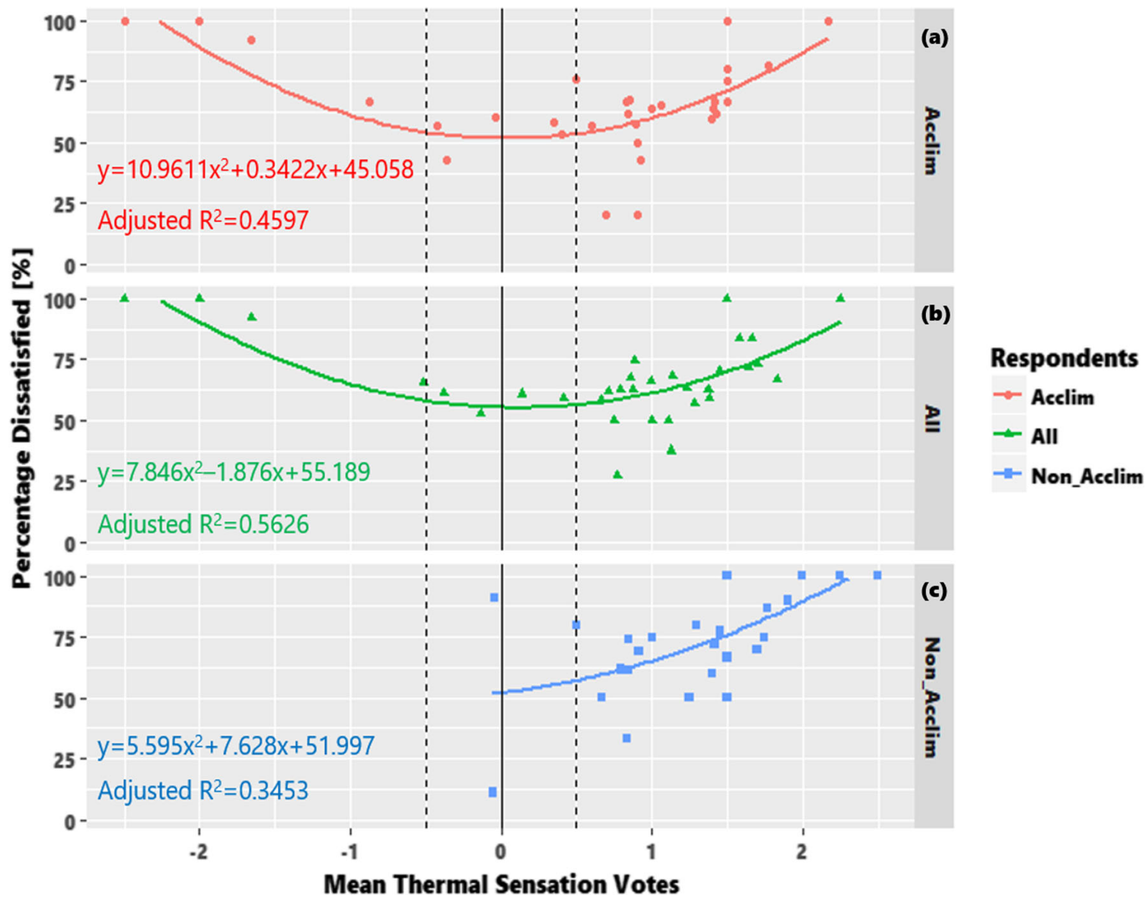

Fig. 3 Percentage of dissatisfied (PD) plots for **a** acclimatised (red), **b** all (green) and **c** non-acclimatised (blue) respondents in SBG plotted against the respective MTSV. Thermal neutrality is experienced when MTSV = 0, and respondents find the ambient temperatures to be acceptable when MTSV ranges from − 0.5 to + 0.5

urban land use within the hot desert city of Tempe (*B* climate). When compared to Yang et al. (2013b), which surveyed respondents over a variety of land uses (i.e. commercial, residential and green space areas) in Singapore, neutral temperatures at the SBG are ~ 1.5 °C lower.

Acceptable temperature based on PET in this study range between 21.6 and 31.6 °C for all respondents. The range of acceptable temperatures (based on ± 0.5 MTSV as applied in the other studies listed) for all respondents in this study is ~ 10 °C, which is larger than most ranges listed in Table 3, with the exception for Tianjin, China (urban park) and Tempe, USA (urban land use). The upper boundary of acceptable thermal comfort conditions in the SBG is similar to other *A* climate cities, and higher than other reported upper bounds except for the cases of Sun Moon Lake and in Tempe. Conversely, the lower bounds of acceptable temperatures are lower than other *A* climate cities, and similar to several *C* climate cities.

Preferred temperatures

While our respondents felt comfortable in a wide range of outdoor thermal conditions in the SBG, these outdoor thermal conditions may not reflect the preferred climatic environment for respondents. Neutral temperatures can be interpreted as thermal conditions where people generally feel comfortable, but preferred temperatures indicate the ideal temperatures that people desire. Using probit analysis (Ballantyne et al. 1977), we estimated preferred temperatures based on sigmoid curves generated via thermal preferences reported by SBG respondents as per the McIntyre scale, i.e. cooler (− 1), no change (0) and warmer (+ 1). The responses were divided into binary groups preferring warmer or cooler conditions. As per Middel et al. (2016), respondents preferring neutral conditions were split randomly between each binary group so that probabilities in each PET bin cumulatively sum up to 100%, and each transition curve intersects at 50% level of probability. For each reported PET interval, we calculated the percent responses in both preference groups and fitted separate probit curves to the data. With other studies adopting this approach, we can ascertain that the intersection of probit curves is the estimated preferred temperature (e.g., Spagnolo and de Dear 2003; Lin 2009; Yahia and Johansson 2013; Hirashima et al. 2016; Kántor et al. 2016; Salata et al. 2016).

Table 4 Summary of calibrated PET and neutral temperatures (in bold) reported from other climatic regions ordered by descending Köppen-Geiger classification. Data reported from urban-only sites are shaded grey, data from urban park spaces are shaded green and data from a combination of urban and park spaces are unshaded. Neutral temperatures were obtained by linear regression except for Rome, Italy, and Sydney, Australia, in which probit analysis was applied

City (*Köppen - Geiger classification*)	**Strong cold (°C)**	**Moderate cold (°C)**	**Slight cold (°C)**	**No stress/ Neutral T (season) (°C)**	**Slight heat (°C)**	**Moderate heat (°C)**	**Strong heat (°C)**
Tianjin, China (*Dfa*)[a]	<-11	-6	11	**15.6** (when air temperature > 0 °C)	24	31	36
Rome, Italy (*Csa*)[b]		5	21	**26.9** (summer) **24.9** (winter)	29	37	45
Central Europe (*Cfb*)[c]	< 8	13	18	**NA***	23	29	>35
Glasgow, UK (*Cfb*)[d]		1	10	**14.2**	18	27	
Curitiba, Brazil (*Cfb*)[d]			13	**19.2**	25	37	
Sydney, Australia (*Cfa*)[e]				**24**			
Belo Horizonte, Brazil (*Cwb*)[f]			19	**27.7** (summer) **15.9** (winter)	27		
Sun Moon Lake, Taiwan (*Cwb*)[g]	14	18	22	**27.2**	34	38	42
Taichung City, Taiwan (*Cwa*)[h]			21	**25.6** (summer) **23.7** (winter)	29		
Changsha, China (*Cfa*)[i]			24	**27.9**	31	35	39
Tempe, USA (*Bwh*)[j]			19	**28.6**	38		
Rio de Janeiro, Brazil (*Aw*)[d]				**NA***	22	36	49
Dar Es Salaam, Tanzania (*Aw*)[k]		15	23	**27.2**	31	40	48
Guayaquil, Ecuador (*Aw*)[l]				**26.9** (dry) **21.9** (wet) **25.7** (both)	31.3		
Singapore, Singapore (*Af*)[i]			24	**28.1**	30	34	38
This study			*21.6*	***26.6***	*31.6*		

NA neutral temperature not reported in the study

[a] Lai et al. 2014

[b] Salata et al. 2016

Matzarakis and Mayer 1996

[d] Krüger et al. 2017

Spagnolo and de Dear 2003

Hirashima et al. 2016

Lin and Matzarakis 2008

[h] Lin 2009

[i] Yang et al. 2013b

[j] Middel et al. 2016

Ndetto and Matzarakis 2017

[l] Johansson et al. 2018

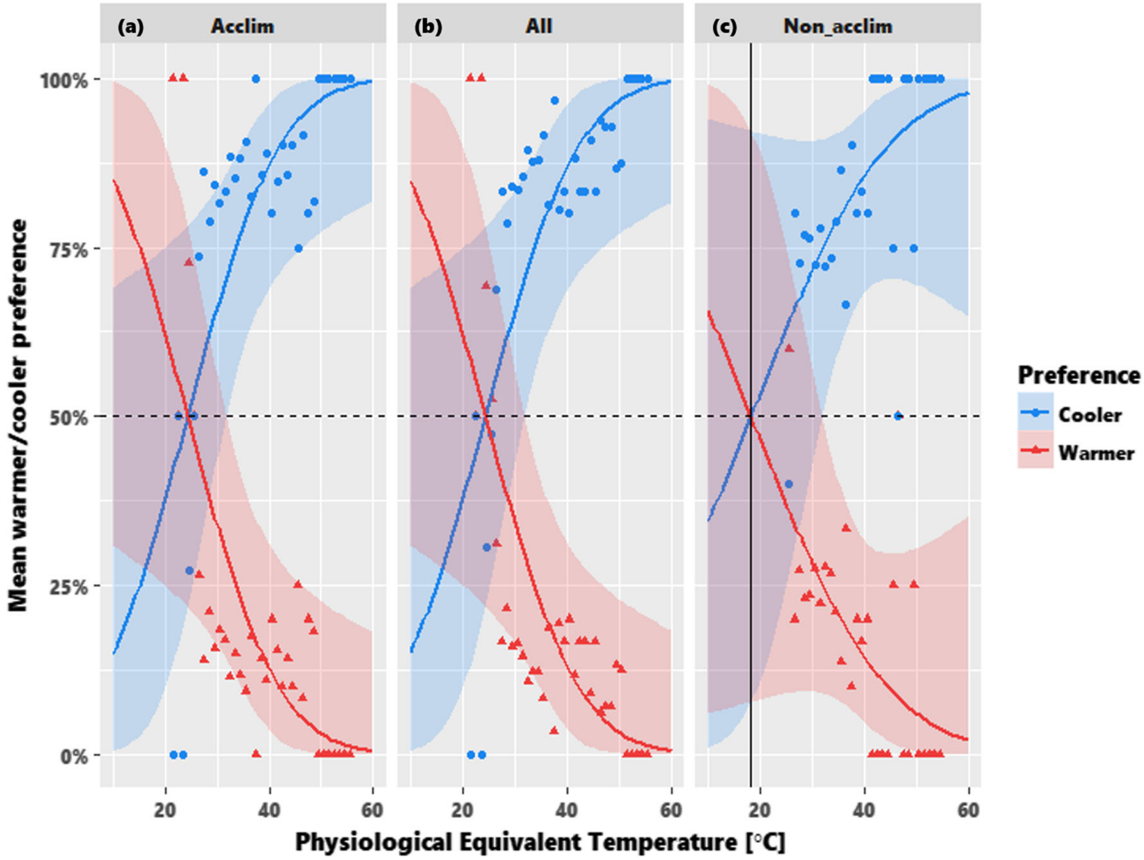

Fig. 4 Probit analysis plots indicating preferred temperatures and respective 95% CIs for **a** acclimatised, **b** all and **c** non-acclimatised respondents. The sigmoid curves in this graph have been predicted beyond the actual collected data to reveal the intersection between the preference for warmer and cooler temperatures and the consequent PET that is preferred by the respondents. This explains the greater CI range as PET decreases, as fewer low PET data points were measured in the SBG

We obtained preferred temperatures in the SBG for all, acclimatised and non-acclimatised respondents (Fig. 4). For all respondents, the preferred SBG temperature is 24.2 °C and significant variations are apparent in preferred temperatures between acclimatised (also 24.2 °C) vs. non-acclimatised (18.0 °C). This comparative result between survey respondents exposed to similar thermal conditions likely demonstrates the influence of expectations on respondent thermal comfort, with short-term visitors from other climate cities (*B–D*) to Singapore expecting cooler conditions in the urban park despite the warm ambient climatic environment. These preferred temperatures in the SBG are lower than reported in both green and urban spaces in Singapore by Yang et al. (2013b), who obtained a value of 25.2 °C via a similar probit sigmoid curve method. Lastly, when compared with reported results from other cities, preferred temperatures for all and acclimatised respondents is comparable to conditions in Taichung, Taiwan (summer 24.5 °C; winter 23.0 °C) (Lin 2009); Rome, Italy (summer 24.8 °c; winter 22.5 °C) (Salata et al. 2016) and Sydney, Australia (all-year 25.0 °C) (Spagnolo and De Dear 2003). However, preferred temperatures in the SBG are warmer than Tempe, USA (all-year 20.8 °C) (Middel et al. 2016); Guayaquil, Ecuador (wet season 18.6 °C; dry season 15.5 °C) (Johansson et al. 2018) and in Belo Horizonte, Brazil (summer 20.9 °C; winter 14.9 °C) (Hirashima et al. 2016).

Discussion

The significant differences in neutral, acceptable and preferred temperatures between acclimatised and non-acclimatised respondents in our study relates to how each group adapts to Singapore's warm and humid climate. As seen in Lin (2009) and Johansson et al. (2018), respondents who spent significant amount of time exposed to local climate (> 6 months in this study) are very likely to be thermally adapted to the SBG's warm and humid environment. Notably, the temperature at which acclimatised respondents achieve thermal neutrality (27.2 °C) approximates to the typical mean monthly air temperatures observed in Singapore. Variations in acclimatisation are also seen in significantly different model β between acclimatised and non-acclimatised regressions (Figs. 1 and 2). It is highly likely that, during their stay in Singapore, acclimatised respondents successfully adapt and modify a combination of physiological (e.g. lower body core temperatures, heart rates and higher sweat rates in acclimatising to heat); behavioural (e.g. altering clothing coverage or type, and changing diet and/or movement patterns to lower heat exposure) and/or psychological (e.g. perceived short-term thermal history towards extremes of heat and cold) circumstances to attain thermal neutrality (e.g. Chen and Ng 2012; da Hirashima et al. 2018).

Although acclimatised respondents have a higher neutral temperature threshold than those non-acclimatised, there is still a high degree of dissatisfaction (~ 50% of respondents) amongst the park users towards their overall thermal comfort in the SBG (Fig. 3). A possible explanation would be visitors to the SBG perceive that sources of thermal discomfort can be controlled easily by personal action, e.g. wide variations in the SBG's vegetation shade cover over short distances means that respondents can readily move to shadier locations if they are exposed to the sun. Nikolopoulou and Steemers (2003) argued that freedom of choice in movement is critical in outdoor spaces, where actual control over microclimates is minimal. Thus, perceived control has the biggest influence in thermal satisfaction, and would theoretically enhance park visitors' tolerance for high temperatures due to changes in their thermal expectations (Rutty and Scott 2015).

Non-acclimatised (18.0 °C) and all/acclimatised preferred temperatures (24.2 °C) are considerably lower than neutral temperatures for all (27.3 °C) and acclimatised (27.8 °C) respondents in the SBG. This difference is similarly observed in several other studies examining PET in warm climates (Lin 2009; Lin et al. 2011; Yang et al. 2013b). As explained by Johansson et al. (2018), the desire towards cooler conditions in warm climates has a psychological component referred to as *alliesthesia*, which is the perception of an external stimulus as pleasant or unpleasant depending on internal stimuli, or its potential to restore the body to a 'normal' thermal state (Cabanac 1971; Parkinson et al. 2012). If an individual feels too hot, a change in conditions cooling him or her down immediately will feel pleasant, even if this stimulus results in cold perceptions over prolonged time periods (Spagnolo and de Dear 2003; de Dear 2011). Respondents in this study desire for cooler environments, as previous OTC research in SBG (Chow et al. 2016) examining the same respondents revealed that 65.7% of all respondents perceived slight to hot thermal discomfort, with 67.3% also voting for cooler preference. Alliesthesia may also be complemented by an individual's perceived desire for a dynamic change to 'cool' conditions from a static 'warm' environment that emerges from the low-wind conditions experienced (Nikolopoulou 2011); in other words, 'a person being in a thermal state above thermal neutrality would perceive a cold stimulus—leading towards thermal neutrality as pleasant' (Schweiker et al. 2018:20). Detailed investigation into the strength of these adaptation factors related to both neutral and preferred temperatures should involve more qualitative methodologies (e.g. through interviews or focus group discussions) to complement commonly used survey questionnaires in thermal comfort fieldwork.

A judicious understanding and application of the preferred temperatures derived from this study is needed, especially in relation to improving local OTC by reducing PET. This is because the preferred temperature results are predicted by extending the probit relationship between the preference for warmer and cooler PET, rather than being calculated off actual data points. As low PET is less observed within the SBG, the uncertainties in the preferences for warmer or cooler thermal conditions increases with lower PET conditions. Specifically, the uncertainty affects the understanding of preferred temperatures for non-acclimatised respondents more than the acclimatised, as the former are more likely to prefer cooler than warmer conditions in the humid tropical climate where PET is consistently higher than the climate that they are acclimatised to.

The beneficial role of urban greenery in UHI mitigation is unequivocal, with lower park air temperatures relative to their more built-up, urban areas being well documented (e.g. Bowler et al. 2010). Consequently, it is expected that OTC is better achieved in urban parks than in more built-up urban areas. It is thus interesting to note the lower neutral and preferred temperatures in this urban park-only study vs. sampling over different Singapore land use types as per Yang et al. (2013b) for all respondents. Specifically, neutral and preferred temperatures for all respondents for this urban park-only study are 0.8 °C and 1.0 °C lower vs. in Yang et al. (2013b), respectively. Similarly, neutral and preferred temperatures for acclimatised respondents (27.8 °C and 24.2 °C, respectively) in our urban park-only study are also lower than those modelled over different Singapore land use types (28.1 °C and 25.2 °C, respectively). While part of this reduction can arise from lower urban park temperatures in the SBG, which likely translates to lower PET relative to more 'urban' areas, there remains the possibility of survey respondents having different expectations of thermal comfort in park locations vs. urban areas dominated by 'non-natural' surfaces like concrete and asphalt. This psychological change in environmental attitude has been observed in urban parks by Knez and Thorsson (2006), in which an individual may perceive a more positive, i.e. cooler condition in a place deemed to be more pleasant. If discerned properly, this psychological aspect can enhance perceived OTC in urban parks and provide an important cultural ecosystem service along with other regulatory and provisioning services implicit in these green spaces. Therefore, survey questions and qualitative approaches delving into contrasts in thermal expectations between urban green spaces and urban areas should be considered to validate the possible influence this psychological aspect of environmental attitudes have in enhancing OTC.

The similarity in magnitudes of preferred PET in Singapore from both this study (24.2 °C) and Yang et al. (2013b) (25.2 °C) is interesting in the context of local acclimatisation to outdoor and indoor climates. In Singapore, air-conditioning use (AC) for climate control is ubiquitous across all urban sectors; for instance, 76% of all residential households in 2014 have AC units installed (Department of Statistics Singapore 2014). Typically, AC usage is high in these residential areas, typically from 9 to 11 p.m. until 6–8 a.m. in the following morning (Chua and Chou 2010). Apart from adults who are commonly exposed to AC in office and commuting settings on a daily basis, AC exposure is elevated amongst non-adults; Happle et al. (2017) noted that average exposure to AC of Singaporean students was 6.2 h per day. In Singapore, one of the suggested practice codes for indoor thermal environment in buildings is to set dry-bulb temperatures between 23 and 25 °C (Singapore Standards Council 2016). We consider that the possibility of familiarity to this indoor AC temperature range exists in influencing the psychology of acclimatised environmental attitudes and potentially leading to the similarity in outdoor preferred temperatures by acclimatised respondents. We obtained respondent data on thermal history, but initial analysis reveals no notable influence given the wide variety of outdoor (shade) and indoor environments surrounding the SBG study site. As such, these results were not reported in this study but will be further examined in subsequent studies based on this dataset.

Comparisons of neutral and acceptable temperatures derived from PET calibration in the SBG with information reported from other studies over a variety of synoptic climates per Köppen-Geiger classification indicate the important influence larger-scale climates have on the magnitude of these thermal comfort indices (Table 4). While there may be commonalities in that warmer *A* and *B* climates generally have higher neutral and acceptable PET ranges vs. studies conducted in cooler *C* and *D* climates, the variations listed indicate the need for local assessments of PET ranges. Accurate neutral and acceptable temperatures can be obtained in lieu of using a 'standard' calibration range of PET (e.g. da Hirashima et al. 2018), if consistency in local environmental conditions (e.g. data obtained from similar urban land use) affecting measured microclimate is kept.

The development of a local OTC threshold through the calibration of PET against thermal sensation, acceptance and preference votes facilitates better understanding of OTC across different climates and geographical context. However, PET calibration against subjective thermal votes should not be the only approach towards understanding OTC; other microclimate data should also be collected to inform the researchers of their composite effects on local OTC. Relative humidity, wind and solar radiation are key OTC microclimate parameters, especially in the context of regulating the microscale climate in urban green spaces. This is because urban greenery enhances thermal comfort via the regulation of these microclimate parameters through shading from direct solar radiation (Middel et al. 2016), lower air temperatures from increased latent heat over sensible heat fluxes (Spronken-Smith et al. 2000; Chow and Brazel 2012); and modifying wind flow via its vegetation configurations (Lai et al. 2014). Further, should respondents be capable of discerning and isolating thermal, humidity, wind and sun sensations from each other, the role of each microclimate parameter in enhancing OTC will provide greater insights to urban greenery management. Results from this study are in the context of a large urban park in the tropical climate, and this park is largely heterogeneous in terms of its land use, land cover and in its horizontal and vertical greenery profile. This limits our results towards other urban green spaces that may be smaller, more scattered and more homogenous in their site characteristics.

Summary and Conclusion

In this study, we analyse an OTC dataset in a large Singapore urban park to estimate the ranges of perceived (i) neutral, (ii) acceptable, and (iii) preferred temperatures respondents felt was 'comfortable.' The findings enhance the results of a previous study (Chow et al. 2016), which was based on this same dataset but did not examine aspects of rational heat based on the PET index. We estimate that neutral temperatures for all surveyed respondents was 26.2 °C, acceptable temperatures range between 21.6 and 31.6 °C, and preferred temperatures are 24.2 °C ($n = 1508$). When compared to other reported and calibrated PET data from OTC studies, our results show that differences in synoptic climate in which a city is located in (as per Köppen-Geiger classes) is linked to differences in the magnitude and ranges of these temperatures. We also discern significant differences in perceptions of OTC between acclimatised vs. non-acclimatised respondents in our study; generally, respondents who have been exposed for a longer duration to Singapore's warm and humid climate have clear and elevated levels of thermal neutrality based on higher neutral, acceptable, and preferred temperatures compared to either all, or non-acclimatised respondents. These differences could indicate a greater degree of thermal adaptation through a combination of physiological, behavioural, and psychological factors that are likely developed during the acclimatisation process. Lastly, our park-only respondents perceive notably lower neutral and preferred temperatures when compared to another Singapore PET-referenced OTC study that surveyed people over a variety of urban land use categories (Yang et al. 2013a). Apart from lower measured ambient temperatures in park spaces relative to their urban surroundings, this difference could also stem from environmental attitudes of how urban vs. park spaces are culturally regarded that potentially influences perceived OTC in respondents.

The results from this study add to the growing body of urban OTC research in tropical/warm climates; a research field within urban climatology that is understudied relative to other aspects, e.g. UHI and air pollution research. Given the conclusions listed from this database, we suggest that future warm climate OTC research can build on these results and investigate, for example, how different configurations of vegetation within park spaces can influence observed and perceived OTC; evaluate factors influencing thermal adaptation through more qualitative methodologies (e.g. those reviewed by Lenzholzer et al. 2018), and discern the influence of air-conditioning exposure towards thermal neutrality of individuals.

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