Heat Stress and Outdoor Activities in Open Spaces of Public Housing Estates in Hong Kong: A Perspective of the Elderly Community

Jianxiang Huang[1], Yang Chen[2], Phil Jones[3], Tongping Hao[1]

[1] Department of Urban Planning and Design, 8/F Knowles Building, The University of Hong Kong, Pokfulam Road, Hong Kong SAR, China

[2] China Academy of Urban Planning & Design Shenzhen, 26/F, No. 7006 Shen'nan Street, Futian District, Shenzhen, China.

[3] Welsh School of Architecture, Cardiff University, King Edward VII Avenue, Cardiff, CF10 3NB, UK

[*]Corresponding author. Email address: please add corresponding author institutional email address.

Abstract

Open spaces in Hong Kong are in short supply and they are often underused due to the adverse climate, especially in hot and humid summer. This is a missed opportunity that can be otherwise realized to promote health and social interactions for local communities. The high density urban environment makes the condition worse by raising the urban heat island effect and leaving planners with fewer mitigation options. This study aims to test the hypotheses that an unfavourable thermal environment disrupts the use of outdoor open spaces; if yes, whether such disruptions differ by age groups. On-site measurement and computer simulations were conducted in three open spaces in public housing estates in Ngau Tau Kok, Hong Kong. Thermal conditions were assessed using the Universal Thermal Climate Index (UTCI). Occupant activities were recorded, together with a questionnaire survey. Results showed that an open space purposefully designed for breeze and shading was 2.0ºC cooler in UTCI compared with the other two. It attracted more optional/social activities, higher frequency of visits, and longer duration of stay. The elderly activities were more susceptible to disruptions from heat stress compared with younger groups. Elderly activities largely diminish when ambient thermal environment exceed 39°C in UTCI. Findings have implications to design and retrofitting of open spaces in order to maximise their use.

Keywords: *Open Space, Outdoor Activities, Heat Stress, Elderly Space, Thermal Environment*

Introduction

An open space provides a place for people to meet, relax, exercise, and play. It serves as a vital function for local communities by promoting health, social interactions. Open spaces in Hong Kong are in short supply and they are often underused due to the adverse climate and Urban Heat Island (UHI) effect, especially in hot and humid summer. This is a missed opportunity that can be otherwise realized to promote health and social interactions for local communities.

Jan Gehl [1] specified three types of outdoor activities in open spaces: necessary, optional and social activities, of which the latter two are expected to be more susceptible to thermal environment. Recent literature suggests that the outdoor thermal environment is a key factor associated with the active use of outdoor open spaces. Variables such as temperature, wind, solar radiation, and humidity explain 12% of the variations in open space attendance San Francisco, USA [2], 12% in Montreal, Canada [3], 23-24% in Japan [4], 50% in Gothenburg, Sweden [5], and up to 60% in Wuhan, China [6]. It is therefore essential to design open spaces with desirable thermal conditions which are conducive to active use and can contribute to a high-quality of urban living [7–9]. A number of UHI mitigation measures were proposed, such as the Urban Ventilation Corridor (UVC), a rectilinear, wide (> 50 m) track consisted of low roughness surface towards prevailing wind [10], which was found to have enhanced urban wind and reduced UHI [11,12]. Similarly, urban greenery can reduce ambient air temperature [13] and it has been adopted by policy agenda such as New York’s Regional Heat Island Initiative [14].

The application of UHI mitigation measures in a high density city, however, is often practically limited. A UVC excludes high rise buildings along its right-of-way and does not apply to existing, dense neighbourhoods. Simulation-based evidence show that a third of Hong Kong’s urban footprint need to be converted to greenery in order to reduce air temperature by 1º C[15], making UHI reduction via urban greenery almost infeasible for a city in shortage of land. Besides, the array of high rise buildings are found to disrupt dispersion of long-wave radiative energy, stagnate airflow and uplift ambient air temperature [16]. Anthropogenic heat sources such as traffic and building HVAC systems are found to be potent contributors to UHI in a dense neighbourhood [17]. One study discovered the amplifying effects of wind via the open ground floor layout can mitigate heat stress and encourage outdoor activities in Hong Kong[18]. More studies are needed in this direction to identify practical means to mitigate heat stress in a high density urban context.

A parallel challenge to Hong Kong’s planners is the city’s growing elderly population, who are more likely to use open spaces next to home for physical activities such as leisure walks, fitness exercise or sports compared with other age groups or peers from other cities [19,20]. The use of outdoor open spaces is a preferred act and an intrinsic lifestyle in Southern China, known by the local communities as 唞凉 in Cantonese, meaning to relax in a shaded, outdoor open space [21]. A recent study on elderly thermal comfort in a nursing home in China found considerable adaptive behaviours in response to seasonal variations of thermal environments[22]. To many elderlies, the use of open spaces during hot period is considered a heat-coping strategy [23], and the behaviour was often formulated prior to the advent of home air conditioning (Loughnan et al., 2014). Physiologically, the elderlies are considered the most vulnerable group under heat stress, due to reduced thermoregulatory responses such as sweating rate, skin blood flow and cardiovascular functions [25,26]. Research literature on thermal preference of the elderly population in outdoor open spaces is thin. Whether the elderly activities are subject to additional disruptions from heat stress compared with other age groups is unclear. As the city invested extensively in the Elderly Fitness Corner, a type of specialized open spaces dedicated to the elderly population [27], more studies are needed to inform the design of these open spaces in order to promote active use.

This paper presents a study of thermal environment and behaviours in open spaces within Hong Kong's public housing estates. The aim is to test the hypotheses whether an unfavourable thermal environment is a key factor affecting the use of existing outdoor open spaces, or whether such effect differ by age groups. Three open spaces of varying physical layouts were chosen: the first two are enclosed plazas surrounded by shops and high-rise apartment buildings; the last one was purposefully designed for breeze and shading in outdoor open spaces. Otherwise, the three open spaces were similar in location, year built, and were used by similar groups of residents of public housing estates. Concurrent on-site measurements included thermal environment, observed behavioural patterns, and occupant surveys were conducted on two hot summer days. To assess the spatial distribution of thermal environments, computer simulations were conducted for the three open spaces using the CityComfort+ method [28].

Methods

A quasi-experiment was adopted in this study (Figure 1). Fieldwork was conducted on three study sites located in public housing estates in Ngau Tau Kok, Hong Kong. On-site measurement and computer simulations were conducted; Occupant activities were recorded, together a questionnaire survey to capture occupant behavioural preference.

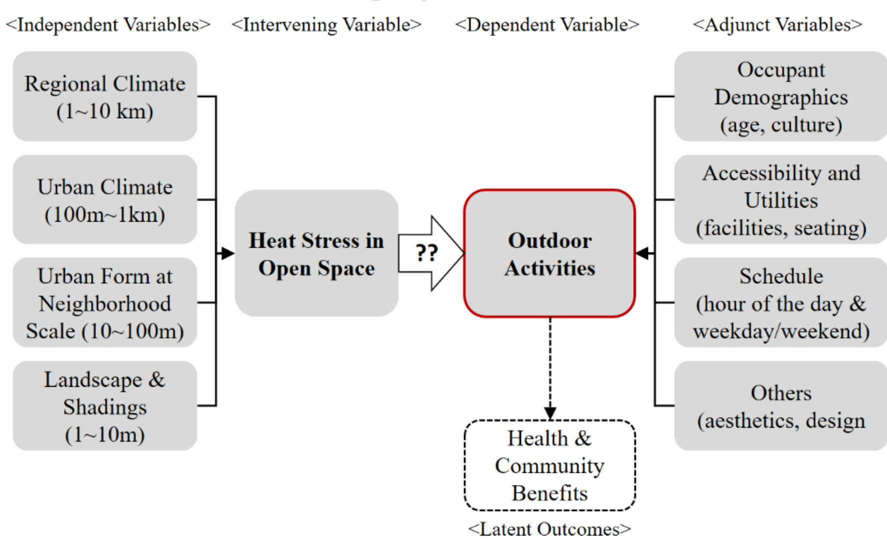


Figure 1 A conceptual framework of heat stress and outdoor activities in open space.

- **Study Sites**

Three major open spaces were selected as study sites from the Ngau Tau Kok Housing Estates located in Kwun Tong District, Hong Kong. Kwun Tong is the most densely populated district among Hong Kong's 18 Administrative Districts with an average residential density at 57,909 people per km^2 [29]. The Ngau Tau Kok Housing Estates are home to 25,000 people. Its location in relation to Hong Kong Island and Kowloon Peninsula is shown in Figure 2.

The three study site were located within 150 m from each other and were built between 2009 and 2012. Their physical layout are shown in Figure 3. Site 1 is the Central Plaza located at the Lower Ngau Tau Kok Estate Phase I (LNKE), an enclosed space surrounded by high-rise towers and podium structure of shops and community services. Site 2 (Entrance Plaza) and 3 (Bird Watching Terrace) are located in Phase II and III of the Upper Ngau Tau Kok Estate, an award winning project purposefully designed to channels breezes and provides shading for the outside environments [30 31]. The two spaces were inside a breezeway between two rows of high-rise buildings, and they are fitted with shading, light surface materials, and tree canopies of varying design to enhance thermal comfort (Figure 4). A summary of the physical layouts, service amenities, landscape features, and transit access for the three sites is provided in Table 1.

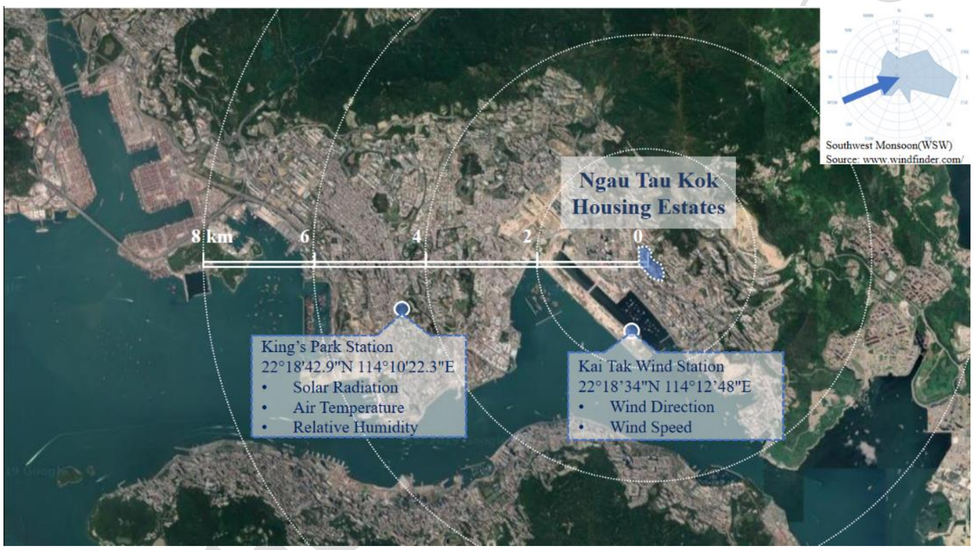


Figure 2 The location of the Ngau Tau Kok public housing estate in relation to Hong Kong Island and Kowloon Peninsula. Nearby weather stations and wind direction during the two study days are depicted.

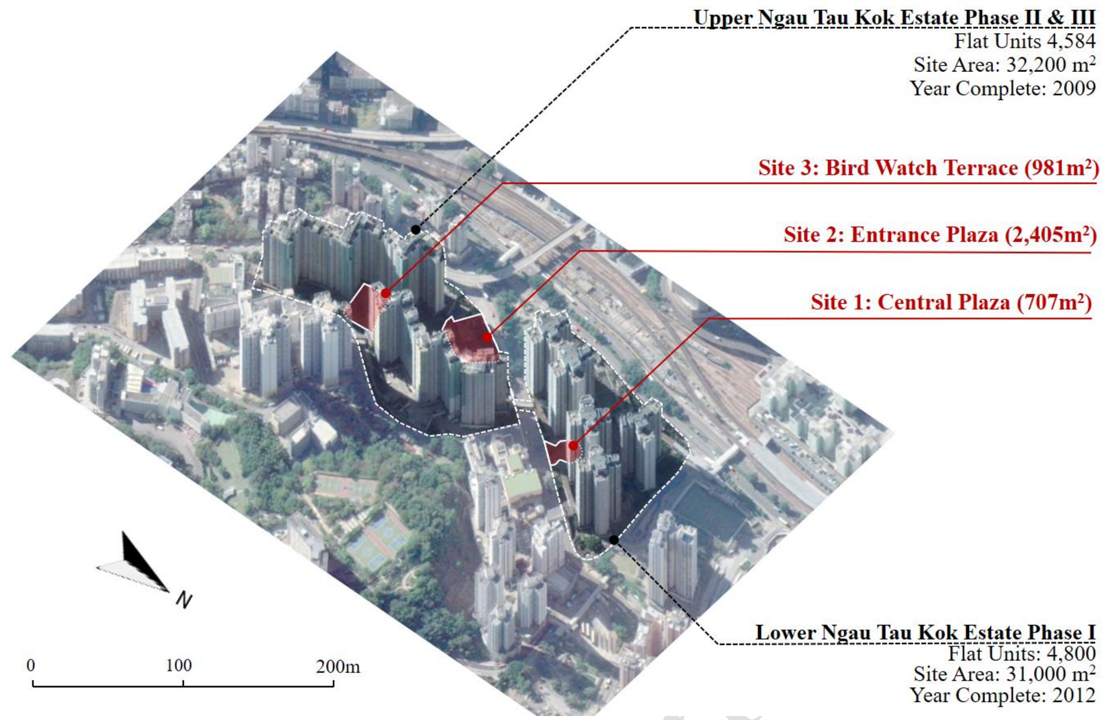


Figure 3 Axonometric view of the three measurement sites in Ngau Tau Kok Housing Estate: 1) Central Plaza, 2) Entrance Plaza, 3) Rest Plaza

Figure 4 The Awarding-Winning Upper Ngau Tau Kok Estate Phase II & III purposefully designed to facilitate breeze and thermal comfort in open spaces. (left) An aerial photograph of the housing estate; (right) A design-stage physical model showing the site layout and breezeway [31]

Table 1 A Summary of access and utility conditions for the three study sites

Site Name	**Site 1** (Central Plaza)	**Site 2** (Entrance Plaza)	**Site 3** (Bird Watch Terrace)
Size (m^2)	707	2,405	981
Transit Access*	200 m to Station KLW	250 m to Station KLW	300 m to Station KLW 350 m to Station NTK
Service Amenities**	6 shops (400 m^2) 1. Restaurant (Maxim's) 2. Restaurant (Yunnan Rice Noodle)	6 shops (1,100 m^2) 1. Restaurant (Maxim's) 2. Supermarket (Uselect)	2 community centres (500 m^2) 1. NTK Youth Integrated Service Centre

	3. Personal Care (Manning's) 4. Convenience Store (7-Eleven) 5. Health Clinic 6. LNTK Heritage Gallery	3. Convenience Store (7-Eleven) 4. Health Clinic 5. Pharmacy 6. NTK Kaifong Welfare Association	2. NTK Neighbourhood Elderly Centre
Tree Cover	3 camphorwood *(Cinnamomum camphora)*	4 banyans (*Ficus microcarpa*)	12 *palms* *(Syagrus romanzoffiana)*
Seating Length	25 m	40 m	30 m
Year Built	2012	2009	2009

* Distance measured from Google Map.
** Data source: The Hong Kong Housing Authority Database, Available at https://www.housingauthority.gov.hk/tc/index.html

Social-demographic such as age, ethnicity, language, marital status, occupation, income, and educationally attainment of residents of the Ngau Tau Kok Housing Estates are listed in

Table 2. Given that tenants of Hong Kong's public housing were allocated to buildings and flat units by a lottery-based system [32], it is reasonable to assume a homogeneous distribution of the above occupant attributes across the estates; hence, the three space are not expected to differ in their occupant behaviour and preference for outdoor activities.

Table 2 Demographic and Unit Attributes of the Ngau Tau Kok Housing Estates, divided into the Lower Ngau Tau Kok Estate (LNTK) and Upper Ngau Tau Kok Estate (UNTK) administratively.

Category	Attributes	Lower Ngau Tau Kok Estate	Upper Ngau Tau Kok Estate
Population	Total Population	9,716	15,004
	Elderly Population	1,790 (18.4%)	4,151 (27.6%)
	Male	4,631 (47.7%)	7,025 (46.8%)
	Ethnic Chinese	9,596 (98.7%)	14,641 (97.5%)
Marital Status	Never married	2,276 (27.1%)	4,299 (31.2%)
	Married	4,483 (53.5%)	6,338 (46.0%)
	Widowed/ Divorced/ Separated	1,619 (19.3%)	3,150 (22.8%)
Literacy / Educational Attainment	Able to Read	8,894 (95.6%)	13,398 (91.0%)
	Primary and Below	3,485 (35.9%)	6,027 (40.2%)
	Secondary	5,000 (51.5%)	6,888 (45.9%)
	Post-Secondary	1,230 (12.7%)	2,089 (13.9)
Economic Statistics	Participation in Labour Force	3,995 (41.1%)	6,195 (41.3%)
	Median Monthly Income	HK$ 11,750	HK$ 12,000
Housing Statistics	Average Domestic Household Size	2.1	2.3
	Median Household Rent	HK$ 1,290 / Month	HK$ 1,590 / Month
	Median Flat Size (m^2)	22.0	22.0

Source: 2016 Population Census for major housing estates [33]

- ## Measurement Protocol

Field studies were conducted on two very hot days in 2015: 17th Jun (Wednesday) and 28th Jun (Sunday). Hot Weather Warnings were issued by the Hong Kong Observatory on both days, in which the public was alerted of health risks and to take precautions measures during outdoor activities [34]. Studies started from 8:00 in the morning and finished at 20:00, excluding lunch break hours between 13:00 and 15:00 when on-site outdoor activities reduced to minimum. Three sets of measurement equipment were used to collect the microclimate data simultaneously on the three study sites: three Kestrel 4500 pocket weather trackers were used to measure air temperature (T_a), relative humidity (RH), wind speed (V_a) and direction; An infrared camera (Testo890-2) was used to measure surface temperature of the three sites periodically; A black ball thermometer made of a 40 mm copper ball and temperature sensor (TMC6-HA) was used to measure the globe temperature (T_g). The Mean Radiant Temperature (T_{mrt}) onsite was computed using the Kuehn's Formula [35] as specified in Formula (1) below, in which T_{mrt} (°C) is expressed as a function of the globe temperature (T_g), diameter (D) (m), emissivity (ε) (default value = 0.95), measured ambient air temperature (T_a) (°C) and wind speed (V_a) (m/s). Data were continuously recorded at the 5-min interval. Specifications of equipment are provided in Table 3.

$$T_{mrt} = \sqrt[4]{(T_g + 273.15)^4 + \frac{1.06 \cdot 10^8 \cdot V_a^{0.58}}{\varepsilon \cdot D^{0.42}} \cdot (T_g - T_a)} - 273.15 \qquad (1)$$

Human body energy balance and thermal regulatory responses were calculated using Universal Thermal Climate Index (UTCI), a thermal comfort metrics popular in recent research literature[36]. UTCI is widely used to asses thermos-physiological effects of the atmospheric environment divided into 10 stress levels to reflect human biometeorology

[36]. Compared with other thermal indices such as the Standard Effective Temperature (SET*)[44], Out_SET[45], and the Physiological Equivalent Temperature (PET)[46], UTCI was considered advantageous in accounting for location-specific climates and weather conditions[47]. The calculation of UTCI follows the principles of human body energy balance and thermal regulatory response shown in formula (2), where bodily energy gain from metabolism (M) equals the sum of external work (W), convection (C), radiation (R), skin diffusion(E_{sk}), dry respiration (C_{res}), latent respiration (E_{res}) and sweat secretion (S_{sk}). The calculation of UTCI was implemented using a polynomial approximation method available to the public domain [37].

$$\mathrm{M} - \mathrm{W} = \mathrm{q}_{\mathrm{sk}} + \mathrm{q}_{\mathrm{res}} + S = (C + R + E_{sk}) + (C_{res} + E_{res}) + (S_{sk} + S_{cr}) \quad (2)$$

Concurrent observations of outdoor activities were conducted on the three sites. Trained researcher recorded attendance and breakdown by age and activity types at 30-min intervals. A panoramic photo was taken every 30 mins for verification purposes (Figure 5). Each occupant count was labelled by age, i.e. the elderly group (≥65) and the younger group (<65), and types of activities, such as necessary, optional and social activities categorized by Jan Gehl (1987). Occupant activities were labelled as sitting, standing, walking, exercising, ranked by the Metabolic Equivalence of Task (MET) by the World Health Organization [39].

A questionnaire was administrated concurrently; occupants at the three sites were invited for participation after they have kept their current activities for 10 mins, i.e. sitting or exercising. After signing a consent form, the participant was asked to fill in a questionnaire containing questions on self-reported Thermal Sensation Vote on the standard ASHARE 7-scale. The questionnaire is included in the Appendix.

Figure 5 Site layout and onsite panoramic photos documenting outdoor activities. Upper image: Site 1 Central Plaza; Middle image: Site 2 Entrance Plaza; Lower image: Site 3 Rest Plaza.

Table 3 A summary of the equipment, variables of measurement, range and accuracy

Instrument Type (quantity)	Variables	Specification Range	Labelled Accuracy
Kestrel 4500 Pocket Weather Tracker (3)	Air Temperature (T_a)	-29.0 ~ 70.0°C	± 1.0°C
	Relative Humidity (RH)	5% ~ 95%	± 3%
	Wind Direction	0 ~ 360°	± 5.0º
	Wind Speed (V_a)	0.4 ~ 40.0 m/s	± 1.0 m/s
Infrared Camera Testo890-2 (1)	Surface Temperature (T_s)	-30 ~ 650ºC	± 2.0ºC
Black ball thermometer (1)	Globe Temperature (T_g)	0.0 ~ +44.0°C	± 0.2ºC

- **Computer Simulation**

Computer simulations were conducted for the three sites. The purpose is to supplement point-based measurement and show spatial distributions of thermal environment in open spaces. The simulation was conducted using CityComfort+, a numerical model developed to simulate micro-scale environmental parameters and human responses in dense urban areas, including solar radiation, air temperature, thermal comfort [40]. The models applies a reverse ray-tracing method to compute the mean radiant temperature [28]; localized air temperature was computed using the STEVE method [41], an empirically derived formula evaluated in Guangzhou, China, a nearby city that is similar to Hong Kong in climate and culture [42]. Localized wind speed was calculated using FlowDesigner, a CFD (computational fluid dynamics) software [43]. Clothing insulation and bodily thermal regulatory responses were computed using the UTCI F90 source code developed by Brode and Wojtach [37]. The extent of heat stress in an outdoor open space was evaluated using UTCI in consistency with Formula (2) mentioned earlier. The input data for the simulation software were hourly weather data obtained from the Hong Kong Observatory [48] and 3D geometries for buildings and topography obtained from the Hong Kong Lands Department[49].

Results

- **Summary of Field Study Data**

A significant amount of heat stress was recorded on the two study days of 17 and 28 Jun, 2015. Ambient air temperature ranged between 29.0 and 33.0°C, relative humidity from 62% to 87%, and solar radiation up to 1,000 W/m^2 (Figure 6). The UTCI indices calculated using on-site measurement data range from 32.0 to 38.0 °C, which were within the "strong heat stress" range indicated by the original UTCI scale [50]. Despite heat, a total of 3,014 counts of optional and social activities were recorded, 1,701 on 17 June (weekday) and 1,313 on 28 June (weekend). Our record also included 1,367 counts of passers-by, or the necessary activity by Jan Gehl's categorization. A total number of 75 effective responses to on-site questionnaires were obtained.

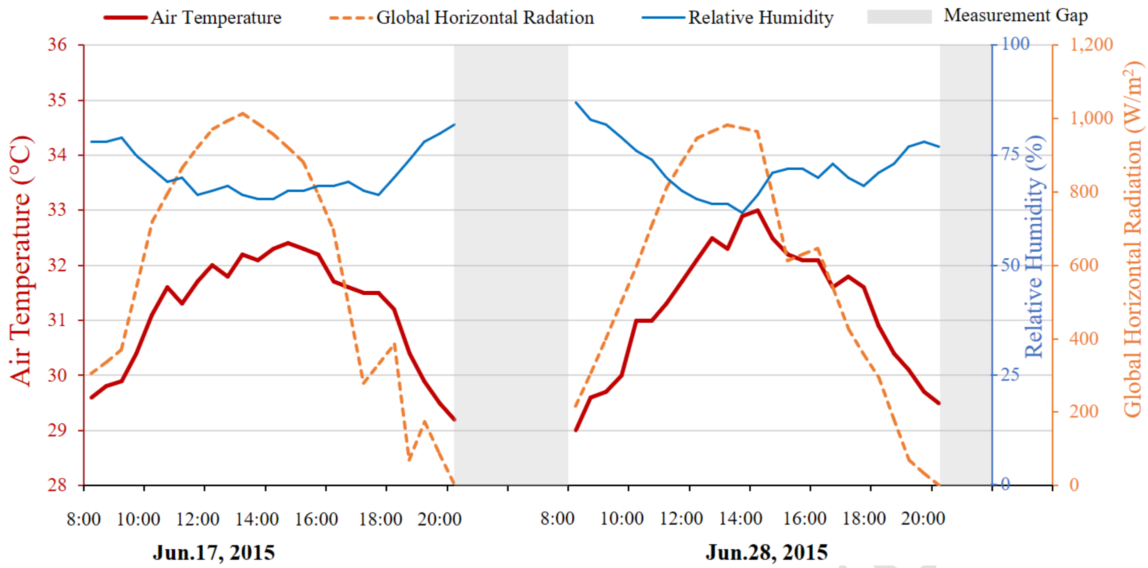


Figure 6 Summary of the weather conditions on the two study days of 17 and 28 Jun., 2015

- ## Measured Data

A sizable variation in thermal environments were observed among the three sites. Figure 7 shows concurrent measurement of pedestrian-level wind speed. Periods of missing data marked in grey due to scheduling constraints. The average wind speed was the highest (2.0 m/s) at site 3 and lowest at site 1 (0.5 m/s). The difference can be as large as 3.0 m/s, peaking at 3.9 m/s on site 3 compared to around 1.0 m/s on site 1. This could be explained by the funnelling of sea breezes through the estate – site 2 and 3 are situated in a breezeway, but not site 1. The air temperatures (Figure 8) across the three sites generally varies within 1°C, with site 3 being the coolest. Site 3 is also the breeziest and has the lowest mean radiant temperature. Figure 9 shows on-site mean radiant temperature (T_{mrt}) measured using blackball thermometers and anemometers. T_{mrt} on site 2 was found to be higher compared to sites 1 and 3, peaking at 73°C under direct sunlight for site 2.

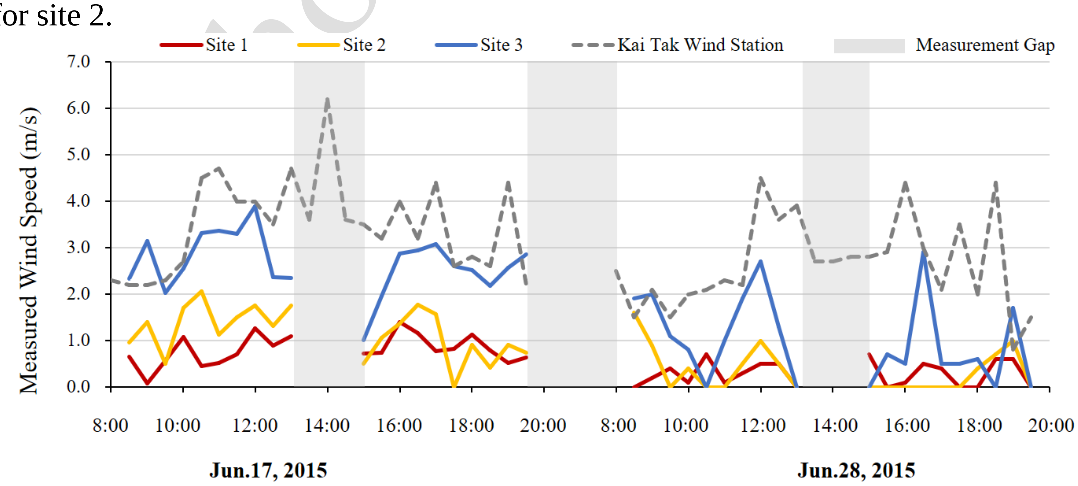


Figure 7 Measured wind speed on the three sites during the two study days.

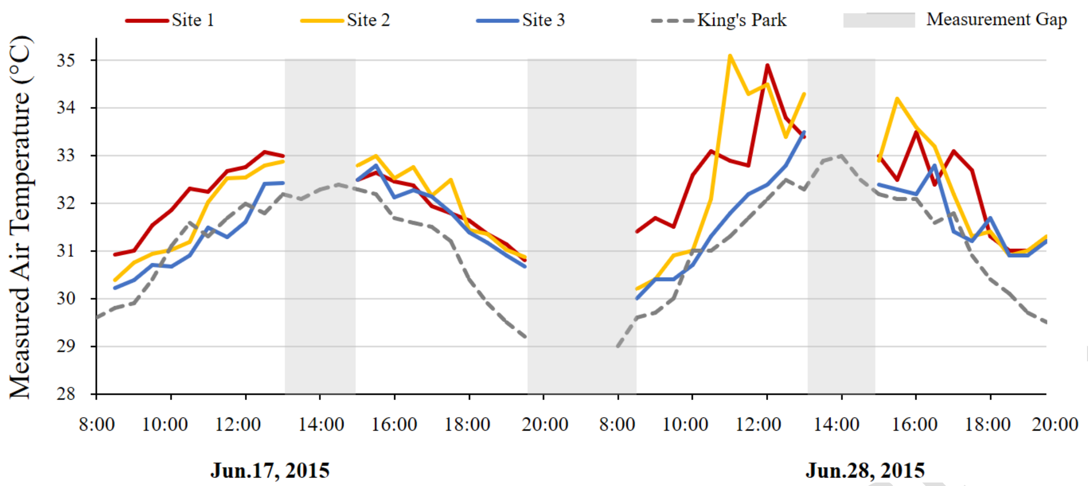


Figure 8 Measured air temperature for the three sites on the two study days.

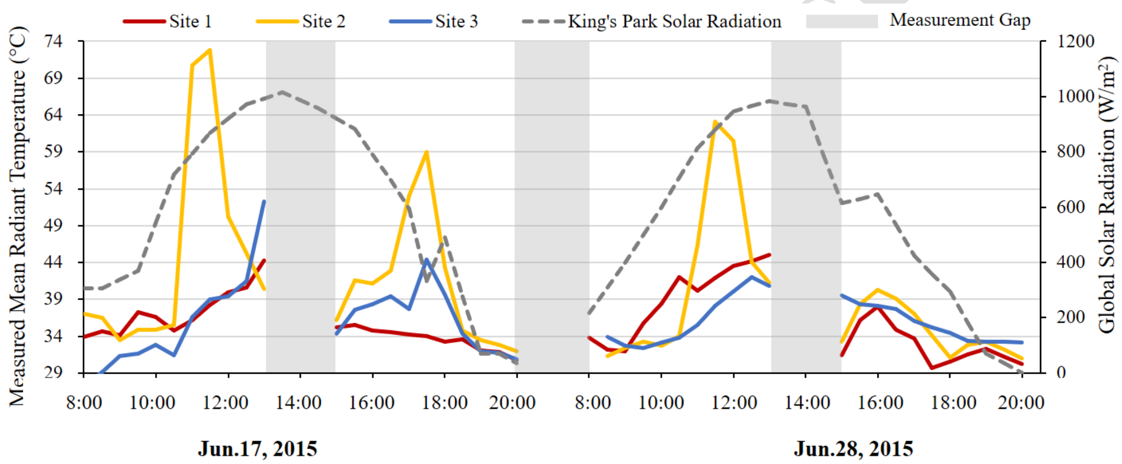


Figure 9 Measured hourly Mean Radiant Temperature for the three sites on the two study days.

Infrared thermography data revealed that site 1 and site 2 were susceptible to strong direct solar radiation and surges in surface temperature. The variation in thermal environment across the three sites can be significantly different due to the relative shading (or the lack) of open spaces, as indicated by the thermographic images of surface temperature taken at two times (11:30 and 15:30) as presented in Figure 10. The surge of surface temperature on site 1 and 2 is expected to contributed to heat stress of occupants.

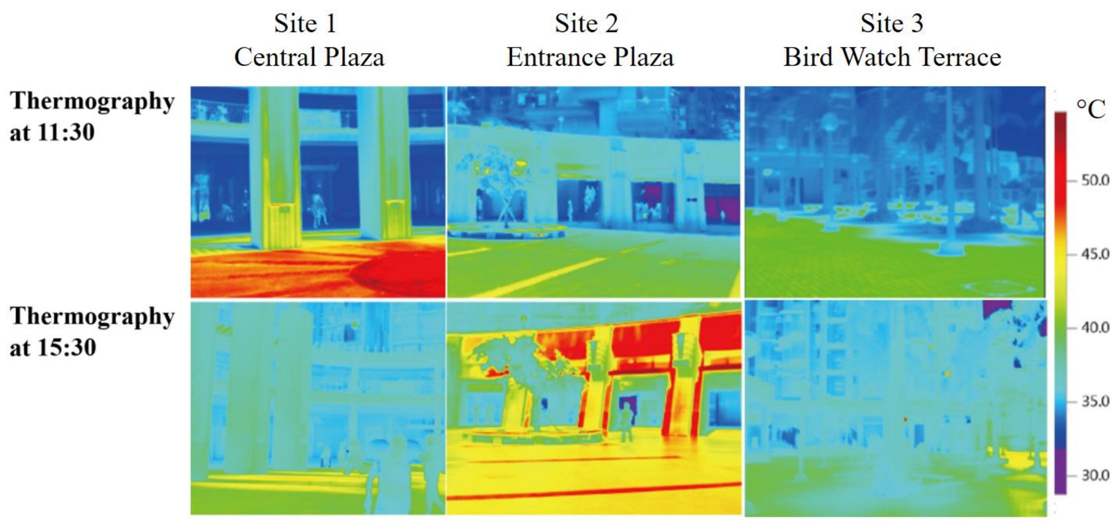


Figure 10 Thermographic photos taken on the three sites at 11:30 and 15:30 on 28 Jun., 2015

The variation of outdoor thermal environment can translate into significant difference in human body perception of heat stress. Figure 11 shows the distribution of UTCI equivalent temperature across the three study sites during the two study days. Site 3 has the lowest mean UTCI value of 33.4 ºC, compared with 35.4 ºC on site 1 and 36.0 ºC on site 2. The t-test between Site 1 and Site 3 yielded a t-stat of 6.96 (p-value = 0.00); the t-test between Site 1 and Site 2 yielded a t-state of 6.77 (p-value = 0.00); both rejected the null hypothesis. A single-factor ANOVA test of the mean values of the three sites yielded a p-value of 0.00, suggesting that the mean UTCI values of the three sites were significantly different during the two study days.

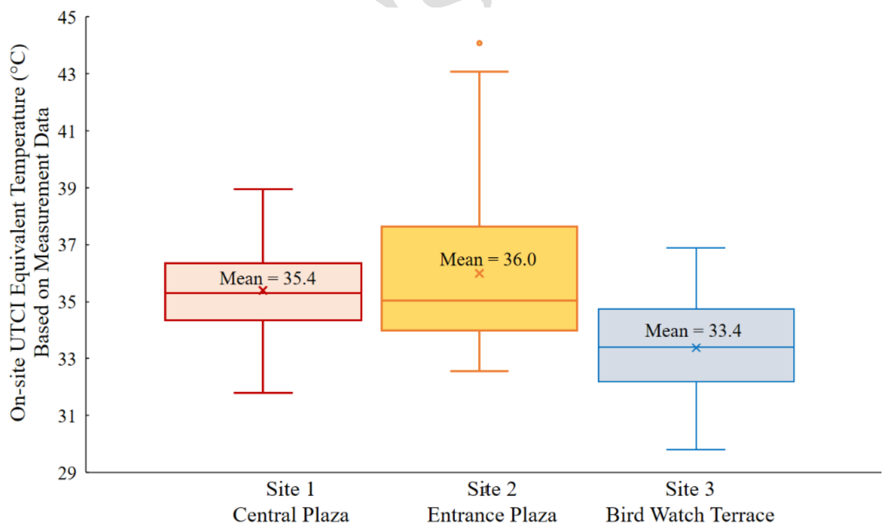


Figure 11. Comparison of UTCI values of the three study sites during the two study experiment. Data were summarized at 30-min interval.

- **Simulation Results**

Figure 12 and Figure 13 show the spatial variation of UTCI equivalent temperature simulated by CityComfort+ software on 17 and 28 Jun., 2015. All three sites had stronger UTCI values at 12: 00 and 15:00 and the maximum UTCI on Site 2 was the highest, similar to the trend of T_{mrt}. Generally, the area exposed directly to sunlight had a higher UTCI than the shaded area, but the value varied from site to site. All the areas in Site 1 and Site 3 experience a strong heat stress condition (31 - 42℃) most of the day, but the difference between shaded and unshaded area in Site 2 could be as large as 11.5℃. The shaded area in Site 2 is in a moderate heat stress condition (26-32℃) all the day while the unshaded area could reach a very strong heat stress condition at 41.5℃.

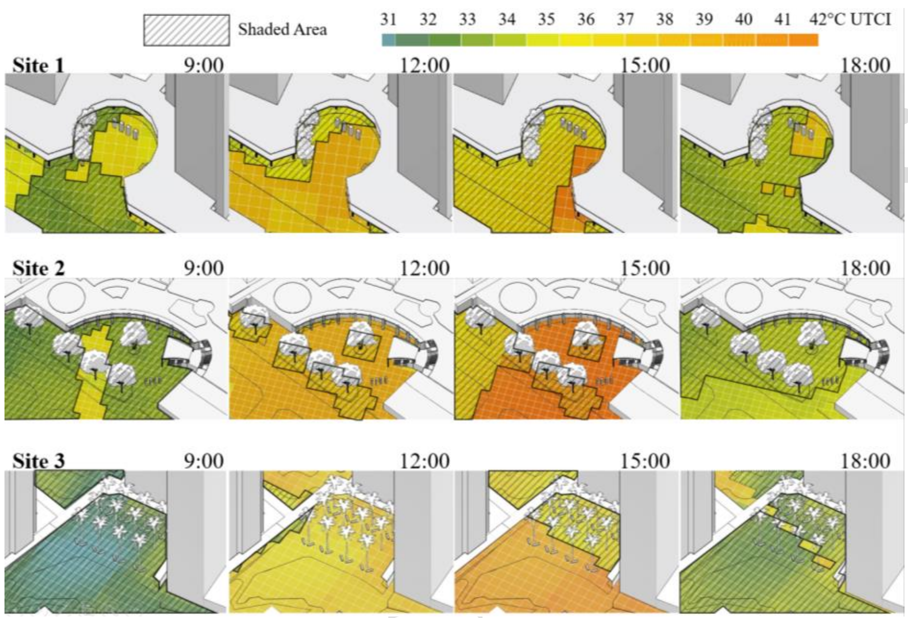


Figure 12 Computer simulation of thermal comfort measured in °C UTCI for the 3 study sites on 17 Jun, 2015. Results are calculated for the 3*3 m grid.

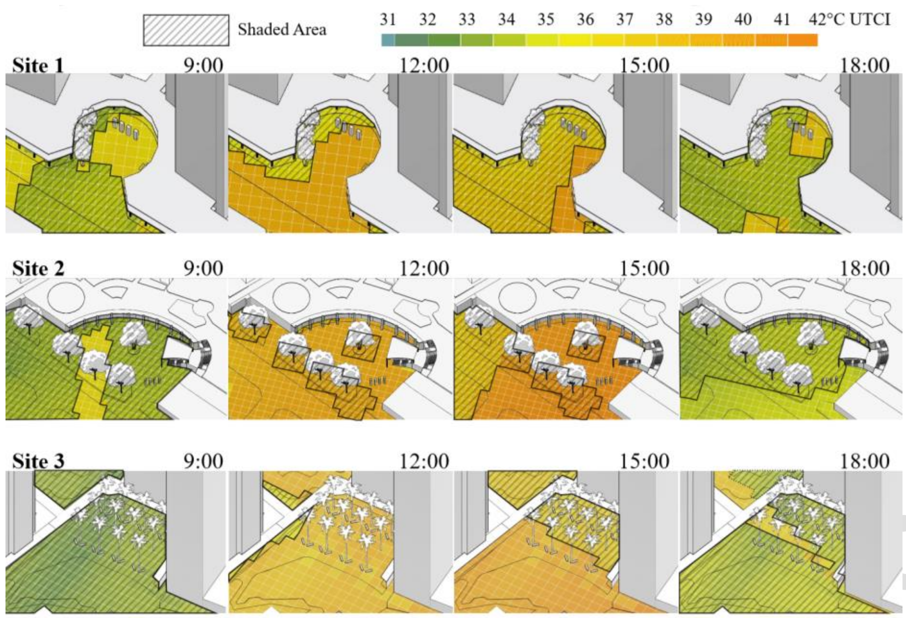


Figure 13 Computer simulation of thermal comfort measured in °C UTCI for the 3 study sites on 28 Jun, 2015. Results are calculated for the 3*3 m grid.

- **Behaviour and Perception**

Abundant outdoor activities were recorded on the three study sites, despite the presence of heat and the "very hot weather warnings" broadcasted over radio and television by the Hong Kong Observatory [51]. Of all occupants engaged in optional and social activities in the three study sites, the elderlies (65+) accounted for 44.0%, higher than their percentage of 25.8% of the total population residing in the housing estates [29]. This notion confirmed findings from previous literature that Hong Kong's elderly population are more likely to use open spaces next to home compared with other age groups or peers from other cities [19,20].

Thermal differences among the three study sites correlated with headcounts of occupants engaged in optional and necessary activities. Site 1, where heat stress levels were high in the morning due to direct sunlight from the east, saw relatively low levels of activities in the morning and high levels of activities in the afternoon (Figure 14). Site 2 had the largest number of people in the morning, which decreased around noon time (Figure 15). Situation in site 1 was the opposite. The people count for site 3 remained relatively stable (Figure 16). Elderly occupants were more likely to appear in the relatively cooler periods of each site: site 1 in the afternoon, site 2 in the morning, and site 3 throughout the day.

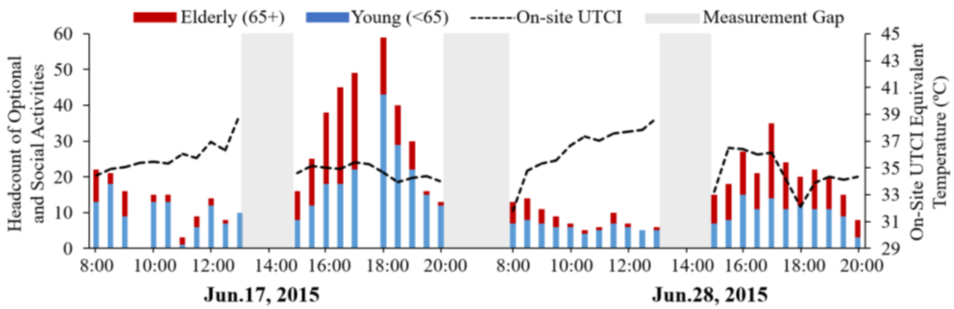


Figure 14 Hourly Headcount by Age Group of Optional and Social Activities on Site 1

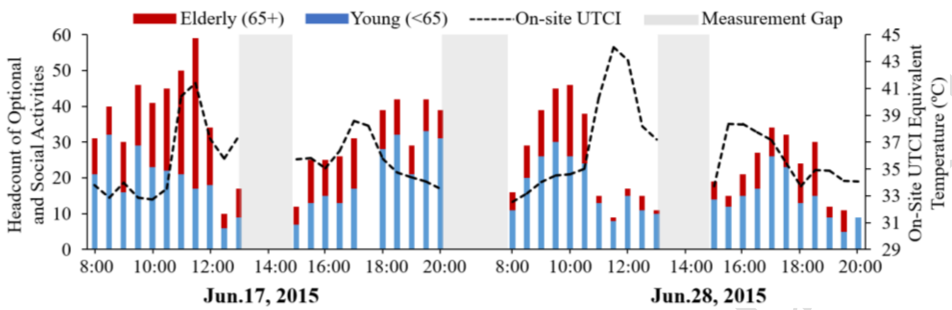


Figure 15 Hourly Headcount by Age Group of Optional and Social Activities on Site 2

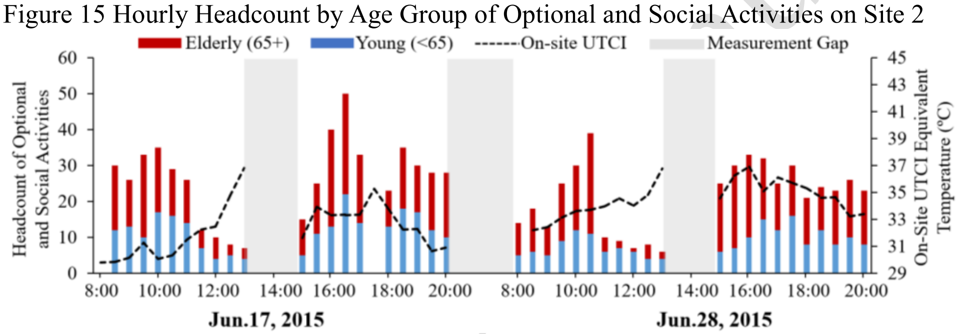


Figure 16 Hourly Headcount by Age Group of Optional and Social Activities on Site 3

The percentage of headcounts by necessary, social, and optional activities were provided in Figure 17. The majority of activities took place on Site 1 was under the category of "Necessary" (51.5%), i.e. passers-by without staying. Site 3 has the highest percentage of social (40.3%) and optional activities (32.3%). Judging by Jan Gehl's criteria, Site 3 was the most successful open space among the three, thanks to a more favourable thermal environment.

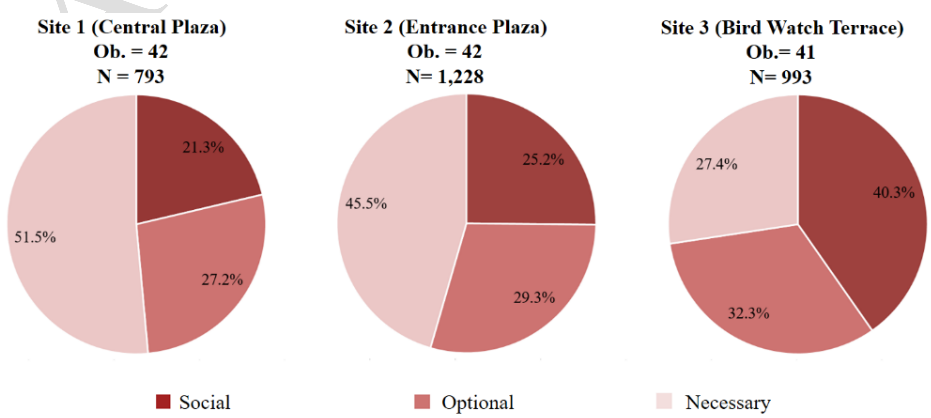


Figure 17 Outdoor activities by Necessary, Optional, and Social Activities for three study sites during the two-day period.

According to questionnaire responses, a majority of occupants spent half to an hour on the 3 sites. Site 3 was the most frequently visited place among the three, while Site 1 was the least one (Figure 18). A majority of respondents surveyed on Site 1 (73%) reportedly visit the place once every 2-3 days; few (18%) expressed willingness to visit daily. On the contrary, 50% of respondents surveyed on Site 2 paid a visit daily, so did the majority (75%) on Site 3. The self-reported length of visit differed, with Site 3 held a small margin over others (Figure 19).

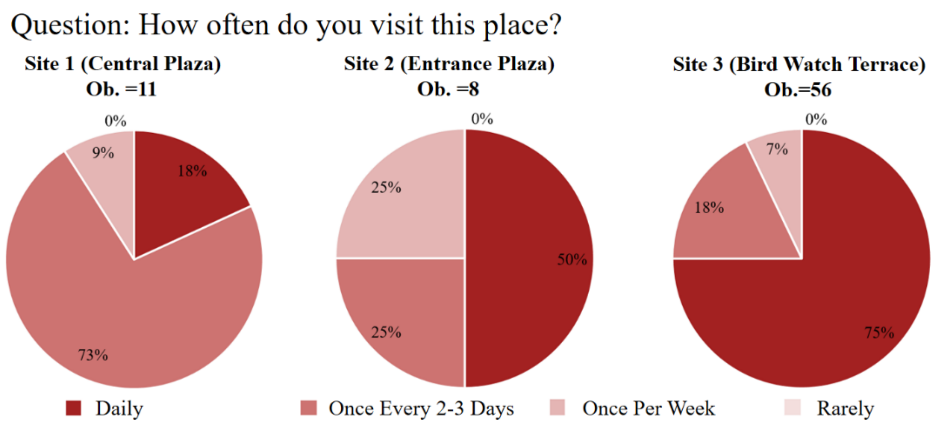


Figure 18 Self-reported frequency of visits from questionnaire

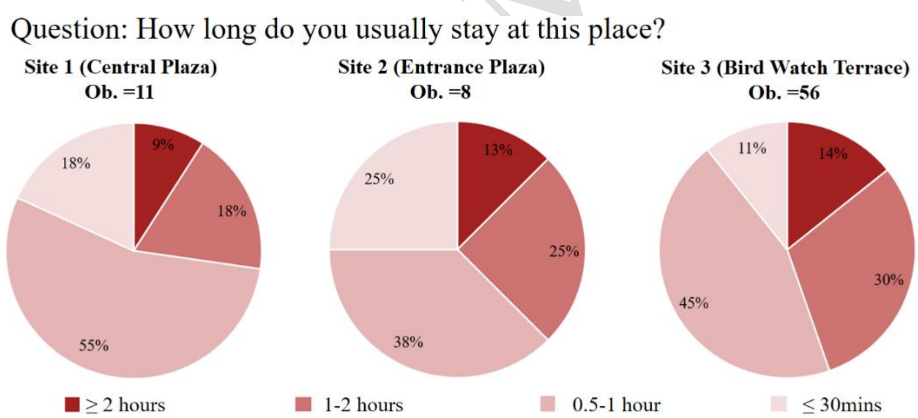


Figure 19 Self-reported duration of visits from questionnaire

When asked about what physical features were considered attractive in open spaces, respondents rated shading and ventilation as the top two concerns (over 20%), followed by greenery, rain shelters and seating facilities (Figure 20). When asked why occupants chose this particular place over others. A common answer from elderly respondents on Site 3 was the space being “breezier and more comfortable than home”. In comparison, most respondents referred to Site 2 as “spacious” and consider the primary reason to use the space is the opportunity to perform physical exercise there, i.e. square dancing or Tai Chi.

Question: What physical features in this place do you consider attractive?

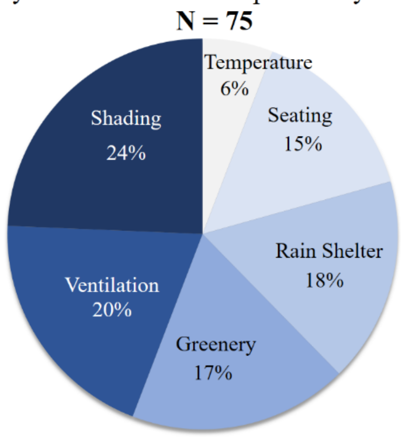


Figure 20 Preferred physical features of open space by questionnaire respondents

Discussion

In summary, the identity and context of the open space determine why people come, and the thermal environment can affect the use of the spaces, such as, how and how long people will use the space. Implications can be drawn that are useful for design and planning practices.

First, the open spaces for the elderly population need to be designed to avoid extreme heat stress, i.e. UTCI > 39 °C. Elderly outdoor activities appeared to be more susceptible to heat stress in outdoor open spaces than the younger group. Headcount of occupants on the 3 study sites were plotted against measured UTCI values in Figure 21. For 1 °C increase of onsite UTCI equivalent temperature, the headcount for the elderly is expected to decrease 1.18, while those of the younger group is expected to decrease 0.42, less than half of those elderly group. A Chow Test, alternatively known as the regression stability test [52], suggested a Chow score of 18.16 ($p < 0.00$), rejecting the null hypothesis that the regression coefficients of the elderly and young groups are statistically indifferent. Figure 21 also suggested the upper limit of 39°C in UTCI, beyond which elderly activities tend to dinimish: the only 3 data entries recorded when ambient UTCI exceeded 39°C can be treated as outliers – these were because of a voting event set up for the District Council Election on site 2 11:00-12:00 on 17 Jun., 2015.

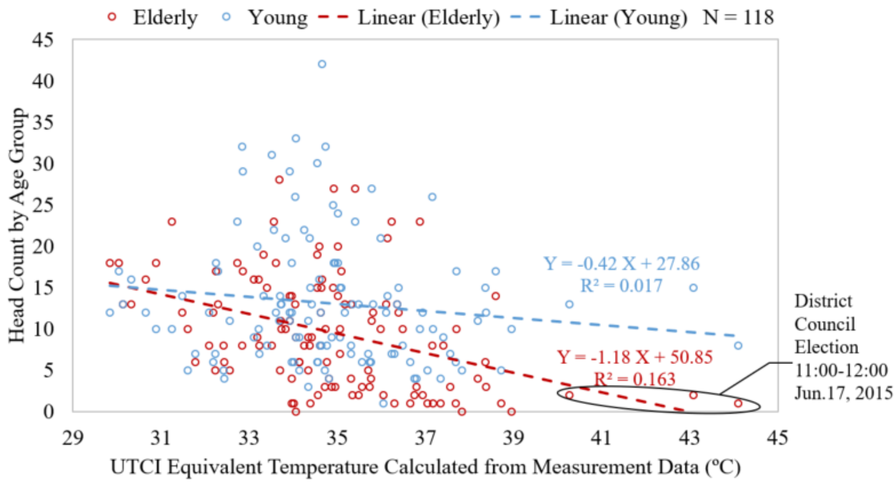
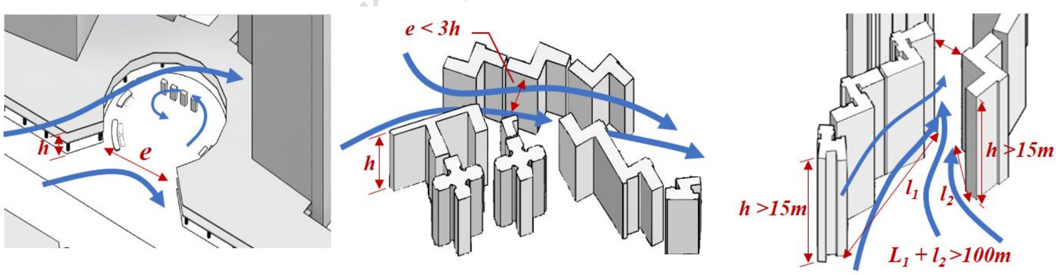


Figure 21 Scatterplot of headcount breakdown by age group on the 3 sites. Data were recorded every half an hour on the two study days.

Moreover, open space layout and massing of surrounding buildings can be used to manipulate wind in order to reduce heat stress. Aerodynamic principles for external spaces were discussed by Gandemer (1975) and exemplified by measured data from this study (Figure 22) : Site 1 is a semi-enclosed open space surrounded by podium structures, which reduces wind and was referred to by Gandemer as the “Mesh Effect”. Site 2 sits in a breezeway towards the summer monsoon, which induces wind in a phenomenon described as the “Channel Effect”. Site 3 features a narrow choking point in the breezeway, which accelerates wind in a way referred to as the “Venturi Effect”. Due to a combination of accelerated wind, shading, and trees, site 3 experienced the lowest level of heat stress of the three and it is a desirable open space configuration for Hong Kong’s hot and humid summer.



(Left) “Mess Effect”: the reduction of wind speed in an enclosed space.

(Middle) “Channel Effect”: wind passes through two rows of buildings;

(Right) “Venturi Effect”, wind accelerates in a funnel known as the Venturi neck.

Figure 22 The modifying effect of wind around buildings on-site in reference to Gandemer (1975).

Lastly, instead of simply planting trees, the use as shelter and shading are also important design elements. Transitional spaces, such as colonnade and corridors should be promoted. Hard pavements should be avoided in general when attractive facilities are placed in the central part of large open space. Areas with lower UTCI, located mostly under the shade and breeze, were a more favourable choice for outdoor activity compared with the large empty areas.

To further establish the relationship between UTCI and people attendance, the Mean Attendance was computed within bins of 1 °C on the UTCI scale, and results are plotted in Figure 23. The curve shows a decline trend on Mean Attendance as the UTCI value increases: for each 2 °C of increase in UTCI equivalent temperature, a decrease of attendance by 1.2 (or by 7%) is expected at the three study sites during the study period. By regressing Mean Attendance on UTCI and UTCI squared, a linear function can be derived that can be used to predict attendance of open space during the study period (Formula 3). The regression model has an R^2 value of 0.81, indicating an 81% of the variation in mean attendance can be explained by the variation of the thermal environment.

$$A = -1.60 * UTCI + 78.06 \quad (3)$$

Although this predictive function is not intended to be applied in conditions beyond the study conditions, i.e. open spaces of Hong Kong's housing estates under heat stress (on-site UTCI > 40 ºC), it is nevertheless a useful measure for the design and planning of a large number of housing development that the city is committed to.

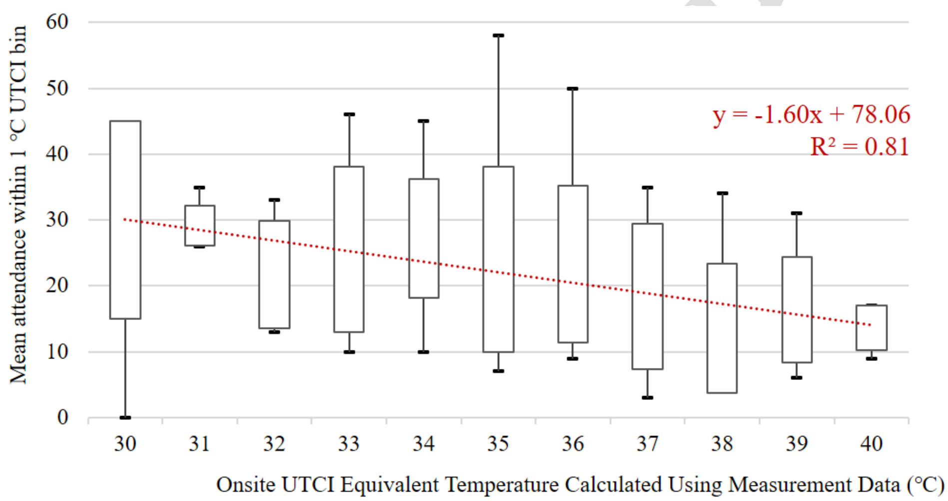


Figure 23 Scatterplot of mean attendance (people count) and outdoor thermal environment measured in UTCI equivalent temperature.

It is acknowledged that field measurement and observations in this study were conducted in two hot days, a relatively short period. The sample size obtained on-site was limited by the number of equipment and manpower available on-site. Given the constraints of traditional research methods such as field observation and questionnaire, we intend in the next steps to use new evidence such as WIFI-scanner or geo-coded social media data, which allow continuous surveillance of open space usage for an extended period of time.

Conclusion

The study presented in this paper focused on the outdoor activity distribution pattern for three sites in a public housing estate with a high density context. The purpose was to quantify the impact of the physical layout of open spaces on thermal environment and its usage. The results show strong negative correlations between heat stress and outdoor activities in open spaces. The correlations are significant across age groups, with the elderly activities appear to more susceptible to disruptions from severe heat in comparison with the younger groups. Elderly activities in open spaces largely diminished when the ambient thermal environment exceeds 39 °C in UTCI. Findings can help to set performance criteria for the development of new open spaces and retrofitting of existing open spaces. Breezeway and the “Venturi Effect”, the funnel phenomenon to accelerate wind, have proven to be effective in reducing heat stress in open spaces in a high density context. On average, the purposefully design open space was able to reduce the equivalent temperature by up to 2 °C in UTCI, increase pedestrian level wind speed by 2 m/s, and attract more social and optional activities; occupants visit the space more often and stay longer during each visit. The environmental simulation methods described can be used to predict spatial usage distribution. Further studies with relative parameters in other season will be explored in the future.

Statements on Author Contribution

Jianxiang Huang came up with the original idea, research design, literature review, manuscript writing, and figures. Yang Chen contributed to field experiment, preliminary data analysis, literature review and manuscript writing. Phil Jones contributed to manuscript writing and editing. Tongping Hao contributed to data analysis, simulation and visualization of results.

Statement on Potential Conflicts of Interest

The authors whose names are listed above certify that they have no affiliations with nor involvement in any organization or entity with any financial or personal interests in the subject matter or materials discussed in this manuscript.

Appendix

Questionnaire on Heat Stress and Activities in Outdoor Open Spaces

Greetings! We are a group of researchers from the Department of Urban Planning at the University of Hong Kong conducting a study on Heat Stress and Activities in Outdoor Open Spaces. We would like to ask you a few questions regarding the use of this particular place, the questionnaire takes approximately 10 mins to fill in. We pledge all data collected will be strictly classified and will be used for research purpose only.

1. How often do you visit this place?
□ daily □ Once Every 2-3 Days □ Once Per Week □ Rarely

2. Where do you live currently?
□ Lower Ngau Tau Kok Estate □ Upper Ngau Tau Kok Estate □ Others (please specify)______

3. What physical features in this place do you consider attractive?
□ Greenery □ Seating □ Shading □ Temperature
□ Ventilation □ Rain Shelter □ Others (please specify)__________

4. When do you usually use this place?
□ 5:00-8:00 □ 8:00-11:00 □ 11:00-14:00 □ 14:00-18:00 □ After 18:00

5. How long do you usually stay at this place?
□ ≥ 2 hours □ 1-2 hours □ 0.5-1 hour □ ≤ 30mins

6. What do you think of the current thermal environment?
□ cold □ cool □ Just right □ warm □ hot

7. Are there other reasons why you choose to use this place? (please write down answers below)

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