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# The influence of perceived aesthetic and acoustic quality on outdoor thermal comfort in urban environment

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ABSTRACT

Thermal comfort in outdoor space is essential for human health and human wellbeing. The comfortable outdoor space enhances urban livability and sustainability. Currently, the influence of environmental quality on human thermal comfort is not conclusive. Research on the interrelation between perceived environmental quality and subjective human thermal comfort is needed to have a concrete argument. This paper examines the relationship between perceived aesthetics, perceived acoustics, and the outdoor thermal comfort in Hong Kong during the hot summer, by conducting questionnaires and on-site meteorological measurement. Thermal sensation vote (TSV) showed a strong, negative association with the perceived aesthetics vote and acoustics vote as calculated for 1 °C UTCI bin. It was also revealed that the groups with satisfactory of perceived acoustic and aesthetics have a significantly higher comfort vote than that of unsatisfactory groups. Findings suggest that humans in a perceptually quiet and beautiful outdoor environment have a significantly higher thermal tolerance, and lower thermal sensitivity. This work provides valuable data on the effects of perceived environmental quality on outdoor thermal comfort in subtropical hot summers in high density urban settings. These findings help the urban development in the outdoor urban environment in our changing climate. Urban planner and designer can create a more satisfactory aesthetic and acoustic environment to improve the thermal tolerance and adaptation of individuals in the outdoor urban environment.

## 1. Introduction

In urban environment, outdoor spaces are important to urban living as they are often perceived as extended living spaces [1]. Well-designed outdoor spaces provide a comfortable environment for citizens and encourage the use of outdoor spaces which has a positive effect on the health and well-being of citizens. It is therefore necessary to comprehensively consider the aspects of neighbourhood and architectural design that affect people's comfort and the quality of the urban environment. Providing high-quality outdoor spaces for equitable access of citizens also contributes to sustainable development and liveability of cities.

Outdoor thermal comfort is related to outdoor microclimates such as air temperature ($T_a$), humidity, wind velocity, mean radiant temperature ($T_{mrt}$) and thermal comfort indices like PET and UTCI [29,35,40,44,45,47]. These microclimatic conditions are determined by urban geometry and urban greenery [2,17,31,32]. It is also apparent that the usage of outdoor spaces is also influenced by the environmental conditions and users' thermal experience [39]. It implies that the design of urban geometry plays a key role in enhancing thermal comfort and hence encouraging the use of outdoor spaces.

Lenzholzer et al. [22] argued that, apart from the thermo-physiological approach which forms the basis of human thermal comfort models, psychological adaptation is also a key element in the evaluation of outdoor thermal comfort. It is an adjustment of the perception of sensory information and dependent on past experience and expectations [5,15,20,21]. [38] revealed that microclimatic conditions only account for approximately 50% of the variance in the relationship between objective and subjective evaluation of thermal comfort while the rest may be due to psychological adaptation. Issues concerning psychological adaptation include naturalness, expectations, short- and long-term experience, time of exposure, perceived control and environmental stimulation.

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### 1.1. Multi-sensory perception of thermal comfort

In the outdoor environment where urban dwellers are exposed to a wide range of environmental stimuli, the conventional understanding of thermal comfort imposing a single stressor, i.e. meteorological conditions, is not adequate for addressing the complex relationship between human thermal comfort and the environment where people are exposed [14]. claimed that thermal comfort is generally governed by physical, physiological and psychological processes. Therefore, it involves multiple sensory interactions apart from the influence of meteorological conditions [10]. They particularly argued that non-tactile stimulations are the key to address the interactions between thermal sensation and thermal comfort in outdoor environment [39]. further suggested that such multi-sensory, environmental stimuli can facilitate psychological adaptation which is apparently individuals' perceived choice over discomfort when they visit an outdoor space [37]. suggested that the noise of the environments and the beauty of architecture and greening might influence on the perception of thermal comfort. Previous thermal comfort studies in an outdoor and indoor environment have no conclusive suggestions between satisfaction of aesthetic and acoustic quality, and subjective thermal comfort. The variations are contributed by the difference of climatic conditions, respondents' cultural background, urban setting of the sites, and other psychological and physical factors [16,26,30,33].

### 1.2. Aesthetic elements

The hue-heat hypothesis states that colours are associated with the perception of temperature due to the psychological distinction between "warm" and "cool" colours (Morgensen and English, 1926). Earlier studies did not find significant influence of colours on physiological response of human body (Bennet, 1972; [18]. Subjective thermal comfort was mainly influenced by indoor temperature and tasks that the subjects were engaged (Berry, 1961). However, recent studies reported conflicting results that subjective feeling of warmth or coldness is affected by different colours of lights or objects (Albers et al., 2015; Baniya et al., 2016; Ziat et al., 2016). It was also shown that subjects regarded cool colours as more comfortable in warm environment and vice versa (Wang et al., 2018).

Illumination is well-known for its effect on the synthesis and release of melatonin, a pineal hormone which modulates sleep patterns (McIntyre et al., 1989). Cagnacci et al. (1992) argued that thermal sensation would change after exposing to bright and dim light under the same ambient temperatures due to the variations in melatonin level, leading to changes in the set-point of the core temperature. Teramoto et al. (1996) further confirmed that people felt cooler when they are exposed to dim light under mild to warm temperatures. Colour temperature of room lighting also affects the subjective feeling and behaviour in response to the atmosphere. Huebner et al. (2016) found that subjects tended to put on more clothes under cold light than warm light. It suggested that colour is an important factor to subjective thermal sensation and comfort, as well as the adaptive behaviour of building occupants. In the outdoor environment, visual stimuli are highly complex and pedestrians do not have sufficient time of exposure to distinguish the effects of individual aesthetic features like colour and illumination. As such, evaluating the effect of overall aesthetics quality on thermal perception is more practical in outdoor settings.

### 1.3. Acoustic elements

The effect of acoustic level on thermal comfort has been widely studied but the results are generally inconclusive [18]; Hancock and Pierce, 1985 [42]. [10]; argued that the conflicting results are largely due to the intrusive factors to corresponding tasks performed by building occupants. Noise level was found to be associated with subjective thermal perception in a warm environment [42]. Subjects felt more thermally unpleasant when noise level increased [43]. However, they did not find any significant relationships between noise level and physiological responses. Their results suggested that the psychological effect of noise is more prominent than its physiological effect in the overall comfort assessment of a place.

The urban soundscape is important to the comfort of urban outdoor environment. Tsai and Lin (2018) found the relationship between background soundscape, in terms of equivalent continuous sound pressure level ($L_{eq}$), and thermal environment in a study on park attendance. Neutral thermal conditions were found to be related to higher $L_{eq}$ while lower $L_{eq}$ was recorded under hot to very hot thermal comfort conditions. Noise was also proved to be a significant factor in thermal perception that people perceiving calmness reported 1.17 times higher chance of reporting warmer thermal sensation than people perceiving urban noise (Galindo and Hermida, 2018). Although the effect varies with other social factors such as age and gender, it suggested that the acoustic environment of outdoor spaces is associated with thermal perception of the users.

### 1.4. Objectives of the study

Unlike the conventional approach of associating subjective perception of the thermal environment with observed microclimatic conditions, the present study incorporates the psychological aspects, in terms of perceived aesthetic and acoustic quality, into the relationship between human thermal perception and microclimatic conditions in outdoor settings. The objectives of the present study are to examine how the satisfactions of aesthetic and acoustic quality affect subjective perception of thermal comfort in the outdoor environment. The interactions between aesthetic and acoustic satisfactions and thermal conditions are also investigated. Findings contribute to a more comprehensive understanding of how human thermal perception is affected by the environmental conditions in outdoor settings. The present study was conducted in Hong Kong, a high-rise compact city with highly complex outdoor environment in urban areas. Implications on urban design are also discussed and findings are expected to contribute to better urban design in high-density urban environment, especially for those with physical constraints of land resources.

## 2. Methodology

### 2.1. Climatic conditions of Hong Kong

Hong Kong has a humid subtropical climate (Köppen climate classification Cwa). It is a hot and humid summer spanning from May to September with occasional showers and thunderstorms. Temperature in the afternoon often exceeds 31 °C while temperature at night generally remains around 26 °C with high humidity. Average summer (May to September) temperature is 27.8 °C and mean maximum and minimum temperatures are 30.2 °C and 25.9 °C respectively. Relatively humidity is generally over 80% in summer. Monthly sunshine hours range from 140.4 to 212.0 h in summer, but cloud amount often exceeds 70% due to the influence of low-pressure system in the region.

### 2.2. Description of study sites

Questionnaire surveys and simultaneous meteorological measurements were conducted in three typical urban settings in Hong Kong, namely pedestrian streets, residential estates, and urban parks/open spaces. A total of 15 sites were selected with respect to the attributes of urban geometry and vegetation at local sites. Eight sites are located in pedestrian streets while four sites are located in residential estates. Three other sites are situated in large urban parks or waterfront areas (Fig. 1). Pedestrian streets are characterized by heavy pedestrian and vehicle traffic, narrow street canyons, and lack of vegetation. Sites situated in residential estates have calmer pedestrian traffic and are

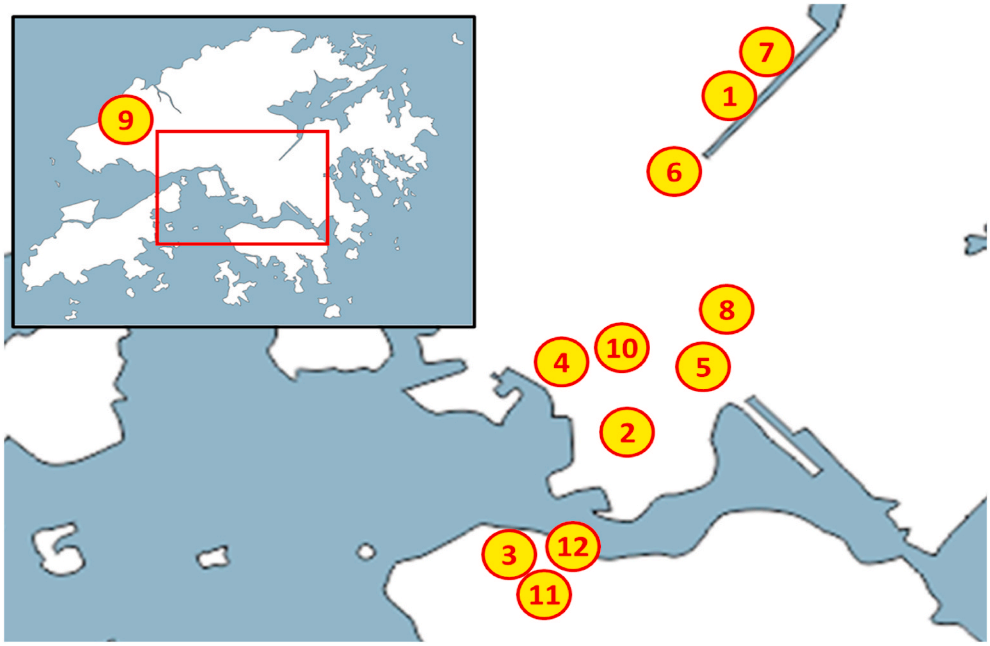


**Fig. 1.** Location of the survey locations.

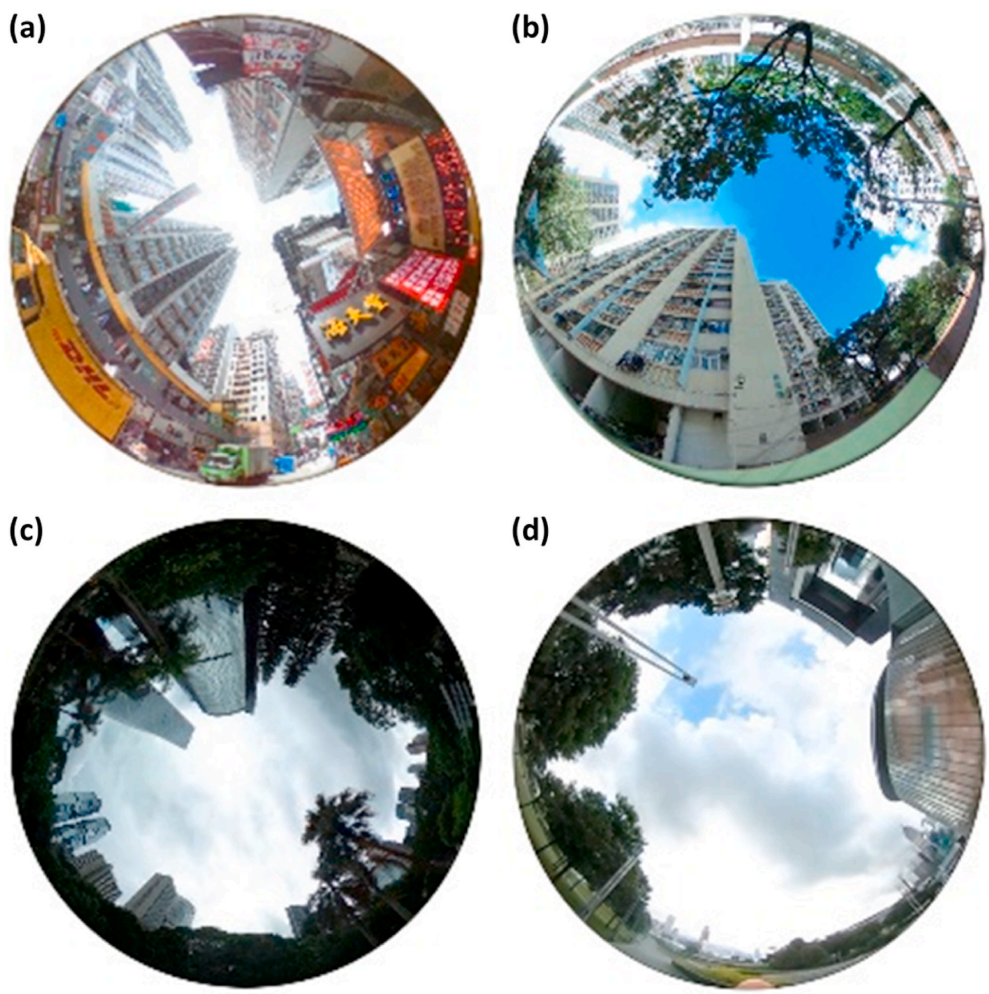


**Fig. 2.** Hemispheric photos of (a) pedestrian street, (b) residential estate, (c) urban park, and (d) waterfront for SVF calculation.

normally distanced from vehicle traffic. Urban parks or waterfront sites are densely vegetated and more open in terms of the environmental settings. Sky view factor (SVF) was calculated from hemispheric photos (Fig. 2) for each survey sites at the height of the meteorological instruments (Table 1). This provides an evaluation of the morphological settings including the aspect ratio, materials, vegetation for subsequent analysis.

### 2.3. Micrometeorological measurements

Micrometeorological measurements were simultaneously conducted with a thermal comfort survey. The measurement and survey campaigns were carried out from 10:00 to 16:00 between June and September 2017 at designated sites on clear summer days with similar weather conditions. Mobile meteorological stations, equipped with a TESTO480 datalogger and probes for measuring air temperature ($T_a$), relative humidity (RH), and wind speed (v), as well as a globe thermometer for measuring the globe temperature ($T_g$), were used in the present study (Fig. 3). The globe thermometer is composed of a thermocouple wire (TESTO flexible Teflon type K) held inside a black painted table tennis ball with a diameter (D) of 38 mm and emissivity ($\varepsilon$) of 0.95. The mean radiant temperature ($T_{mrt}$) is determined using the following equation from [46]:

$$T_{mrt} = \left[ \left(T_g + 273.15\right)^4 + \frac{1.10*10^8*v^{0.6}}{\varepsilon*D^{0.4}} \left(T_g - T_a\right) \right]^{1/4} - 273.15 \quad (1)$$

Universal Thermal Climate Index (UTCI) was selected as the thermal index in the present study [23]. UTCI is defined as "the air temperature which would produce under reference conditions the same thermal strain as in the actual thermal environment" [7]. It is therefore a one-dimensional quantity which represents the human physiological reaction to the actual thermal conditions defined by multiple dimensions. It was developed based on the UTCI-Fiala model which was adapted to predict human responses to outdoor climate conditions. The model also considers behavioural adjustments of the clothing insulation with outdoor air temperature as well as the effect of air movement, walking speed and clothing's thermal and evaporative resistances (Havenith et al., 2011). UTCI has been widely used in the assessment of outdoor thermal environment [9,28,41]. Since the calculation of UTCI requires wind speed at a height of 10 m above ground, the following equation was adopted to extrapolate wind speed at 10 m height (z) from the instrument height ($z_r$ = 1.5 m) based on the logarithmic law.

$$v(z) = v_r \frac{\log\left(z/z_0\right)}{\log\left(z_r/z_0\right)} \quad (2)$$

where $v_r$ is the wind speed measured at the instrument height and $z_0$ is the roughness length (0.01 for flat ground surface). The software Bio-Klima was used to calculate UTCI in the present study. It consists of different methods of bioclimatic studies and provides easy calculations of more than 60 various biometeorological and thermophysiological indices [8,9]. The mandatory inputs of meteorological variables include air temperature, relative humidity, globe temperature, wind speed, metabolic rate and clothing level (thermal insulation).

**Table 1**
Details of survey locations.

| | Location | Type | SVF | Sample |
|---|---|---|---|---|
| 1 | Shatin Town Hall and Park | Park/Waterfront | 0.345 | 239 |
| 2 | Mong Kok | Street | 0.211 | 184 |
| 3 | Central | Street | 0.158 | 75 |
| 4 | Sham Shui Po | Street | 0.276 | 100 |
| 5 | Kowloon City | Street | 0.366 | 180 |
| 6 | Tai Wai | Street | 0.458 | 201 |
| 7 | Lek Yuen Estate | Residential Estate | 0.315 | 185 |
| 8 | Wong Tai Sin Estate | Residential Estate | 0.286 | 175 |
| 9 | Yuen Long | Street | 0.230 | 56 |
| 10 | Kowloon Tong | Residential Estate | 0.529 | 91 |
| 11 | Hong Kong Park | Park/Waterfront | 0.436 | 155 |
| 12 | Central Pier | Park/Waterfront | 0.573 | 151 |

### 2.4. Thermal comfort survey

The thermal comfort survey was simultaneously conducted with micrometeorological measurements at designated sites from June to September 2017 to acquire information of the subjective thermal perception and perceived environmental quality of the respondents. The surveys were conducted in a spot within 10 m from the micrometeorological station. 1917 effective responses were obtained and included in subsequent statistical analyses. The questionnaire consists of questions for evaluating the thermal perception and perceived environmental quality (see Appendix 1). Thermal sensation vote (TSV) was reported from cold (−3) to hot (+3), with neutral sensation as 0 based on the seven-point ASHRAE scale [3] while overall state of thermal comfort (TCV) was rated on a four-point Likert scale from very uncomfortable (−2) to very comfortable (+2), without any option for the neutral state. Two aspects of perceived environmental quality, namely aesthetic (AeSV) and acoustic (AcSV), were evaluated using a five-point Likert scale from very unsatisfactory (−2) to very satisfactory (+2), with a neutral option. The demographic background of the participants was also obtained, and the activity level of the participants was recorded to represent the metabolic rate. The clothing levels were observed by the interviewers using the checklists from ANSI/ASHRAE Standard 55 [3].

### 2.5. Characteristics of respondents

A total of 1842 respondents participated in the questionnaire survey (Table 2). Male and female respondents accounted for 829 (45.0%) and 1013 (55.0%) respectively. 25.6% of the respondents were below 18 years of age while 25.7% of them were above 55 years of age. Approximately 30% of the respondents were between 18 and 34 years old while 18.5% of them were between 35 and 54 years of age. Respondents who were under air-conditioned environment accounted for 64.4% while 35.6% of the respondents were not air-conditioned 15 min before the survey. Over half of the respondents were walking before the survey while 32.6% of them were standing at the locations where the survey was conducted. 12.7% of the respondents were sitting 15 min before the survey while only 0.9% of the respondents were doing exercise. These data provide a comprehensive background of the respondents to ensure a fair distribution of respondents' characteristics and allow potential adjustments to these factors in the statistical analyses.

### 2.6. Statistical analysis

Descriptive statistics and boxplots were used to provide a summary of perceived aesthetic and acoustic quality, as well as subjective thermal perception. Wilcoxon rank sum test was used to compare the median difference of the subgroups [36]. The distributions of $T_a$ and UTCI between perceived satisfactory and unsatisfactory subgroups for both aesthetic and acoustic quality were also analyzed. Kolmogorov-Smirnov (KS) test was used to compare the probability distribution of different perceived aesthetic and acoustic vote group. A conservative level of significance of 0.05 was adopted for a two-tailed test with the null hypothesis ($H_0$) that the two distributions are equal.

Spearman's rank correlation test between AeSV/AcSV and TSV was determined. Weighted linear regression models of thermal sensation and environmental quality perceptions were developed. The binned data, based on 1 °C $T_a$ and UTCI bins, were employed for the weighted linear regression model. Weighted linear regression model was used to investigate the relationship between TSV/TCV and $T_a$/UTCI. The slope and coefficient of determination ($R^2$) of the weighted linear regression

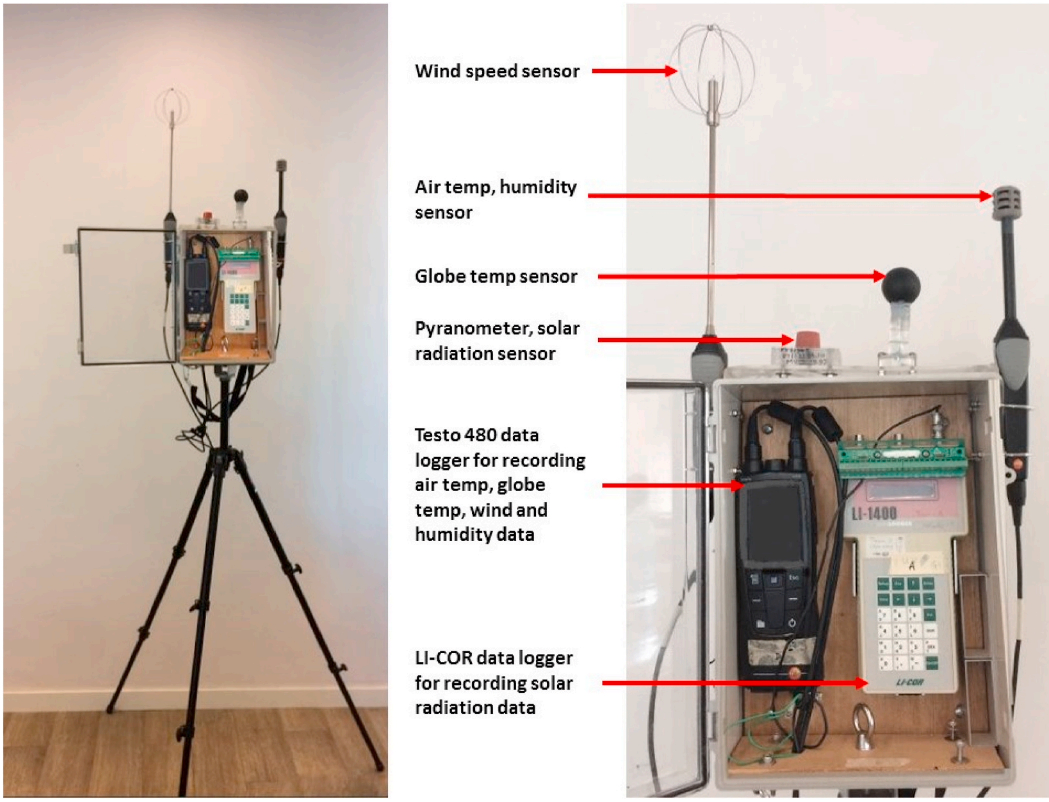


**Fig. 3.** Mobile meteorological station and the instrumental setup used in this study.

**Table 2**
Characteristics of respondents.

| Sex | n | % | 15-min AC Environment | n | % |
|---|---|---|---|---|---|
| Male | 829 | 45.0 | Yes | 1186 | 64.4 |
| Female | 1013 | 55.0 | No | 656 | 35.6 |
| **Age** | **n** | **%** | **15-min activity** | **n** | **%** |
| <18 | 472 | 25.6 | Sitting | 234 | 12.7 |
| 18–24 | 343 | 18.6 | Standing | 600 | 32.6 |
| 25–34 | 204 | 11.1 | Walking | 991 | 53.8 |
| 35–44 | 165 | 9.0 | Doing Exercise | 17 | 0.9 |
| 45–54 | 175 | 9.5 | | | |
| >55 | 473 | 25.7 | **Location** | **n** | **%** |
| Prefer not revealed | 10 | 0.5 | Residential Estate | 443 | 24.1 |
| | | | Pedestrian Street | 896 | 48.6 |
| **Total no. of respondents** | 1842 | | Park/Waterfront | 503 | 27.3 |

model were used to compare across different perceived acoustic and aesthetic groups. All statistical analyses were performed with the 'R' programming language.

## 3. Results

### 3.1. Micrometeorological measurements

Meteorological conditions recorded during the survey campaign were able to represent the typical summer conditions in Hong Kong, especially in the late-morning and afternoon where heat stress is commonly experienced (Table 3). Maximum $T_a$ recorded on site often exceeded 35 °C due to the intense heat accumulated in the pedestrian environment. This high $T_a$ was not reflected in the $T_a$ recorded at the HKO Headquarter station where the instruments were set up in a relatively vegetated site. Wind speed (v) was also low in most cases with average wind speed of 1.64 m/s only at maximum on August 16, 2017, indicating the reduced air ventilation in the urban environment.

**Table 3**
Meteorological conditions of the survey days.

| Date | $T_a$ Range (°C) | RH (%) | V (m/s) | $T_{mrt}$ (°C) | UTCI (°C) | Daily Range of $T_a$ at HKO | RadG (W/m$^2$) |
|---|---|---|---|---|---|---|---|
| 20170607 | 32.1–35.7 | 59.8 | 1.11 | 35.1 | 37.2 | 27.2–34.0 | 312.3 |
| 20170608 | 31.1–31.9 | 66.0 | 1.09 | 38.1 | 37.5 | 28.3–32.5 | 262.4 |
| 20170609 | 31.9–35.2 | 64.6 | 1.06 | 37.2 | 38.2 | 28.1–31.9 | 260.5 |
| 20170725 | 29.9–35.1 | 73.1 | 0.69 | 33.9 | 35.7 | 27.7–33.1 | 304.1 |
| 20170807 | 33.3–38.3 | 61.1 | 0.84 | 40.3 | 40.1 | 27.3–33.0 | 302.0 |
| 20170808 | 29.8–33.9 | 76.4 | 0.83 | 34.7 | 36.5 | 28.4–32.8 | 268.9 |
| 20170815 | 30.9–35.8 | 66.4 | 0.94 | 34.7 | 35.8 | 28.1–32.9 | 276.9 |
| 20170816 | 32.2–35.1 | 57.4 | 1.64 | 39.6 | 38.6 | 28.2–31.2 | 207.9 |
| 20170817 | 32.5–36.9 | 55.7 | 0.80 | 40.7 | 37.6 | 27.9–33.0 | 252.7 |
| 20170821 | 32.8–38.9 | 55.2 | 1.00 | 39.5 | 39.2 | 28.6–34.5 | 272.6 |
| 20170906 | 30.4–33.7 | 68.9 | 0.66 | 32.9 | 35.6 | 27.3–32.3 | 200.9 |
| 20170911 | 31.8–37.2 | 57.7 | 0.60 | 37.1 | 37.3 | 27.6–32.4 | 264.5 |
| 20170912 | 32.2–37.3 | 60.0 | 1.02 | 42.3 | 39.5 | 27.9–32.8 | 160.8 |

Average $T_{mrt}$ ranged from 33.9 °C to 42.3 °C, suggesting that the radiant environment also contribute to the intense heat at the study sites. UTCI, as calculated from the measured meteorological parameters, generally falls into the categories of “strong heat stress” (UTCI value of 32–38 °C) and “very strong heat stress” (UTCI value of 38–46 °C) according to [9].

### 3.2. Relationship between thermal perception and satisfaction of aesthetic and acoustic environment

Fig. 4a shows that there was a moderately strong relationship between mean TSV and mean AeSV as calculated for 1 °C UTCI bin ($R^2$ = 0.63). Respondents tended to report cooler TSV when they were more satisfied with the aesthetic quality of the environment that they were exposed to. Spearman rank-order correlation coefficient (ρ) was calculated to examine the significance of the association between TSV/TCV and AeSV/AcSV. The relationship between TSV and AeSV was marginally insignificant ($S = 1.08 \times 10^9$, p-value = 0.084, $\rho = -0.040$). Nonetheless, Kolmogorov-Smirnov (KS) test was also conducted to examine whether the distribution of TSV and TCV across three groups of the aesthetic/acoustic satisfaction (i.e. satisfactory, neutral, and unsatisfactory). KS tests showed that the TSV distribution is significantly different across the three groups of aesthetic satisfaction ($p < 0.0001$). 46.4% of the respondents who were unsatisfied with the aesthetic environment felt hot, compared to about 48% for the other two groups (Fig. 5a), suggesting the potential influence of aesthetic quality on thermal perception. Moreover, there was also a strong relationship between percentage of TCV (%TCV) and mean AeSV at 1 °C UTCI bin ($R^2$ = 0.84, Fig. 4b). More comfortable votes were reported if the respondents were satisfied with the aesthetic quality. It is notable that there was a significant outlier (43 °C UTCI bin) in the linear regression, suggesting that this relationship may not be valid under extreme heat stress conditions. Spearman rank-order correlation coefficient indicated significant association between TCV and AeSV ($S = 8.43 \times 10^8$, p-value = < 0.0001, $\rho = 0.191$) while KS test also revealed that the TCV distribution was significantly different across the three groups of aesthetic satisfaction ($p < 0.0001$). It was also shown in the proportion of uncomfortable votes for the “unsatisfactory” and “satisfactory” group (85.6% and 60.2% respectively, Fig. 5b).

There was a significant association between mean TSV and mean AcSV at 1 °C UTCI bin ($R^2 = 0.63$, Fig. 4c). Respondents felt cooler when they were more satisfied with the acoustic quality of the environment. Spearman rho (ρ) revealed that TCV was significantly correlated with AcSV ($S = 1.13 \times 10^9$, p-value = 0.0004, $\rho = -0.083$). KS test indicated that the distribution of TSV was different among the three groups of acoustic satisfaction, with higher proportion of “hot” votes in respondents who were unsatisfactory with the acoustic environment

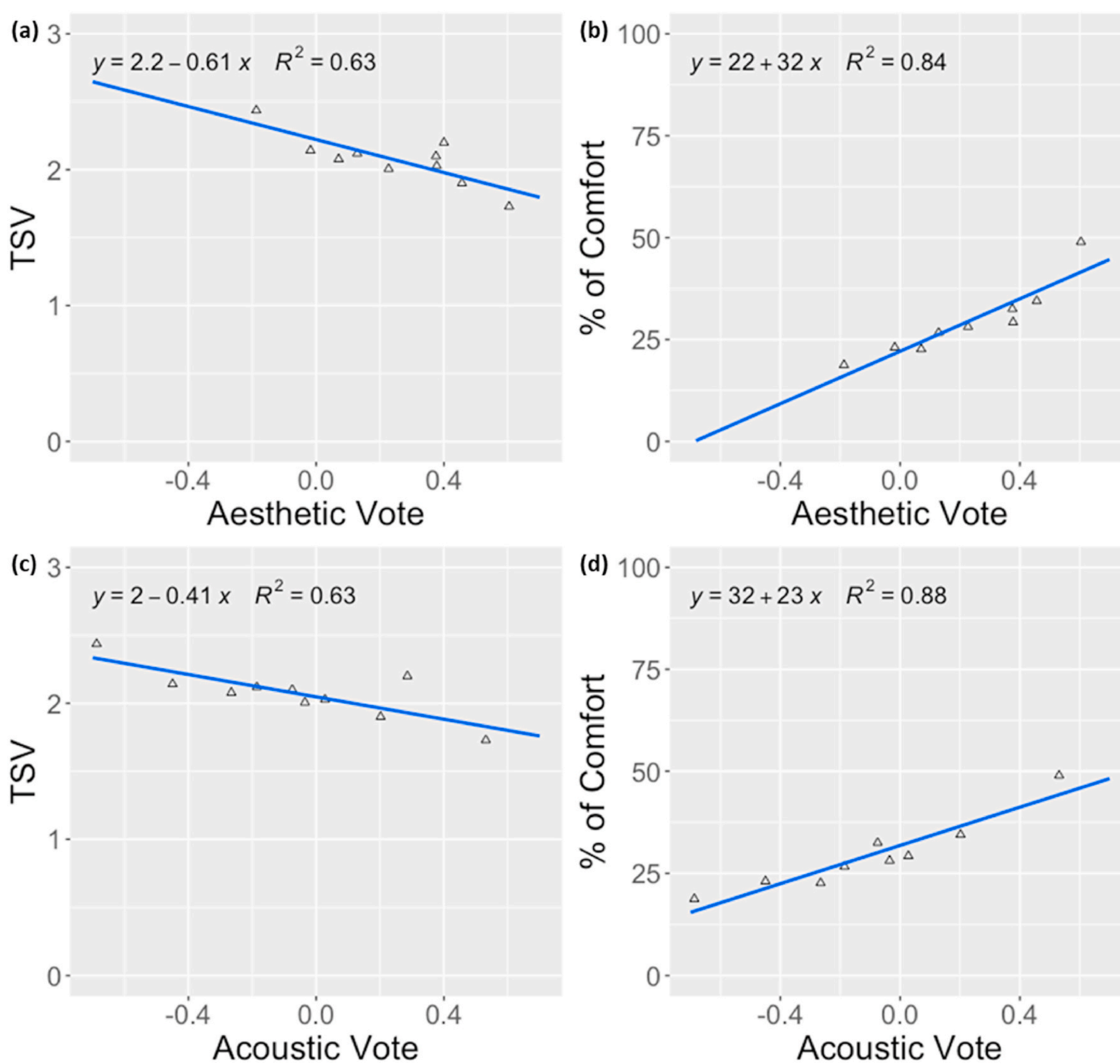


**Fig. 4.** Scatterplots between (a) mean TSV and (b) percentage of TCV and mean aesthetic satisfactory vote per 1-°C UTCI bin. Scatterplots between (c) mean TSV and (d) percentage of TCV and mean acoustic satisfactory vote per 1-°C UTCI bin.

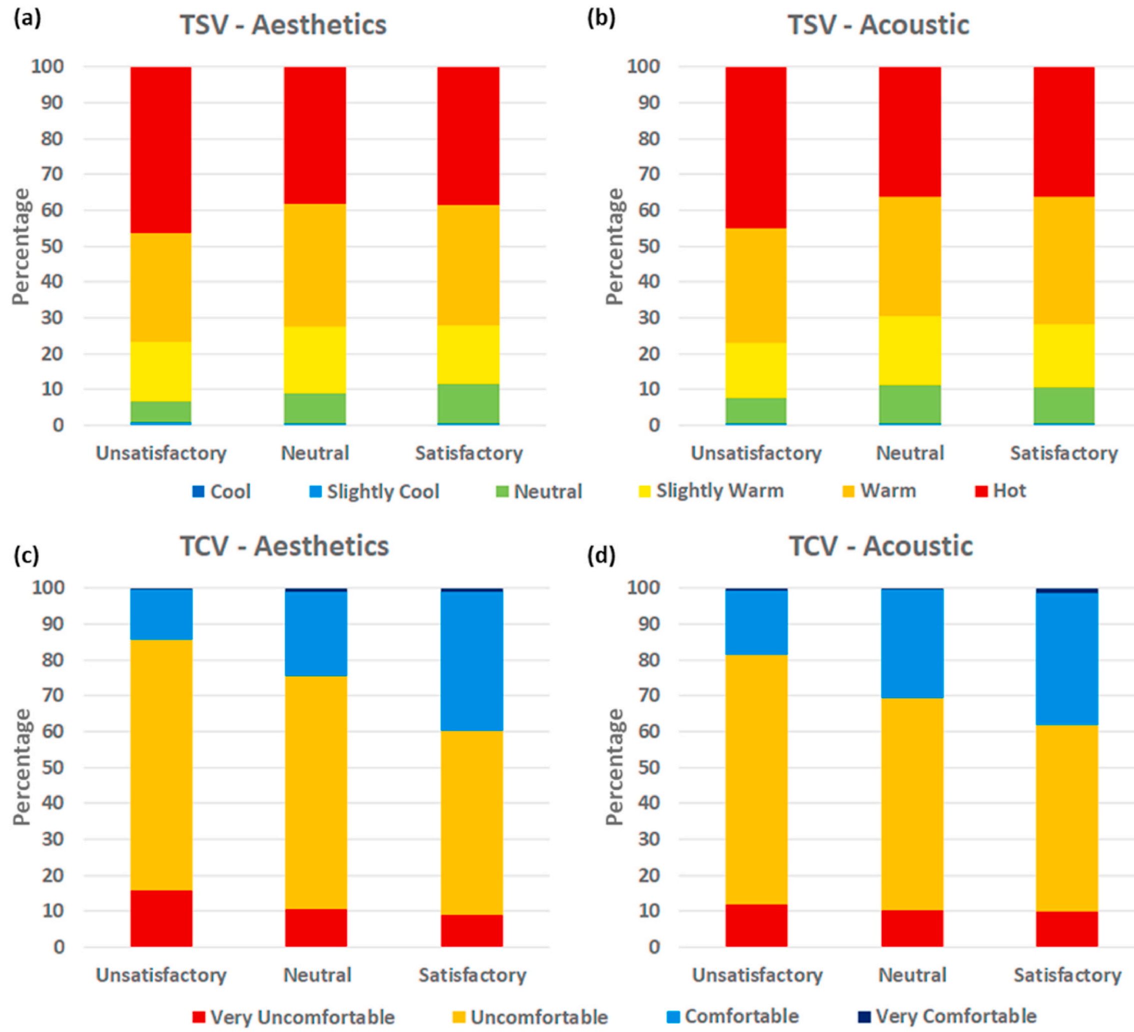


**Fig. 5.** Distribution of the TSV according to satisfaction of (a) aesthetic and (b) acoustic quality. Distribution of the TCV according to satisfaction of (c) aesthetic and (d) acoustic quality.

(45.2%, Fig. 5c). %TCV was also found to have a strong relationship with mean AcSV ($R^2$ = 0.88, Fig. 4 hemispheric photos 5 d). Similar proportion of comfortable votes was obtained with lower mean AcSV compared to the aesthetic quality, implying that people's expectation on acoustic quality may be less that aesthetic quality. Spearman rho also indicated significant association between TCV and AeSV ($S = 8.71 \times 10^8$, p-value $< 0.0001$, $\rho = 0.163$) while KS test showed that the TCV distribution of the unsatisfactory groups was significantly different from the neutral and satisfactory groups ($p < 0.0001$). However, it was not significant between the neutral and satisfactory group ($p = 0.0672$), suggesting that respondents expressing neutral acoustic satisfaction perceived overall comfort in a similar way to those who are satisfied with acoustic quality. The proportion of uncomfortable votes for the "unsatisfactory" and "satisfactory" group were 81.3% and 61.6% respectively (Fig. 5d).

### 3.3. *Influence of thermal conditions on thermal perception and aesthetic satisfaction*

Fig. 6a and b shows the boxplots of UTCI and $T_a$ based on the three groups of aesthetic satisfaction. Median UTCI was higher in the unsatisfactory group (38.2 °C) than the neutral (37.2 °C) and satisfactory group (36.7 °C). Leaving out the outliers, the spread of the data was narrower in the satisfactory group (S.D. = 1.85 °C) than the unsatisfactory group (S.D. = 2.03 °C). The difference in median $T_a$ between satisfactory and unsatisfactory groups was slightly smaller. Median $T_a$ was lower in the satisfactory group (32.7 °C) than the neutral (33.3 °C) and unsatisfactory groups (33.7 °C). The variation in the thermal conditions was lower in the satisfactory group (S.D. = 1.33 °C) than the unsatisfactory group (S.D. = 1.63 °C). The near-extreme value (90th-percentile) of UTCI was 39.7 °C for the satisfactory group while the 90th-percentile of UTCI was 40.6 °C for the respondents reporting unsatisfactory vote for aesthetic quality. The difference between the 90th-percentile of $T_a$ observed for satisfactory and unsatisfactory groups (1.8 °C) was larger than that of UTCI (0.9 °C).

Aesthetic satisfaction was found to play an important role in thermal sensation. Fig. 6c shows the relationship between TSV and UTCI for raw and binned data for the three groups of aesthetic satisfaction. In line with previous studies (Gautam et al., 2019; [24], the coefficients of determination ($R^2$-value) for the binned data were higher than those for the raw data (Table 4). However, the regression coefficients were found to be similar, indicating that both the raw and binned data share a similar linear trend in general. Respondents who were not satisfied with the aesthetic quality reported higher TSVs than those who showed neutral or positive satisfaction with the aesthetic quality in the surrounding environment (Fig. 6c). The sensitivity of thermal sensation to the changes in thermal conditions (in terms of UTCI) was similar in the satisfactory and unsatisfactory groups (slope = 0.047 and 0.051 respectively), except that the neutral group was less sensitive (slope = 0.044). Percentage of comfort votes (%TCV) per UTCI bin exhibited

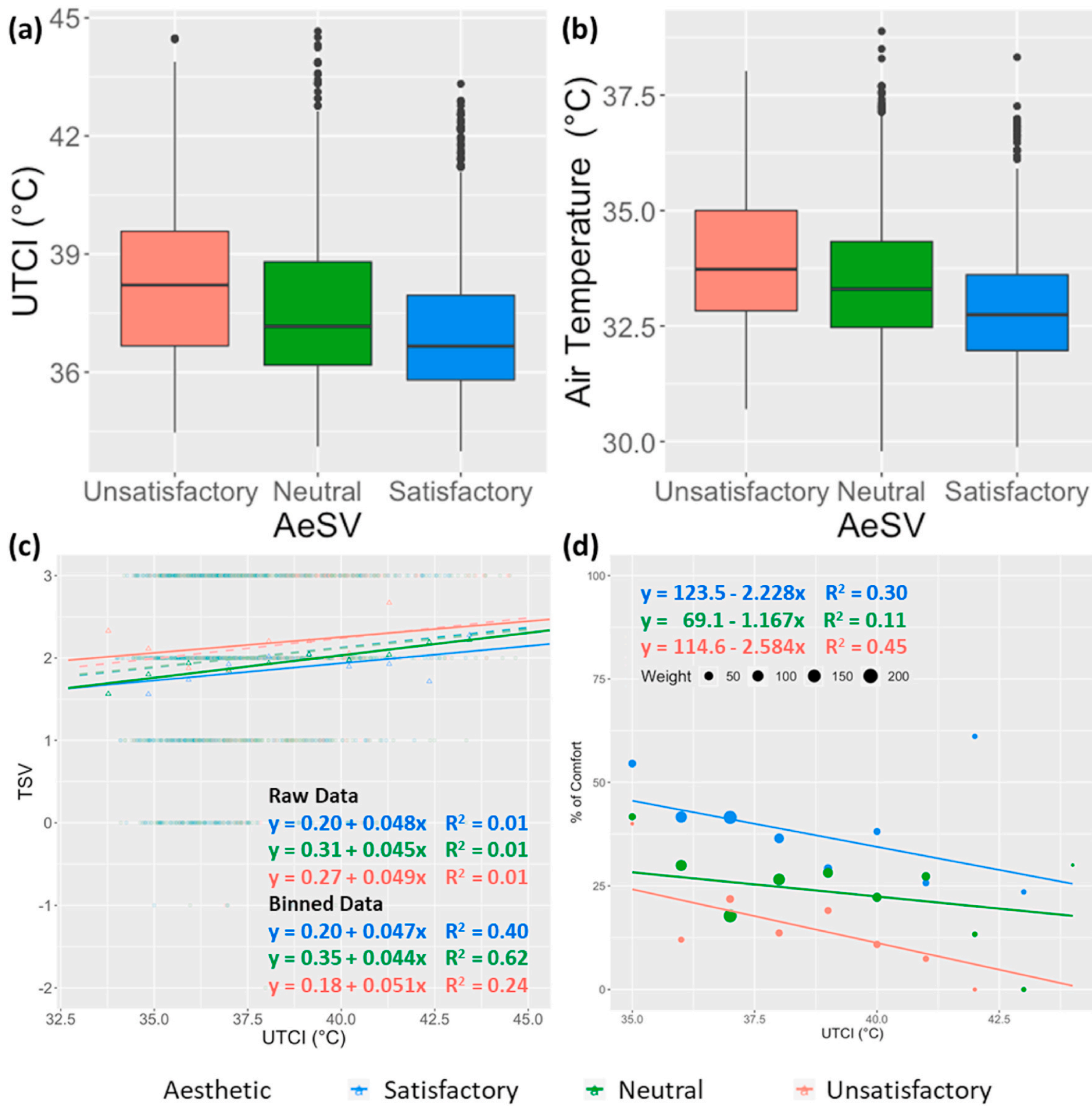


**Fig. 6.** Boxplots of UTCI (a) and $T_a$ (b) for satisfactory, neutral and unsatisfactory groups of aesthetic votes. Scatterplots between (c) mean TSV and UTCI, and (d) percentage of TCV and UTCI.

similar trend in the satisfactory and neutral groups (Fig. 6d). %TCV dropped 2.2% with every 1 °C increase in UTCI in respondents who were satisfied with aesthetic quality while it decreased at a rate of 1.2% for people who expressed neutral aesthetic perception. However, for the respondents who were unsatisfactory with the aesthetic environment, the proportion of comfort votes dropped more considerably with increasing UTCI (slope = 2.6).

The thermal conditions exposed by the respondents were under relatively stronger heat stress due to the high air temperature and prolonged exposure to solar radiation during summer in Hong Kong. Mann-Whitney-Wilcoxon *U* test was conducted to determine if the median TSV and TCV are significantly different between the two UTCI classes (strong heat stress and very strong heat stress). It showed that there were significant differences in TSV ($W = 3.39 \times 10^5$, p-value = 0.0006) and TCV ($W = 4.07 \times 10^5$, p-value = 0.0005) between the two UTCI heat stress classes. Moreover, the AeSV was also significantly different across the strong and very strong heat stress ($W = 4.50 \times 10^5$, p-value < 0.0001), suggesting that the thermal conditions of the surrounding environment affect how urban dwellers feel the thermal and aesthetic environments.

### *3.4. Influence of thermal conditions on thermal perception and acoustic satisfaction*

Boxplots of the UTCI and $T_a$ based on the three groups of acoustic satisfaction are shown in Fig. 7a and b. Median UTCI was higher in the unsatisfactory group (37.6 °C) than the neutral (36.9 °C) and satisfactory group (36.7 °C). The difference between the unsatisfactory and satisfactory groups of acoustic quality (0.9 °C) was slightly smaller than that of the aesthetic satisfaction (1.5 °C). The variability of thermal conditions is the highest in the unsatisfactory group (S.D. = 1.99 °C), with similar S.D. observed in neutral and satisfactory group (1.87 °C and 1.89 °C respectively). In terms of $T_a$, the median value of the respondents who felt unsatisfied with the acoustic environment was higher (33.5 °C), compared to the neutral and satisfactory groups. The 90th-percentile of the unsatisfactory group was 40.5 °C while that of the satisfactory group was 39.8 °C. It indicates that the perception of acoustic quality is affected by the thermal conditions which the respondents are exposed to.

Satisfaction of the acoustic quality was found to influence subjective thermal perception. Unlike the aesthetic satisfaction, it was found that the binned data had higher slopes than the raw data for the satisfactory

**Table 4**
Equations of the weighted linear regression between TSV and UTCI.

| | | Regression Equation | N | $R^2$ | p-value | S.E. |
|---|---|---|---|---|---|---|
| *Aesthetic* | | | | | | |
| Satisfactory | Raw | TSV = 0.200 + 0.048 UTCI | 738 | 0.008 | **0.017** | 0.067 |
| | Binned | TSV = 0.204 + 0.047 UTCI | 10 | 0.400 | 0.068 | 1.099 |
| Neutral | Raw | TSV = 0.310 + 0.045 UTCI | 839 | 0.008 | **0.009** | 0.068 |
| | Binned | TSV = 0.354 + 0.044 UTCI | 10 | 0.617 | **0.007** | 0.0637 |
| Unsatisfactory | Raw | TSV = 0.270 + 0.049 UTCI | 265 | 0.011 | 0.091 | 0.130 |
| | Binned | TSV = 0.178 + 0.051 UTCI | 10 | 0.241 | 0.217 | 0.996 |
| *Acoustic* | | | | | | |
| Satisfactory | Raw | TSV = 0.200 + 0.048 UTCI | 685 | 0.008 | **0.018** | 0.072 |
| | Binned | TSV = −0.398 + 0.063 UTCI | 10 | 0.686 | **0.011** | 0.809 |
| Neutral | Raw | TSV = 0.920 + 0.027 UTCI | 498 | 0.003 | 0.265 | 0.082 |
| | Binned | TSV = 1.073 + 0.023 UTCI | 10 | 0.134 | 0.373 | 0.373 |
| Unsatisfactory | Raw | TSV = 0.170 + 0.052 UTCI | 659 | 0.011 | **0.006** | 0.080 |
| | Binned | TSV = 0.114 + 0.053 UTCI | 10 | 0.581 | **0.028** | 0.773 |

group, with the differences of 0.015 (Table 4). The slopes between the raw and binned data were similar for the neutral and unsatisfactory group. Respondents who were not satisfied with the acoustic quality generally reported higher TSV than those felt neutral or satisfactory (Fig. 7c). They are also sensitive to the changes of thermal conditions as indicated by the slope (0.053). The sensitivity of the respondents who felt satisfactory with acoustic quality was higher (slope = 0.063) than the neutral group (0.023).

Similar trend was also observed in the scatterplot between %TCV and UTCI. There were a 2.1% decrease in TCV reported by the respondents with 1 °C increase in UTCI for the unsatisfactory group but the decrease was slightly higher (3.5%) per 1 °C increase in UTCI for the satisfactory group. Interestingly, although the regression coefficient for the neutral group was considerably lower than the other two groups, the percentage of comfort votes reported by the respondents remained relatively stable over the UTCI range recorded during the survey campaign. It suggests the possibility that people's perception to thermal comfort may remain unchanged if they do not feel good or bad with the acoustic quality, regardless of the changes in thermal conditions. Meanwhile, Mann-Whitney-Wilcoxon *U* test showed that there were significant differences in AeSV across the strong and very strong heat stress classes ($W = 4.50 \times 10^5$, p-value $< 0.0001$), indicating the potential influence of thermal conditions on people's perception of acoustic quality.

## 4. Discussion

Outdoor thermal comfort is an important aspect of urban design, which affects the usage of outdoor spaces and the behaviour of urban dwellers. Climate change induces the increasing air temperature, and this is exacerbated by urban heat island effect as a result of rapid urban development. This causes persistently uncomfortable conditions experienced by urban dwellers. However, it is difficult to improve the thermal experience of urban dwellers by changing microclimatic conditions only in dense urban areas where thermal conditions are highly constrained by the physical settings. As such, the quality of outdoor spaces emerges as potential means of improving thermal experience.

The present study examines the effect of aesthetic and acoustic quality on thermal perception in outdoor spaces. It shows that people's satisfaction of aesthetic quality is significantly associated with their thermal perception in outdoor spaces. Respondents unsatisfied with the aesthetic quality tended to report warmer sensation votes and vice versa. The influence of pleasant aesthetics on overall comfort perception was previously discussed in an indoor study [11]. They found that people's satisfaction of comfort was positively affected by the pleasant aesthetics at their workplace. Illuminance is another factor affecting human perception of thermal comfort. According to [48]; thermal comfort is not only affected by temperature but also the level of illuminance. There is also an interactive effect between temperature and illuminance exposed by the participants. Aesthetic qualities of outdoor spaces, highly associated with visual comfort, play an important role in how people perceive thermal comfort.

Findings of the present study suggested that acoustic environment is another quality affecting individuals' perception of thermal comfort. Fanger (1977) first reported that there are synergistic interactions between noise level and temperature. The present study shows similar findings that respondents who were exposed to warmer thermal conditions tended to feel unsatisfied with acoustic quality [42]. also discovered that there is a trade-off between noise and temperature and the corresponding effect on discomfort [43]. p roposed that there is a 1 °C deviation from thermoneutral conditions could equal 2.6–2.9 dBA increase in noise level. They concluded that noise may alter thermal pleasantness in warm conditions. However, in this study, thermal sensation was similar between satisfactory and unsatisfactory groups under warmer thermal conditions, and the difference of mean thermal sensation between groups was more similar in hotter conditions. The sensitivity of thermal sensation is also higher in the group that are satisfied with acoustic quality. People in an unsatisfactory of acoustic quality is more likely feeling thermal discomfort than that of a neutral or satisfactory of acoustic quality. These suggestions are consistent with previous woks that high noise levels increase thermal discomfort significantly, but the effects on thermal sensation are not significant [43,49].

Environmental stimulation is also associated with psychological processes that affect human thermal comfort (Throsson et al., 2004) [4]. first discussed the role of psychological issues in thermal comfort and argued that thermal expectation and past climatic experience must be included to improve the physiological approach and models. It was also found that a person's mood also affects thermal assessment of the place [26,27]. On the other hand [38], found that psychological adaptation is important to human response to a physical stimulus, which is dependent on how people perceive the environment and corresponding contextual information. Hence thermal satisfaction is influenced by past experience [40], naturalness [19], expectations [13], and time of exposure [6]. As people can tolerate a wider range of physical conditions in outdoor environment, the adaptive opportunity, referring to the degree to which people can adapt to the environment, is highly related to perceived environmental quality, particularly in high-density cities where there are considerable variations in the urban areas [31]. Understanding people's perception of environmental quality of outdoor spaces is therefore necessary for providing appropriate qualities of outdoor spaces in Hong Kong.

[34] found that people who perceive public squares as too wide tend to report thermal discomfort and they are more sensitive to changes in microclimatic conditions. They also suggested that materials appearing cold caused more thermal discomfort. Green infrastructure, as a major aesthetic component in outdoor spaces, generally perceived thermal comfort [25]. People perceived green urban spaces as the most thermally comfortable spaces and the thermal conditions, in terms of physiological equivalent temperature (PET) were also lower during the hottest time of the day. Such design parameters also form an integral part of human thermal perception in outdoor environment.

Present study has a few limitations. The surveys were conducted in strong heat stress conditions, with a range of UTCU from 33 °C to 45 °C. The suggestions of relationship between environmental qualities and

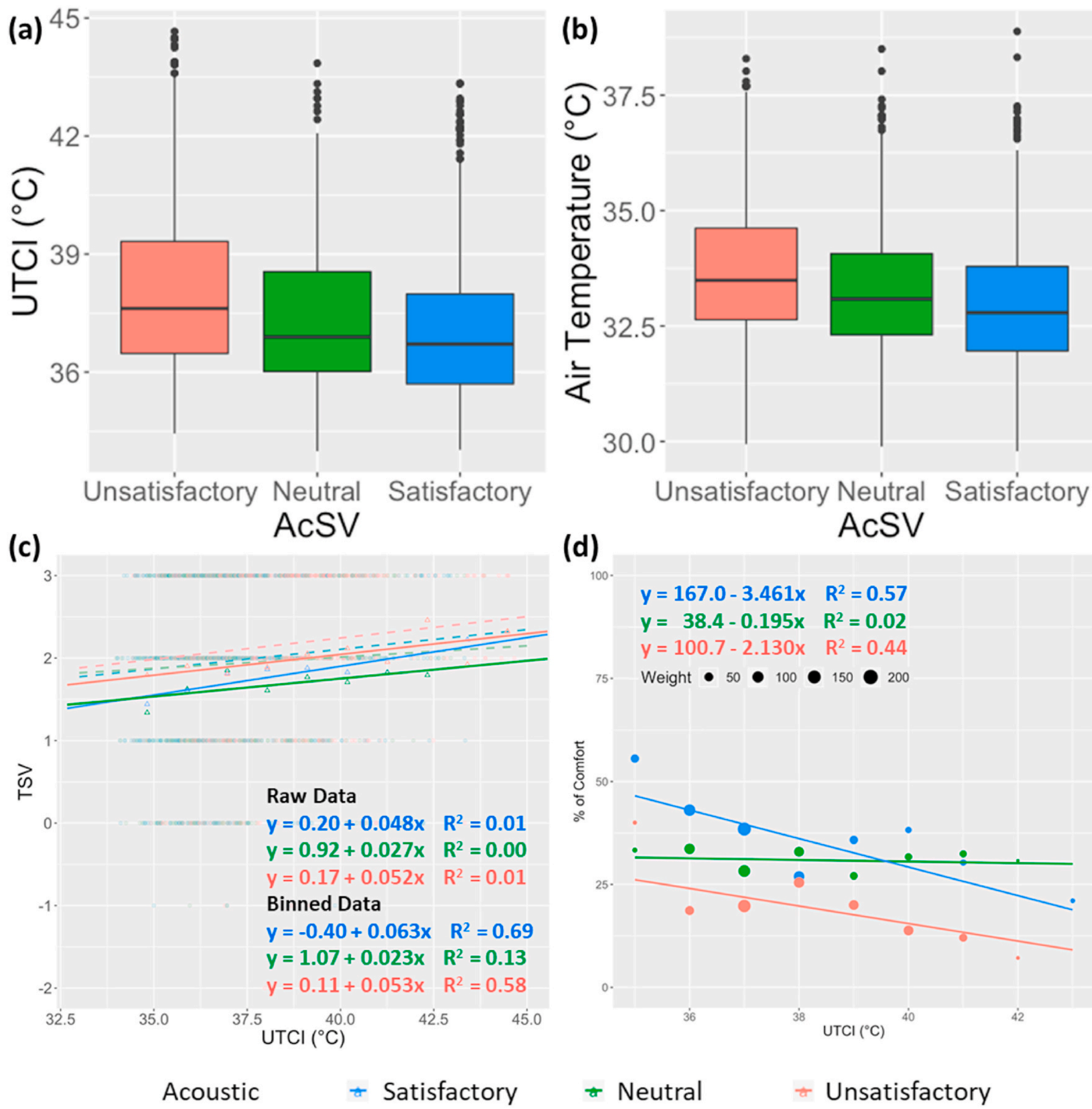


**Fig. 7.** Boxplots of UTCI (a) and $T_a$ (b) for satisfactory, neutral and unsatisfactory groups of acoustic votes. Scatterplots between (c) mean TSV and UTCI, and (d) percentage of TCV and UTCI.

subjective thermal comfort might only apply in hot conditions. The neutral perceived qualities groups have a large variation of thermal sensation and thermal comfort vote. Other lurking variables might contribute to this large variation. The complex urban setting and diverse respondents' background in Hong Kong might be one of the variables leading a large difference in thermal perception. Further work is required to examine other environmental qualities and individual variables to reduce the uncertainty of the effects of other factors on thermal comfort.

## 5. Conclusions

Present study suggested that the environmental qualities have significant effects on subjective thermal sensation and thermal comfort. The effects of aesthetic and acoustic qualities were analyzed. In the hot conditions, the perceived aesthetic and acoustic votes show negative associations with thermal sensation vote. The group with satisfaction of aesthetic has a significantly lower thermal sensation vote than that of group with unsatisfaction. The acoustic quality did not affect thermal sensation significantly. The groups with satisfaction of these two environmental qualities have a higher percentage of feeling comfortable than that of groups with unsatisfaction. These results are consistent with the previous works, that people in the quiet and beautiful environments have a higher thermal comfort.

In high-density cities like Hong Kong, outdoor spaces are characterized by congestion in urban areas and high level of pedestrian activities. Designing outdoor spaces for better thermal comfort is of utmost importance to mitigate the heat stress and encourage the use of outdoor spaces with limited land resources. Further work is therefore required to identify the environmental qualities and features for better outdoor thermal comfort in high-density urban environment.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix 1. Outdoor Thermal Comfort Questionnaire

香港中文大學 The Chinese University of Hong Kong CityU 香港城市大學 City University of Hong Kong INSTITUTE OF Future Cities

**Outdoor Thermal Comfort Survey** **Survey No.:** ____________

**Name of Interviewer:** ______________________ **Location:** __________ **Date:** ___________ **Start Time:** ________

Interviewer's observation

A. Is the interviewee under direct sunlight? ☐ 1. Yes ☐ 2. No

B. What was the interviewee doing just before the interview?
☐ 1. Sitting ☐ 2. Standing ☐ 3. Walking ☐ 4. Exercise

---

1. Have you done this questionnaire before?
☐ 1. Yes ☐ 2. No (If the answer is "Yes", the interview will be terminated.)

2. Have you been staying in Hong Kong in the past 6 months? ☐ 1. Yes ☐ 2. No

3. In the past 15 minutes, have you been to (or stayed in) indoor spaces with air-conditioning or heating system (including bus, taxi, minibus, etc)? ☐ 1. Yes ☐ 2. No

4. What were you doing in the past 15 minutes?
☐ 1. Waiting for people or cars ☐ 2. Resting ☐ 3. Standing ☐ 4. Sitting ☐ 5. Working
☐ 6. Grocery shopping ☐ 7. Passing by ☐ 8. Doing exercises ☐ 9. Others: ______________

5. How are you feeling now in terms of thermal perception? (Thermal Sensation Vote)
(7-point scale from +3 to -3 according to the ASHRAE thermal sensation scale)
☐ -3. Cold ☐ -2. Cool ☐ -1. Slightly Cool ☐ 0. Neither Cold nor Hot ☐ +1. Slightly Warm ☐ +2. Warm ☐ +3. Hot

6. Do you find this environment...
☐ 0. Comfortable ☐ -1. Slight uncomfortable ☐ -2. Uncomfortable ☐ -3. Very uncomfortable

7. Please state how you would prefer it to be now.
☐ -3. Much Cooler ☐ -2. Cooler ☐ -1. Slightly Cooler ☐ 0. Neither Cooler nor Warmer
☐ +1. Slightly Warner ☐ +2. Warmer ☐ +3. Much Warmer

8. On a personal level, this environment is for me...
☐ 0. Acceptable rather than unacceptable ☐ 1. Unacceptable rather than acceptable

9. Do you agree that it is aesthetically pleasing (or beautiful) here?
☐ -2. Strongly Disagree ☐ -1. Disagree ☐ 0. Neutral ☐ +1. Agree ☐ +2. Strongly Agree

10. Do you agree that it is quiet/calm here?
☐ -2. Strongly Disagree ☐ -1. Disagree ☐ 0. Neutral ☐ +1. Agree ☐ +2. Strongly Agree

11. Age of the interviewee: ______________________

12. Sex of the interviewee: ☐ 1. Male ☐ 2. Female ☐ 3. Preferred not to be revealed

13/14. Height and weight of the interviewee 19. ___________ cm 20. ___________ kg

15. Clothing of the interviewee (by interviewer's observation)

| | | | |
|---|---|---|---|
| Head 頭: | ☐ 1. Hat | 帽 | |
| Upper Body: 上身： | ☐ 2. Bare | 赤身 | |
| | ☐ 3. Vest (No Sleeves) | 背心(冇袖) | clo = 0.06 |
| | ☐ 4. T-shirt/shirt (Short Sleeves) | T恤/恤衫 (短袖) | clo = 0.09 |
| | ☐ 5. T-shirt/shirt (Long Sleeves) | T恤/恤衫 (長袖) | clo = 0.25 |
| | ☐ 6. Jacket / Coat (Suit) | 厚外套/大褸/西裝褸 | clo = 0.60 |
| | ☐ 7. Wind Breaker | 薄外套/風褸 | clo = 0.25 |
| | ☐ 8. Shirtdress (No Sleeves) | 連身裙(冇袖) | clo = 0.23 |
| | ☐ 9. Shirtdress (With Sleeves) | 連身裙(有袖) | clo = 0.29 |
| Lower Body: 下身： | ☐ 10. Long Pants | 長褲 | clo = 0.24 |
| | ☐ 11. Short Pants | 短褲 | clo = 0.10 |
| | ☐ 12. Skirt | 半截裙 | clo = 0.10 |
| | ☐ 13. Long Dress | 長裙 | clo = 0.22 |
| Feet: 腳： | ☐ 14. Bare Feet | 赤腳 | |
| | ☐ 15. Socks | 襪 | clo = 0.02 |
| | ☐ 16. Shoes | 鞋 (不露腳趾) | clo = 0.04 |
| | ☐ 17. Sandals/Thongs | 拖鞋/涼鞋 (露腳趾) | clo = 0.02 |

22. Remarks: ______________________________

End time: ____________

## Appendix 2. Accuracy of TESTO 480 data logger and probes

| Measured Parameter | Unit | Instrument | Measurement range | Accuracy |
|---|---|---|---|---|
| Air Temperature | °C | Testo 480 Air Temperature and Relative Humidity Probe | 0–50 °C | 0.01 °C |
| Globe Temperature | °C | Globe thermometer connected to the TESTO 480 Data Logger | 0–120 °C | 0.1 °C |
| Relative Humidity | % | Testo 480 Air Temperature and Relative Humidity Probe | 0–100% | 0.1% |
| Wind Speed | m/s | Testo 480 Air Flow Probe | 0–20 m/s | 0.01 m/s |

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