



Short-term changes in thermal perception associated with heatwave conditions in Melbourne, Australia

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Abstract

Variations in human thermal perception have been described on timescales from minutes to seasons. However, the effect of weather-related thermal extremes on inter-daily changes to outdoor thermal perception has not been well characterised. This study used human thermal comfort data from an outdoor botanic garden in sub-urban Melbourne, Australia as a case study. We examined inter-daily variations in local visitors' thermal perception before (11–12 January 2014) and after (18–19 January 2014) a severe heatwave from 14 to 17 January 2014, when daily maximum temperature exceeded 41 °C for 4 consecutive days. We compared thermal comfort survey results (pre-heatwave: $n = 342$, post-heatwave: $n = 294$) with air temperature and the Universal Thermal Climate Index (UTCI) measurements. Even though the days preceding and following the heatwave had a similar range in temperature (19–25 °C) and UTCI (26–32 °C), the visitors felt cooler in the days following the heatwave (i.e. lower thermal sensation votes). In the 2 days following the heatwave, visitors also wore less clothing compared with before the heatwave. Our results show that the thermal perception of visitors changed significantly following their exposure to the heatwave, even after controlling for changes in clothing choices and the ages of survey participants. Psychological adaptation to heat (such as thermal history and expectation) might be one of the possible explanations for this inter-daily variability of local visitors' thermal perception.

1 Introduction

Climate change is associated with an increase in the frequency and intensity of heatwaves (Sheridan and Allen 2015). One key adaptation strategy for improving heat-health outcomes is heat acclimatisation (Hanna and Tait 2015). Past studies have shown that people's thermal perception can change from minutes (Ji et al. 2017), within a day (Becker et al. 2003) to across seasons (Kántor et al. 2016; Nikolopoulou and Lykoudis 2006). However, the changes in thermal perception at the inter-daily timescale are not well-understood, and this study addresses this gap in the literature.

According to the adaptive model of thermal comfort (de Dear and Brager 1998), people develop physiological (Périard et al. 2015), psychological (Nikolopoulou and Steemers 2003), and behavioural adaptations (Morgan and de Dear 2003) to alleviate thermal discomfort. Although theories such as the expectation hypothesis (Halawa and van Hoof 2012) and thermal history (Nikolopoulou et al. 2001) have been proposed to explain changes in thermal perception, few outdoor studies have supported those theories. Additionally, thermal indices such as the Universal Thermal Climate Index (UTCI) have yet to incorporate psychological adaptation to heat in their design (Bröde et al. 2012). Considering the synergistic feedback effect of behavioural adjustment and psychological adaptation, an indoor study in China suggested that occupants typically took 4.25 days to completely adapt to a step-change in outdoor temperature (Liu et al. 2014). However, it is problematic to untangle the associated psychological and physiological contributions to thermal perception, as the timescales of psychological adaptation to heat are uncertain (de Dear et al. 1997; Luo et al. 2016).

Previously, Lam et al. (2018b) discovered that there was a cultural difference in thermal perception and

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clothing choices between visitors from different countries of origin in summer. This result could be due to the differences in thermal history and expectation, as well as a lack of adaptation of overseas visitors, who travelled from a Northern Hemisphere winter to a Southern Hemisphere summer. Lam et al. (2018a) compared the thermal sensation votes (TSVs) of visitors who experienced heatwave conditions with those visitors under non-heatwave conditions. They suggested that thermal expectation might explain the higher TSVs under heatwave conditions over a similar UTCI range at different locations (Lam et al. 2018a). However, Lam et al. (2018a,b) did not investigate short-term acclimatisation and the TSVs of visitors right before and after a heatwave. This study is different from Lam et al. (2018a,b), because the main point of this study is about short-term acclimatisation.

In view of the findings of Lam et al. (2018a,b), this study aims to examine the short-term changes in local visitors' thermal perception before and after a heatwave. In theory, when visitors of similar demography encounter non-heatwave conditions over similar UTCI ranges, their TSVs should be similar. However, this assumption might not always be true. This study tests this assumption by analysing meteorological and survey data before and after the January 2014 heatwave in a botanic garden near Melbourne, Australia, in order to provide evidence for people's adaptation to extreme heat at the inter-daily timescale. It is beneficial to examine the timescale of thermal perceptions during extreme heat events, because this information indicates how quickly people adapt to such conditions, including associated behavioural adaptation such as changes in clothing. Clarifying the timescale of heat adaptation is also beneficial for public health (Bi et al. 2011) and urban planning (Nikolopoulou and Steemers 2003).

2 Materials and methods

The study was conducted in the Royal Botanic Garden, Cranbourne (RBGC), which is located 45 km southeast of Melbourne, Australia (38° 7' S 145° 16' E) (Fig. 1). Melbourne has a temperate oceanic climate (Köppen climate classification Cfb), which is characterised by fluctuating weather conditions (Sturman and Tapper 2006). The Melbourne region experiences occasional extreme hot spells during the summer months (December–February) associated with persistent incursions of hot, dry continental air. The study period spanned 11–19 January 2014. Surveys were deployed to determine the thermal perception of visitors, and meteorological measurement sites were established for comparison with these surveys.

2.1 Meteorological measurements and calculation of thermal indices

Three automatic weather stations were established in the RBGC (see Fig. 1 for specific locations). We used a Campbell Scientific weather station (CR211X data logger) at the Visitor Centre. Specifically, air temperature and relative humidity were measured using Vaisala HMP155 Probe. Wind speed was measured using Met One 014A-L anemometers. We measured globe temperature using a globe thermometer consisting of a thermocouple (Omega 44031 precision thermistors), which was held at the middle of a 150-mm diameter black copper ball. It was not possible to set up Campbell Scientific weather stations at the Rockpool Waterway and Promenade due to logistics. Instead, we used a Kestrel Heat Stress Tracker 4400 (with a 25-mm black copper ball) to measure the above four climate variables at the Rockpool Waterway and Promenade. All instruments measured the climate variables at 10-min intervals at a height of approximately 1.3 m above ground. Campbell Scientific and Kestrel weather stations were calibrated in laboratory settings to ensure there were no significant differences in measured temperature and relative humidity.

We used Eq. (1) to calculate the mean radiant temperature (T_{mrt}) (ASHRAE 2001; Thorsson et al. 2007):

$$T_{\text{mrt}} = \left[(T_g + 273.15)^4 + \frac{h_{\text{cg}}}{\varepsilon D^{0.4}} \times (T_g - T_a) \right]^{1/4} - 273.15 \quad (1)$$

where T_g is the globe temperature (°C), T_a is the air temperature (°C), v is the wind speed (m/s), h_{cg} is the globe's mean convective coefficient ($1.1 \times 10^8 v^{0.6}$), D is the globe diameter (m), and ε is the globe emissivity (0.95 for black globe).

We acknowledge that there are some limitations of using the black globe to calculate the T_{mrt} . The black colour of the globe overestimates the absorption of short-wave radiation, and it takes about 15 minutes to reach equilibrium for the standard black globe (Kántor et al. 2015). Sometimes, this equilibrium is not reached as wind speed can fluctuate rapidly (Kántor et al. 2015). To address this issue, black globe temperature data were averaged into 10-min intervals to reduce the black globe's sensitivity to wind variations (Johansson et al. 2014).

In Melbourne, Coutts et al. (2016) did a calibration of the T_{mrt} of the 150-mm black globe against integral radiation measurements (CNR1, Kipp and Zonen). Coutts et al. (2016) adjusted h_{cg} to $0.65 \times 10^8 v^{0.53}$ to account for the overestimation of 150-mm black globe thermometer's T_{mrt} . Our Melbourne study used the same black globe thermometer as Coutts et al. (2016). Therefore, we also changed h_{cg} to $0.65 \times 10^8 v^{0.53}$ in Eq. (1) to calculate the T_{mrt} of our 150-mm black globe thermometers. In addition, we undertook a calibration of the T_{mrt} of Kestrel weather station's 25-mm black globe against the T_{mrt} of our 150-mm black globe in a street. The



Fig. 1 The Melbourne region (top) and the locations of weather stations and survey sites in the Royal Botanic Garden Cranbourne (RBGC) (Nearmap, January 2014)

T_{mrt} of Kestrel weather station's 25-mm black globe was overestimated compared with the 150-mm black globe's T_{mrt} calculation. After conducting a linear regression between the T_{mrt} calculated from the 150- and 25-mm black globe, we used Eq. (2) to correct the T_{mrt} of Kestrel weather station's 25-mm black globe ($T_{mrt25mm}$).

$$T_{mrt25mm} = 0.8052 \times T_{mrt150mm} + 4.0038 \quad (2)$$

where $T_{mrt150mm}$ is the mean radiant temperature ($^{\circ}\text{C}$) calculated from the 150-mm black globe, using the mean convective coefficient suggested by Coutts et al. (2016) (i.e. $0.65 \times 10^8 v^{0.53}$).

We used the UTCI as the thermal index in this study (ISB Commission 6 2014; Jendritzky et al. 2012). UTCI refers to "an equivalent ambient temperature ($^{\circ}\text{C}$) of a reference environment providing the same physiological response of a reference person as the actual environment" (Blazejczyk et al.

2012: 521). UTCI reflects thermal stress levels by combining a thermo-physiological model, clothing model, and meteorological factors (air temperature, wind, radiation, and humidity) (Gosling et al. 2014). Moreover, UTCI is calculated based on a standard environment with fixed parameters in meteorological factors, clothing, and activity levels (Bröde et al. 2012). The UTCI categories correspond to different levels of physiological responses in that standard environment (Błażejczyk et al. 2010). In particular, the UTCI ranges from no thermal stress (+9 to +26 °C), moderate heat stress (+26 to +32 °C), strong heat stress (+32 to +38 °C), very strong heat stress (+38 to +46 °C), to extreme heat stress (> 46 °C) (Bröde et al. 2012).

We calculated the UTCI using RayMan Pro 2.1 (Matzarakis et al. 2010). To calculate the UTCI, we input air temperature, relative humidity, wind speed at 10 m above ground, as well as mean radiant temperature (T_{mrt}), which was derived from globe temperature. We chose Promenade for the UTCI analysis instead of Rockpool Waterway and Visitor Centre. This is because Promenade was an open site with no shade, which eliminated shading as a confounding factor for thermal comfort (Coutts et al. 2016; Toy and Yilmaz 2010).

We used Eq. (3) to convert our 1.3-m wind speed (v) to 10 m above ground, which was required for calculating UTCI (Bröde et al. 2012).

$$v_{10m} = v_{xm} \times \frac{\log\left(\frac{10}{0.01}\right)}{\log\left(\frac{x}{0.01}\right)} \quad (3)$$

where x is the height of the weather station (i.e. 1.3 m in our study).

2.2 Thermal comfort surveys

We surveyed local Melbourne visitors about their thermal comfort between 10 am and 3 pm each day from 11 to 19 January 2014. This study focused on analysing the pre-heatwave (11–12 January 2014, $n = 342$) and post-heatwave days (18–19 January 2014, $n = 294$). We did not examine the survey data during the heatwave period (14–17 January 2014), because that topic was discussed in Lam et al. (2018a). Survey entries without gender or age information were excluded in the analysis. In addition, we also excluded visitors from other states in Australia and overseas visitors, because their lack of acclimatisation to Melbourne weather might confound the analysis. A group of volunteers was recruited to conduct surveys with visitors over 18 years old about their thermal comfort. We obtained information about the visitors' demographic background, the perception and preference of current thermal and shading conditions, clothing, as well as activity and exposure prior to the survey (details of the survey can be found

in Lam et al. 2018b). The survey examined visitors' thermal perceptions indicated by the TSV and their clothing insulation (clo). The TSV was represented in a seven-point scale, ranging from hot (+3) to cold (−3), with 0 being neutral (ASHRAE 2010). To obtain visitors' TSV, we asked them the question "please circle how you feel now" from the 7-point scale. The thermal insulation of clothing is represented by a unit called clo, and one clo is equal to 0.155 m² K/W (ISO 2005; Schiavon and Lee 2013). Table 1 shows the clothing combination worn by the survey respondents, and it is divided into 0.1 clo bins for our analysis. We examined changes in clo to identify changes in visitors' clothing choices after the heatwave.

2.3 Statistical analysis

An independent-samples t test compared the statistical significance of the differences in local visitors' TSV before and after the heatwave, using a threshold of $p < 0.05$. To examine which air temperature and UTCI range recorded differences in TSV, we used 1 °C temperature and 3 °C UTCI bins in the analysis (Table 2). We stratified temperature and UTCI into different bins, so the sample size in each bin would be large enough for pre- and post-heatwave comparison ($n > 20$ for air temperature analysis and $n > 10$ for UTCI analysis in each bin, respectively). We did not use 1 °C bins for UTCI because the sample size became too small in each bin. In addition, we excluded 17–18 °C (air temperature) from the t test analysis, because no survey was conducted at those temperature ranges after the heatwave.

There are potential confounding factors affecting the changes in TSV post-heatwave, namely an increase in elderly respondents (age 65+) and difference in clothing choices after the heatwave. The elderly are generally more sensitive to heat, because their thermoregulation is often poorer (Blatteis 2012). We conducted an independent samples t test without the 65+ age group, in order to control for the increase in elderly respondents after the heatwave. To test for clothing choices confounding the analysis, we selected the two clo bins (0.3–

Table 1 Examples of clothing choice for each clo bin. clo values are derived from Olesen and Dukes-Dubos (1988)

clo	Examples of clothing choice
0.2–0.3	Singlet top, shorts, thongs
0.3–0.4	T-shirt, shorts, thongs or shoes
0.4–0.5	T-shirt, shorts or jeans, shoes
0.5–0.6	T-shirt or long sleeved shirt, jeans, shoes
0.6–0.7	Long sleeved shirt, jeans, shoes
0.7–0.8	Jacket, T-shirt or long sleeved shirt, jeans, shoes
0.8–0.9	Jumper or jacket, long sleeved shirt, jeans, shoes

Table 2 Air temperature (all sites) and UTCI bin (Promenade at RBGC) for analysing the TSV difference before and after the heatwave (respective survey sample size shown in each bin)

Air temperature (°C)	Pre-heatwave <i>n</i>	Post-heatwave <i>n</i>	UTCI (°C)	Pre-heatwave <i>n</i>	Post-heatwave <i>n</i>
17–18	45	0	24–27	13	0
18–19	41	8	27–30	7	8
19–20	75	21	30–33	11	35
20–21	50	63	33–36	38	95
21–22	66	102	36–39	27	23
22–23	37	74			
23–24	23	21			
24–25	5	5			

0.4 and 0.4–0.5, corresponding to T-shirt and shorts or jeans) for a separate analysis. These clo bins represented more than 55% of survey respondents both before and after the heatwave. In other words, these two clo bins reflected respondents who were dressed appropriately for the Melbourne summer weather conditions. Therefore, we conducted an independent samples *t* test for these clo bins only (0.3–0.4 and 0.4–0.5), in order to assess whether there may be a difference in TSV before and after the heatwave beyond clothing choices. We also conducted an independent samples *t* test for respondents with different activities and exposure (i.e. previous thermal environment) for the previous 10 min before the survey.

3 Results

3.1 Meteorological conditions

The days preceding and following the January 2014 heatwave had similar meteorological conditions (Table 3). Rainfall was mostly absent during this period except for 17 January (1.2 mm), and the skies were mostly cloudless on all days.

Table 3 Meteorological conditions during the days of conducting surveys (10 am to 3 pm) at RBGC Visitor Centre

Date (2014)	Air temperature (°C)		Relative humidity (%)		Wind speed (m/s)		T_{mrt} (°C)		UTCI (°C)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
11 Jan ^b	17.5	24.4	50.7	75.3	0.1	1.2	21.4	62.1	20.1	34.0
12 Jan ^b	17.7	24.8	47.3	68.4	0.1	1.0	24.8	63.1	21.0	34.3
14 Jan ^a	34.0	41.1	20.0	29.9	2.8	4.7	58.5	66.3	37.8	46.4
15 Jan ^a	33.5	41.0	19.9	31.1	0.5	2.4	32.1	73.7	33.0	48.2
16 Jan ^a	34.0	42.7	21.6	38.8	0.5	1.6	61.7	75.1	41.2	50.8
17 Jan ^a	35.8	42.2	15.2	21.2	2.4	4.4	57.1	69.4	38.6	48.2
18 Jan ^c	21.3	25.0	57.9	77.1	0.2	1.0	24.1	53.4	23.6	33.1
19 Jan ^c	18.0	23.2	46.8	62.9	0.5	1.0	25.0	60.3	20.7	32.7

^a Heatwave days

^b Pre-heatwave days

^c Post-heatwave days

Unprecedented heatwave conditions in the RBGC area occurred from 14 to 17 January 2014, with 4 consecutive days of daily maximum daily temperature exceeding 41 °C (Fig. 2a). The maximum temperature, relative humidity, wind speed, and T_{mrt} were similar before and after the heatwave, which resulted in a similar maximum UTCI range (32.7–34.3 °C) (Table 3).

3.2 Study population

The gender distribution of respondents, as well as activity and exposure before the survey, were similar before ($n = 342$) and after ($n = 294$) the heatwave (Table 4). In both pre-heatwave and post-heatwave periods, more than 70% of respondents walked for the past 10 min before they were surveyed. Other respondents were either sitting (21.3% pre-heatwave vs. 16.3% post-heatwave) or standing (5.6% pre-heatwave vs. 8.5% post-heatwave) before the survey. In addition, more than 75% of respondents spent time in outdoor, exposed locations, and about 14% of respondents were in outdoor, shaded locations for the previous 10 min prior to the survey. Respondents who had spent time in indoor locations before the survey were relatively few (8.8% pre-heatwave vs. 1.4%

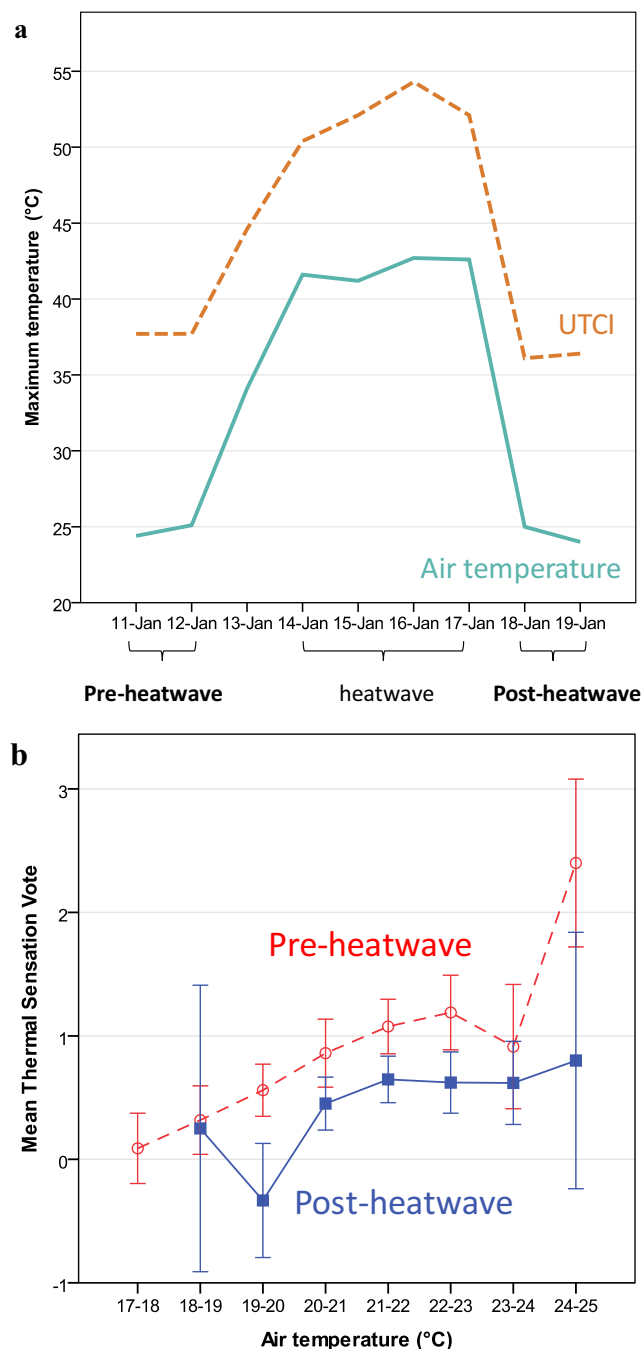


Fig. 2 **a** Daily maximum air temperature and UTCI at RBGC visitor centre from 11 to 19 January 2014 (survey period). **b** Air temperature and local visitors' thermal perception in RBGC before ($n = 342$) and after the heatwave ($n = 294$)

post-heatwave). The only notable difference between the pre- and post-heatwave group was an 11.1% decrease in the elderly respondents (65+), as well as a 10.5% increase in respondents aged 25–44 (i.e. 13 more respondents) after the heatwave. Since visitors of a similar demography encountered similar meteorological conditions before and after the heatwave, it is valid to compare the thermal perceptions of pre- and post-heatwave visitors.

3.3 Visitor perceptions of thermal comfort assessed by thermal indices (pre- and post-heatwave)

The survey results highlighted significant differences in the thermal perception of visitors after the heatwave for a range of temperatures (Fig. 2b). At air temperatures between 19 and 25 °C, visitors reported a significantly lower TSV after the heatwave (TSV pre-heatwave: 0.91 ± 0.98 , $n = 256$ vs. TSV post-heatwave: 0.53 ± 0.98 , $n = 285$, $t(539) = 4.54$, $p < 0.001$). There was a larger difference in the reduction of TSV post-heatwave for temperatures of 24–25 °C. There was also no significant difference at temperatures below 19 °C, but this result may be a function of the small sample size of surveys at these temperature ranges ($n = 8$ post-heatwave), which only occurred for brief periods in the days preceding and following the heatwave.

The same t test analysis was conducted for other sub-groups of survey respondents. One analysis excluded elderly respondents aged 65+, as an 11.1% increase in elderly respondents after the heatwave might confound the results. When air temperature was 19 to 25 °C, the t test shows a same trend in the reduction of TSV after the heatwave for visitors below 65, except between 20 and 20.9 °C (Table 5). Our results show that there were changes in visitors' thermal perception after controlling for the difference in elderly respondents' number before and after the heatwave.

A t test was also conducted for visitors with different activity and exposure for the previous 10 min before the survey (see Table 5). When temperature was between 19 and 25 °C, visitors who had been walking before the survey showed a significant reduction in TSV after the heatwave. The same trend of TSV reduction also applied to visitors who had been sitting before the survey. However, the reduction in TSV post-heatwave was not observed for visitors who had been standing prior to the survey ($p = 0.446$), possibly due to the small sample size of this group of respondents before the heatwave ($n = 19$).

Visitors who had been in an outdoor, exposed environment before the survey felt significantly cooler after the heatwave, when temperature was between 19 and 25 °C (Table 5). At the same temperature range, visitors who had been in an outdoor, shaded environment before the survey also reported a decrease in TSV after the heatwave, but the difference in TSV was not significant. The sample size for respondents who had been in an indoor environment before the survey was too small ($n < 5$ post-heatwave), so we did not conduct t -test for this group of respondents. Our results show that shade could be a confounding factor in our analysis.

The UTCI analysis yielded a similar result compared with the air temperature analysis, with visitors reporting a lower TSV at the Promenade (a site without shade) after the heatwave (Fig. 3). When UTCI was between 26 and 36 °C (moderate to strong heat stress), the thermal sensation of post-heatwave visitors (TSV: 0.49 ± 1.09 , $n = 138$) was

Table 4 Characteristics of local RBGC respondents from Melbourne before ($n = 342$) and after the heatwave ($n = 294$). Metabolic Equivalent of Task (MET) values are adapted from Ainsworth et al. (2011). One MET is defined as the energy cost of a person resting and sitting quietly (1 kcal/kg/h) (Ainsworth et al. 2011)

		Pre-heatwave		Post-heatwave	
		<i>n</i>	%	<i>n</i>	%
Gender	Female	189	55.3%	158	53.7%
	Male	147	43.0%	121	41.2%
	Missing	6	1.7%	15	5.1%
Age	18–24	14	4.1%	15	5.1%
	25–44	127	37.1%	140	47.6%
	45–64	120	35.1%	102	34.7%
	65+	81	23.7%	37	12.6%
	Missing	0	0%	0	0%
Activity 10 min prior to survey	Lying down (0.8 MET)	0	0%	0	0%
	Sitting (1 MET)	73	21.3%	48	16.3%
	Standing (1.2 MET)	19	5.6%	25	8.5%
	Walking (1.9 MET)	249	72.8%	220	74.8%
	Running (9.5 MET)	1	0.3%	0	0%
	Missing	0	0%	1	0.3%
Exposure 10 min prior to survey	Outdoor, exposed	258	75.4%	242	82.3%
	Outdoor, shaded	51	14.9%	42	14.3%
	Indoor (no air conditioning)	30	8.8%	4	1.4%
	Air-conditioned	3	0.9%	5	1.7%
	Missing	0	0%	1	0.3%

significantly lower than pre-heatwave visitors (TSV: 1.02 ± 0.95 , $n = 62$), $t(198) = 3.27$, $p = 0.001$. The large error bar (post-heatwave) at UTCI between 27 and 30 °C was possibly due to a small sample size at that bin ($n < 10$). Our results showed that a decrease in TSV post-heatwave still occurred at certain ranges of UTCI after controlling for the effect of shading.

3.4 Visitors' clothing choices and thermal perception (pre- and post-heatwave)

Changes in clothing choice might explain at least some of the pre- and post-heatwave differences in thermal perception by local visitors. The surveys showed that in the 2 days following the heatwave, there was a reduction in the amount of clothing

worn by visitors (Fig. 4). The percentage of visitors who wore T-shirts and shorts (clo 0.3–0.5) were similar both before (58.4%) and after the heatwave (58.9%). After the heatwave, 6.8% fewer visitors wore thicker clothing (clo > 0.5) (pre-heatwave 34% vs. post-heatwave 27.2%), whereas 6.3% more visitors wore thinner clothing (clo < 0.3) (pre-heatwave 7.6% vs. post-heatwave 13.9%). As there were limited data from other survey dates with similar weather conditions, it is uncertain whether the differences in local visitors' clothing are significant.

To examine whether there was a difference in TSV pre- and post-heatwave beyond clothing choices, we conducted a separate t test only for visitors who wore clothing with clo between 0.3 and 0.5 (corresponding to T-shirt and shorts, see also Table 1). This group of visitors felt significantly cooler

Table 5 Independent samples t test results, showing differences in TSV between different sub-groups of local RBGC visitors before and after the heatwave (at air temperature range between 19 and 25 °C)

Respondents sub-group	TSV: pre-heatwave			TSV: post-heatwave			<i>df</i>	<i>t</i>	<i>p</i>
	Mean	SD	<i>n</i>	Mean	SD	<i>n</i>			
Age < 65	0.93	0.98	254	0.55	0.96	193	445	4.08	< 0.001
Activity for the previous 10 min before the survey									
Walking	1.05	0.95	181	0.60	1.01	212	391	4.53	< 0.001
Sitting	0.59	1.00	59	0.10	0.81	48	105	2.74	0.007
Exposure for the previous 10 min before the survey									
Outdoor, exposed	1.06	0.96	189	0.57	1.02	233	420	5.02	< 0.001
Outdoor, shaded	0.70	0.99	43	0.33	0.82	42	83	1.85	0.068

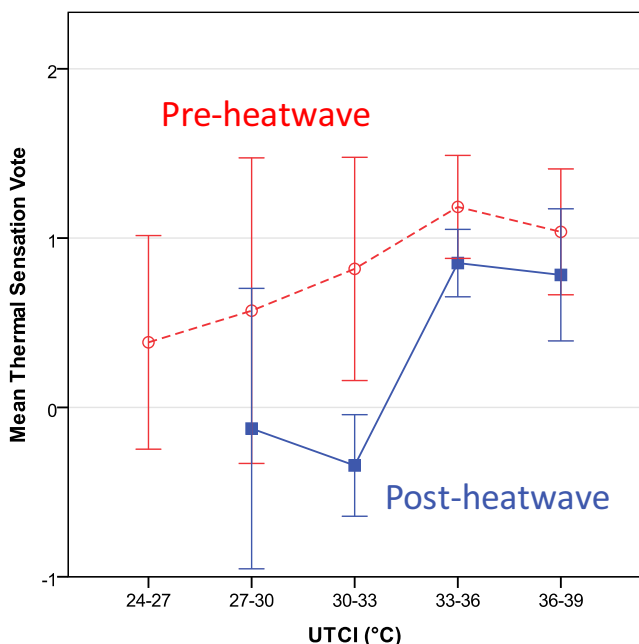
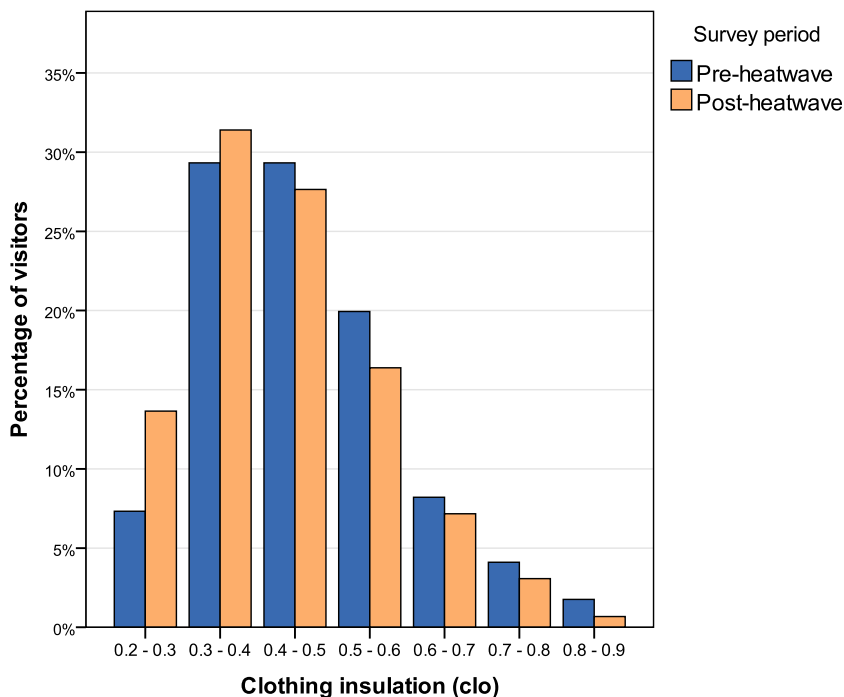


Fig. 3 UTCI and local visitors’ thermal perception at the Promenade (RBGC), before ($n = 96$) and after the heatwave ($n = 161$)

after the heatwave (TSV: 0.46 ± 1.00 , $n = 153$) than before the heatwave (TSV: 0.86 ± 0.96 , $n = 140$), $t(291) = 3.42$, $p = 0.001$, when air temperature was 19–23 °C. In other words, visitors also felt cooler after the heatwave when we controlled for the changes in clothing choices. However, the reduction in TSV occurred in a narrower temperature range (19 to 23 °C) compared with the analysis of all visitors (19 to 25 °C).

Fig. 4 Clothing worn by local visitors to RBGC before the heatwave ($n = 341$) and after the heatwave ($n = 293$). Two survey entries were removed due to incomplete clothing data



4 Discussion and conclusions

Past studies show that expectation and short-term experience can influence an individual’s thermal perception (Nikolopoulou and Steemers 2003). In this study, we show the possibility of this influence in the context of exposure to an extreme weather event. The weather conditions were very similar in the 2 days prior to and the 2 days after the heatwave. Despite the similar weather conditions, visitors reported a lower TSV at similar range of temperature and UTCI (moderate to strong heat stress) in the days following the heatwave, compared to the days preceding it.

People’s concept of a comfortable temperature can vary across seasons (Baranowska and Gabryl 1981; Culjat and Erskine 1988; Lenzholzer et al. 2016), which Nikolopoulou and Lykoudis (2006) suggested is related to their expectations of their thermal comfort in particular temperature ranges. Thermal perception can vary on timescales from minutes (Parkinson et al. 2012) to during the course of 1 day (Becker et al. 2003). Even with similar level of physiological strain in the same day, any expectation of the prospect of a cooler environment was shown to reduce thermal sensation in extreme heat conditions (Becker et al. 2003). However, there has been limited research on whether changes in thermal perception occur at an inter-daily timescale.

Memory can influence inter-daily expectation and thermal expectation (Nikolopoulou and Steemers 2003). In a transitional space study, Krüger et al. (2017) compared the Dynamic Thermal Sensation predicted by the UTCI-Fiala model with the TSV from surveys. Right after a 3-day

heatwave, they discovered the same male German participants ($n = 16$) showed a greater thermal tolerance to heat and underestimated the thermal conditions. Our results appear to agree with the findings of Krüger et al. (2017). In particular, local RBGC visitors reported a lower TSV after the heatwave, over similar UTCI range compared with before the heatwave. Our study also demonstrates that these variations in outdoor thermal perception can vary over the course of several days when people are exposed to thermal extremes.

It is likely that visitors' memory of the heatwave and expectation of a cooler post-heatwave environment might cause them to wear thinner clothing (Fig. 4). In a Sydney study, people's thermal memory and the weather forecast were shown to influence their clothing choices (Morgan and de Dear 2003). After controlling for visitors' clothing choices (behavioural adaptation) and differences in the number of elderly respondents, visitors still reported a decrease in TSV after the heatwave.

Partial acclimatisation might occur when people can control the degree of exposure and activity level in the ambient heat (Hanna and Tait 2015). When people are passively exposed to heat during normal daily routine, the acclimatisation process is much slower (de Dear et al. 1997). Past studies show that physiological adaptation to heat (acclimatisation) requires at least a few days to 2 weeks of exercising in a hot environment (Koppe et al. 2004; Périard et al. 2015; Pandolf 1998). Therefore, it is conceivable, although we would suggest unlikely, that local RBGC visitors might become partially acclimatised to extreme heat after 4 days. Physiological measurements of survey participants were not made as this line of research was not the intent of the study, so aspects of physiological adaptation could not be tested here. Psychological adaptation to heat (expectation and thermal history) by visitors might also be a possible explanation for the change in visitors' thermal perception after the heatwave.

We acknowledge that the relatively small sample size in our study could affect our results. This study had a relatively small sample size as we excluded overseas visitors in our analysis. Furthermore, we chose a location without any shading (i.e. Promenade) for the UTCI analysis, in order to remove the influence of shade on thermal perception before and after the heatwave. This factor also reduces our sample size in our UTCI analysis. With a larger sample size, it is possible to yield a clearer difference in people's thermal perception before and after the heatwave.

This study reveals an inter-daily variation of thermal perception, a phenomenon that has yet to be considered in current thermal index design. Past research has identified the time-scale of physiological heat adaptation, but studies on the time-scale of psychological heat adaptation have been limited. In developing future thermal indices, incorporating short-term changes in thermal perception would provide a better indication of outdoor thermal comfort.

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