



Effects of environmental perception on thermal sensation in sub-tropical and high-density cities: a case study of Hong Kong

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Abstract: Outdoor thermal comfort is crucial in sub-tropical regions where summer heat stress impede outdoor space usage. Research on the effects of environmental perception on thermal comfort has increased in recent years as a result of intensified urban development and it has been found that urban geometry design can modify the relationship between climate and thermal comfort. Despite this, there is a lack of holistic studies focusing on the effects of qualities of urban space on thermal adaptation and comfort.

This study investigates the relationship between environmental perception and outdoor thermal comfort under typical summer conditions in streets and parks in Hong Kong by conducting questionnaire survey on thermal sensation and environmental perception in terms of convenience, visual and acoustic comfort, air quality and safety. Simultaneous micrometeorological measurements were also conducted to obtain objective conditions of thermal comfort in designated urban spaces. A total of 1921 responses were collected between June 2017 and September 2017 in 12 locations. Overall, we found that environmental perceptions, particularly the perceived air quality, acoustic comfort and visual comfort, significantly affect thermal sensation and comfort. Improved perception of each investigated environmental parameter could lead to a substantial increase in the percentage of people feeling thermally comfortable.

Keywords: Outdoor thermal comfort, thermal adaptation, environmental perception, hot humid climate, urban design

1. Introduction

Thermally comfortable outdoor spaces are essential as they provide places for people to gather, interact and carry out outdoor activities. It is particularly important in sub-tropical countries where high temperature can lead to discomfort and thus decrease the time spent outdoors and increase heat-related health risks (Johansson and Emmanuel, 2006, Yang et al., 2013). Previous studies revealed that microclimatic parameters strongly affect thermal sensations. There have been several attempts to quantify the effect of each microclimatic parameter on human thermal comfort. Though there has not been a solid conclusion of which of these parameters are the most important, it is generally believed that air temperature and radiative temperature are the most significant factors in the subtropical regions because wind speed and relative humidity are stable throughout the year (Lin et al., 2011). However, in a study on different European countries, relatively weak correlations have been found between subjective thermal evaluation and single microclimatic parameters alone which suggest that this approach may not be adequate when it is applied in outdoor environment (Nikolopoulou and Lykoudis, 2006). As such, thermal indices (e.g. Physiologically Equivalent Temperature

(PET), Standard effective temperature (SET)) which account for multiple parameters are commonly used to study the relationship between objective and subjective thermal evaluation (Johansson et al., 2014).

Despite the importance of microclimatic parameters, they are found to only contribute to around 50% of the variance in subjective thermal comfort evaluation (Nikolopoulou and Steemers, 2003). This has resulted in the study of thermal adaptation including physical (e.g. by changing the environment or one's metabolic heat), physiological (long-term acclimatization due to repeated exposure to a stimulus) and psychological adaptations (change in perception due to 'information' they have for a situation). It is suggested that urban design could play a role in the psychological adaptation of outdoor space users and be able to increase their thermal tolerance (Nikolopoulou and Steemers, 2003). For instance, Hirashima et al. (2016) showed that under the same thermal conditions, people were more thermally tolerant in a square with scenery of green areas, water features, natural sounds (e.g. birds) and low rise historical buildings, as oppose to another square surrounded by high-rise buildings, heavy traffic and no water features. Similarly, a study found that green environment was perceived as most thermally comfortable, followed by water environments, and built environments were perceived as neutral (Klemm et al., 2015).

While there is increasing evidence for the ability to increase thermal tolerance with urban design, it is necessary to evaluate and quantify the impacts of different qualities of urban space on human thermal comfort in order to strategize urban planning. Thus, instead of site specific comparisons in terms of thermal comfort, this study focuses on the impact of various qualities of an outdoor space. This study aims to investigate the relationship between subjective thermal comfort and the perception of qualities of outdoor space in terms of convenience, visual comfort, acoustic comfort, air quality and safety under typical summer conditions in Hong Kong, as thermal discomfort commonly occurs in sub-tropical summer.

2. Methodology

2.1 Study Area

Hong Kong is one of the most densely populated cities in the world, with a population density of 6,780 persons per square kilometre and a total population of nearly 7.2 million in 2016. It is located at 22°15'N 114°10'E and has a subtropical monsoon climate. Summertime in Hong Kong (May to September) is typically hot and humid, with 80% of the total annual rainfall during this period. Summer 2017 was unusually hot and wet with a mean daily maximum temperature of 31°C and a record breaking daily maximum temperature of 36.6°C preceding the strike of Typhoon Hato. As thermal discomfort in subtropical regions commonly occurs in summer, our study was performed on hot, sunny days between June and September 2017.

Hong Kong has a diverse urban environment and a total of 12 sites were selected to carry out the field campaign in order to capture a wide range of environment. The study sites (figure 1) include residential areas of different urban density (two high density public housing estates, and a low density residential area), street environments in areas of mixed purpose (residential and commercial) and the financial and business hub in Central, as well as urban park (Hong Kong Park) and pier (Central Pier) environments.

(a) Residential area (high density)



(b) Residential area (low density)



(c) Street environment (mixed landuse)



(d) Street environment (Central)



(e) Hong Kong Park



(f) Central Pier



Figure 1 Examples of study sites showing the diverse urban environment in Hong Kong

2.2 Micrometeorological Measurement

Two mobile meteorological stations each containing a TESTO 480 data logger, a TESTO 480 Digital Microclimatic Sensor Set for measurements of air temperature (T_a , °C), relative humidity (RH, %) and wind speed (V_a , m/s) and a globe thermometer for measuring globe temperature (T_g , °C) (fig. 2). The globe thermometer is a TESTO flexible Teflon type K wire held inside a black painted table tennis ball with a diameter (D) of 38-mm and emissivity (ϵ) of 0.95. Mean radiant temperature (T_{mrt}) is determined by using measurements of globe temperature, air temperature and wind speed using the equation (Thorsson et al., 2007):

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.335 \times 10^8 V_a^{0.71}}{\epsilon D^{0.4}} (T_g - T_a) \right]^{1/4} - 273.15$$

The stations were placed very closely together and while one of the stations, with a sun shield attached to the humidity sensor, was placed under direct sunlight, the other (without shield) was placed under shade in a well-ventilated condition.

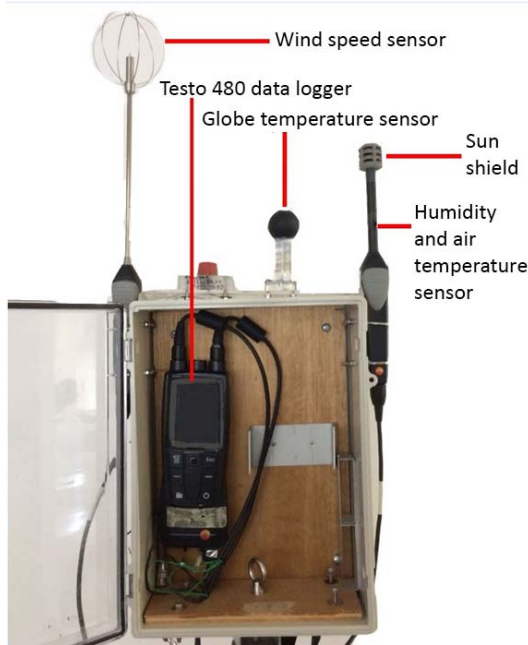


Figure 2 Set up of microclimatic measurement station

2.3 Questionnaire Survey

To collect the subjective outdoor thermal and environmental perception of outdoor space users in Hong Kong, a questionnaire survey (shown in figure 3) was utilized. The general public at the study sites during the survey sessions were invited to participate. Random sampling technique was used to reduce the effects of gender and age biases on survey results.

The questionnaire contains questions on the subjects' sensation to the thermal, wind, solar and humidity environments (using the 7-point ASHRAE scale) (e.g. thermal sensations were reported from "cold" (-3) to "hot" (3)), overall state of thermal comfort on a 4-point scale of "very uncomfortable" (-2), "uncomfortable" (-1), "comfortable" (1) and "very comfortable" (2). In addition, the subjects' environmental perception was recorded on 5-point scales in terms of convenience (from -2: "very inconvenient" to 2: "very convenient"), visual comfort (from -2: "very unpleasant" to 2: "very pleasant"), acoustic comfort (from -2:

“very noisy” to 2: “very quiet”), air quality (from -2: “very poor” to 2: “very good”) and safety (from -2: “very unsafe” to 2: “very safe”). These qualities of outdoor space were chosen because, along with thermal comfort, they were suggested to be able to attract space users (Lai et al., 2014)

In addition to subjective thermal and environmental perception, demographic information such as gender and age were collected. Furthermore, the questionnaire recorded a number of observations made by interviewers including time and location of interview, whether the subject was under shade, and subject’s activity and clothing level using the activity and garment checklists from ASHRAE Standard 55 (2004).

2.4 Thermal indices

To account for the composite effect of metabolic activities, clothing and weather parameters (i.e. air temperature (T_a), mean radiant temperature (T_{mrt}), solar irradiation, wind speed (WS), relative humidity (RH)) on thermal perception, thermal indices such as the Physiologically Equivalent Temperature (PET) and Universal Effective temperature (UTCI) were developed (Coccolo, 2016). Conforming to the existing literature (e.g. Lin et al. 2010, Johansson and Emmanuel, 2006), PET, defined as the “air temperature at which the heat balance of the human body is maintained with core and skin temperature equal to those under the conditions being assessed” (Hoppe, 1999), was used in this study. PET was estimated on RayMan software by importing measured micrometeorological elements T_a , WS and RH), T_{mrt} (estimated using globe temperature (T_g), T_a , WS and diameter and emissivity of globe employed to measure globe temperature (Thorsson, 2003), and metabolic activity and clothing level recorded on questionnaire.

2.5 Statistical analysis

Since evaluation of thermal comfort were non parametric and not normally distributed, Kruskal-Wallis Test was applied to test the significance of the relationship between each environmental perception and thermal comfort and thermal sensation vote. As microclimatic factors also affect perceptions of thermal comfort and thermal sensation, ANOVA was performed to see whether PET, as an attribute that account for climatic and physiological elements, were statistically different across levels of environmental perception.

Table 1 Questionnaire used in this study

<p>1. Thermal sensation vote 你覺得而家熱唔熱？</p> <p style="text-align: center;">Slightly Slightly</p> <p style="text-align: center;">Cold Cool Cool Neutral Warm Warm Hot</p> <p><input type="checkbox"/>3 非常凍 <input type="checkbox"/>2 幾凍 <input type="checkbox"/>1 有少少凍 <input type="checkbox"/>0 啱啱好 <input type="checkbox"/>1 有少少熱 <input type="checkbox"/>2 幾熱 <input type="checkbox"/>3 非常熱</p>
<p>2. Solar sensation vote 你覺得而家太陽曬唔曬？</p> <p style="text-align: center;">Very Slightly Slightly Very</p> <p style="text-align: center;">Weak Weak Weak Neutral Strong Strong Strong</p> <p><input type="checkbox"/>3 非常唔夠 <input type="checkbox"/>2 幾唔夠 <input type="checkbox"/>1 有少少唔夠 <input type="checkbox"/>0 啱啱好 <input type="checkbox"/>1 有少少曬 <input type="checkbox"/>2 幾曬 <input type="checkbox"/>3 非常曬</p>
<p>3. Wind sensation vote 你覺得而家大唔大風？</p> <p style="text-align: center;">Very Slightly Slightly Very</p> <p style="text-align: center;">Weak Weak Weak Neutral Strong Strong Strong</p> <p><input type="checkbox"/>3 冇風 <input type="checkbox"/>2 幾唔夠風 <input type="checkbox"/>1 有少少唔夠風 <input type="checkbox"/>0 啱啱好 <input type="checkbox"/>1 有少少大風 <input type="checkbox"/>2 幾大風 <input type="checkbox"/>3 非常大風</p>
<p>4. Humidity sensation vote 你覺得而家空氣潮唔潮濕？</p> <p style="text-align: center;">Very Slightly Slightly Very</p> <p style="text-align: center;">Dry Dry Dry Neutral Humid Humid Humid</p> <p><input type="checkbox"/>3 非常乾燥 <input type="checkbox"/>2 幾乾燥 <input type="checkbox"/>1 有少少乾燥 <input type="checkbox"/>0 啱啱好 <input type="checkbox"/>1 有少少潮濕 <input type="checkbox"/>2 幾潮濕 <input type="checkbox"/>3 非常潮濕</p>
<p>5. Thermal comfort 總括嚟講，你覺得依個天氣舒唔舒服？</p> <p style="text-align: center;">Very Very</p> <p style="text-align: center;">Uncomfortable Uncomfortable Comfortable Comfortable</p> <p><input type="checkbox"/>2 好唔舒服 <input type="checkbox"/>1 唔舒服 <input type="checkbox"/>1 舒服 <input type="checkbox"/>2 好舒服</p>
<p>6. Convenience perception 你覺得依到方唔方便？</p> <p style="text-align: center;">Very Very</p> <p style="text-align: center;">Inconvenient Inconvenient Neutral Convenient Convenient</p> <p><input type="checkbox"/>2 非常唔方便 <input type="checkbox"/>1 唔方便 <input type="checkbox"/>0 一般 <input type="checkbox"/>1 方便 <input type="checkbox"/>2 非常方便</p>
<p>7. Visual comfort perception 你覺得依到靚唔靚？</p> <p style="text-align: center;">Very Very</p> <p style="text-align: center;">Unpleasant Unpleasant Neutral Pleasant Pleasant</p> <p><input type="checkbox"/>2 非常唔靚 <input type="checkbox"/>1 唔靚 <input type="checkbox"/>0 一般 <input type="checkbox"/>1 靚 <input type="checkbox"/>2 非常靚</p>
<p>8. Acoustic comfort perception 你覺得依到安唔安靜？</p> <p style="text-align: center;">Very Very</p> <p style="text-align: center;">Noisy Noisy Neutral QuietQuiet</p> <p><input type="checkbox"/>2 非常唔安靜 <input type="checkbox"/>1 唔安靜 <input type="checkbox"/>0 一般 <input type="checkbox"/>1 安靜 <input type="checkbox"/>2 非常安靜</p>
<p>9. Air quality perception 你覺得依到空氣好唔好？</p> <p style="text-align: center;">Very Very</p> <p style="text-align: center;">Poor Poor Neutral Good Good</p> <p><input type="checkbox"/>2 非常差 <input type="checkbox"/>1 差 <input type="checkbox"/>0 一般 <input type="checkbox"/>1 好 <input type="checkbox"/>2 非常好</p>
<p>10. Safety Perception 你覺得依到安唔安全？</p> <p style="text-align: center;">Very Very</p> <p style="text-align: center;">Unsafe Unsafe Neutral Safe Safe</p> <p><input type="checkbox"/>2 非常唔安全 <input type="checkbox"/>1 唔安全 <input type="checkbox"/>0 一般 <input type="checkbox"/>1 安全 <input type="checkbox"/>2 非常安全</p>

3. Results and Discussion

3.1 Outdoor climates ²

Microclimatic measurement campaigns in this study were conducted between 10:00 and 16:00 on 16 days between June and September 2017 in Hong Kong. Although the measurements were taken on different days, days of site visits were carefully chosen to ensure similar weather conditions were recorded. Recorded air temperature ranged from 29.6°C to 39.1°C and PET ranged from 29.1°C to 57.2°C. Mean Ta and PET were 33.8°C and 42.3°C respectively. It was previously found that mean PET in Hong Kong under shade in summer is between 32°C and 34°C and neutral PET for Hong Kong citizens is around 28°C in summer (Cheng et al., 2012). Our measurement results indicated the severity of heat stress in Hong Kong during its hot and humid summer in 2017. Under extreme heat stress, it was suggested that wind speed of more than 1.0 m/s would be necessary to ensure thermal comfort in outdoor spaces (Cheng et al., 2012). However, more than half of the recorded wind speed were below 1 m/s and less than 10% were above 1.5 m/s.

3.2 Subjective thermal sensations and thermal comfort

Due to high air temperature during the survey campaign, most popular thermal sensation votes (TSV) were in the “hot” (+3) and “warm” (+2) categories with 38.7% and 33.2% of votes respectively. Only 28% of TSV were between -1 and 1, which is considered to be the comfortable range for thermal perception (Spagnolo and de Dear, 2003). Measured microclimatic parameters showed weak correlation with TSV and the Pearson correlation coefficients with air temperature and mean radiant temperature were 0.16 and 0.12 respectively. Although it further confirmed the previous findings that thermal sensation is mostly related to effects of air temperature and solar irradiance, our results suggest that the strong relationship between TSV and temperature, found in existing outdoor thermal comfort studies, deteriorate in extreme heat stress conditions (Nikolopoulou and Lykoudis, 2006).

Overall thermal comfort was also found to be weakly related to microclimatic parameters, and its correlation coefficients with air temperature, relative humidity, mean radiant temperature and wind speed were -0.150, 0.103, -0.05 and 0.002. This suggests that subjects tended to feel more comfortable in conditions with lower mean radiant temperature and air temperatures, while the impact of wind was very small. Thermal comfort is more significantly related to elements of climatic sensation such that the correlation coefficients with thermal, solar, wind and humidity sensation vote were -0.36, -0.23, 0.26 and -0.07. This suggests that the subjective evaluation of thermal comfort is most strongly related to thermal sensation, followed by wind and solar sensation. Although this might suggest that perception of the weather has a stronger influence on thermal comfort than the physical microclimatic environment itself, such correlation results cannot serve as evidence for causal relationships between variables.

3.3 Impacts of environmental perception on thermal sensation and thermal comfort

There are complex interrelationships between environmental perception and thermal sensation and comfort because positive evaluations of outdoor spaces can attract users and increase their tolerance to the thermal environment. On the other hand, thermal comfort as well as a physically thermal comfortable environment can lead to better perception of

environmental qualities. However, it is important to understand the relationship between environmental perception and thermal perception in order to increase the range of thermal adaptation with appropriate urban design.

Based on Kruskal-Wallis Test, distributions of thermal comfort were significantly different across categories of convenience, visual comfort, acoustic comfort, air quality and safety at a significance level of 99% for all environmental variables. Similarly, distributions of TSV were different across categories of all investigated environmental parameters, with slightly lower significance levels of 95%. Results of ANOVA test between PET and environmental perceptions showed that PET did not vary significantly across levels of convenience ($P = 0.21$) and visual comfort ($P = 0.20$) perceptions, whereas they varied significantly ($P < 0.05$) across levels of acoustic comfort, air quality and safety.

The percentages of different TSV and thermal comfort votes in each category of environmental perception are shown in figure 3 and 4. Overall, the percentage of “comfortable” and “very comfortable” increased as environmental perception improved. While “-2” votes for each environmental parameter coincided with more than 80% votes being in the two hottest categories +2 (warm) and +3 (hot), the percentage of hot thermal sensation generally decreased as the perception of environment improved.

As the perception for convenience increased from -2 (very inconvenient) to 0 (neutral), the percentage of “hot” and “warm” TSV decreased from 83% to 70%. This decreasing trend reversed as perception of convenience improved from “neutral” to “very convenient”. Contrastingly, the percentage of thermal comfort is lowest when convenience perception was neutral and there was a 10% increase in this percentage as convenience perception increased to +2 (very convenient). This suggests that although people tended to feel hot when they perceive the place as convenient, they also tended to be in a state of thermal comfort rather than discomfort. A possible explanation is that when a place is more convenient, or is perceived as so, it might be more connected to indoor spaces. This could mean that participants who voted for convenience level “1” or “2” either have shorter outdoor exposure time, or felt more thermally comfortable because of the ease of going to into air conditioned space.

The percentage of TSV 2 and 3 decreased steadily by 18% as the perception of visual comfort improved from -2 (very unpleasant) to 2 (very pleasant), while the percentage of thermal comfort votes increased by 36%. This indicates the large influence of visual comfort on reducing thermal sensation in extreme summer conditions and improving thermal comfort. It has been proposed that visual cues affect climate perception such that bluish and pale colors suggests coldness whereas warm colors indicate warmth (Vigier et al., 2015). Furthermore, it has been suggested that the presence of green and blue space can improve satisfaction with the visual environment as well as thermal comfort (Klemm et al., 2015). However, where green and blue space is present, wind speed may also be higher. Further studies are required to find out how much of the improvement in thermal comfort was purely due to the psychological processes of improving visual perception rather than changes in the physical environment.

As the perception of acoustic comfort improved from -2 (very noisy) to 2 (very quiet), the percentage of TSV 2 and 3 decreased by 12%. Meanwhile, the percentage of thermal comfort votes increased by 25%. Similarly to visual comfort perception, people significantly generally felt less warm and more thermally comfortable when they are more satisfied with

the acoustic environment. The perception of noise might have indicated the presence of more people and cars, which can generate negative feeling of crowdedness and lead to warm sensation and thermal discomfort.

The percentage of 'hot' and 'warm' TSV decreased by 25% while percentage of thermal comfortable vote increased by 45% as perception of air quality increased from "very poor" to "very good". This indicates a striking improvement in thermal perception as the perception of air quality improved. Poorly ventilated places surrounded by high rise buildings with lower wind speed and higher air temperature might cause the perception of poor air quality, whereas open space with higher wind speed could result in the perception of good air quality. Moreover, By the same token as acoustic comfort, the perception of poor air quality might suggest crowdedness and therefore lead to warm sensation.

The percentage of thermal comfort votes increased by 24% as safety perception improved from -2 (very unsafe) to 2 (very safe), which indicates that thermal comfort improve significantly with safety perception. While all participants who voted for "-2" in terms of safety perception also voted for the two hottest TSV categories, the percentage of TSV 2 and 3 fluctuated between 69% to 75% in other safety perception categories. This suggests that unless a place is perceived as very unsafe, the perception of safety does not affect thermal comfort significantly.

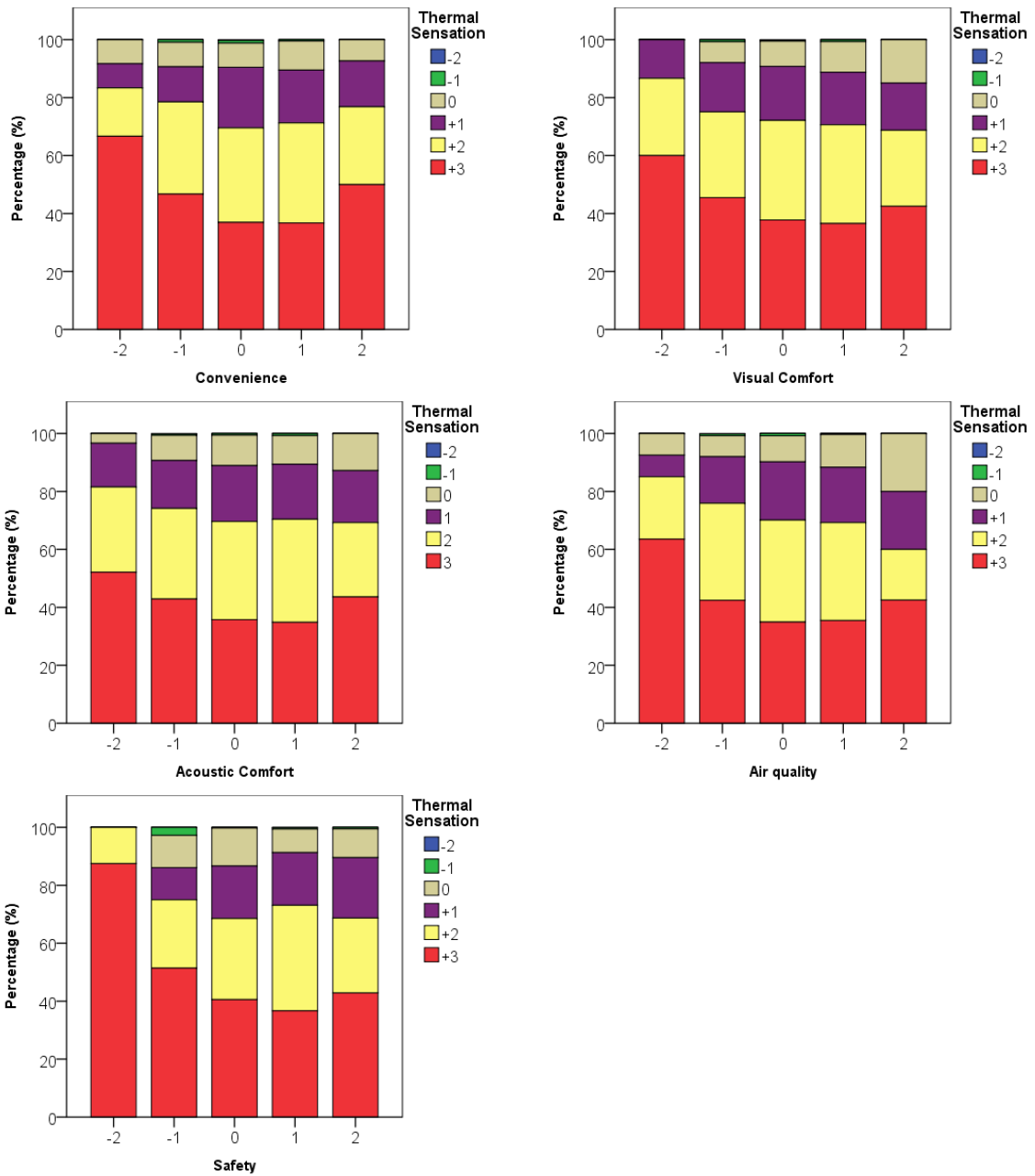


Figure 3 Percentage of thermal sensation votes as a function of environmental perception levels

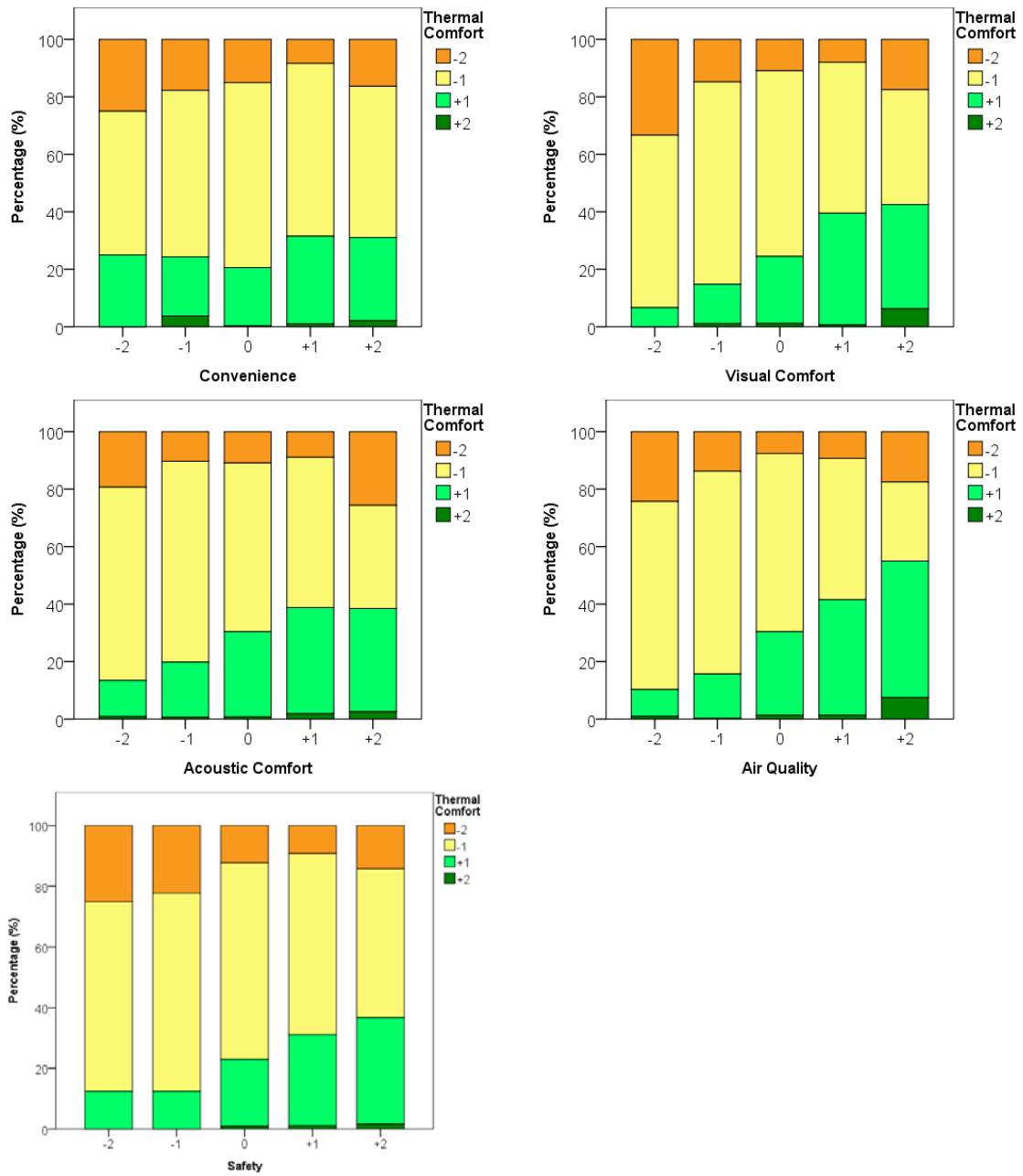


Figure 4 Percentage of thermal comfort votes as a function of environmental perception levels

4. Urban planning implications

In correspondences to the existing literature (e.g. Lin et al., 2013), correlation analysis in this study suggests the high importance of air temperature and mean radiant temperature in affecting thermal comfort. It is particularly important to provide shading facilities in urban outdoor spaces during extreme heat stress in the subtropics.

Additionally, our results show that perceptions of the environment are of significant importance to thermal comfort. Although previous studies have identified links between thermal comfort and the visual and acoustic environment, these studies usually focused on the presence and absence of few specific visual and acoustic cues such as green areas, water features, high/low rise buildings. A different approach is proposed in this study where the relationship between thermal comfort and the degree of positive feeling towards aspects of environmental perception are evaluated. It is shown that thermal comfort increases with all investigated qualities of an outdoor environment. The increase in percentage of thermally comfortable votes (+1 and +2) was substantial for air quality, acoustic comfort and visual comfort. While improvements in city scale planning is required to improve outdoor air quality within parts of Hong Kong, local scale planning strategies should attempt to increase overall visual and acoustic comfort as they have considerable ability to increase thermal tolerance.

Despite the significant impacts of various environmental perception on thermal perception and comfort in this study, further studies are required to separate the impact of microclimatic environments from psychological effects on thermal tolerance. Furthermore, investigations of factors that influence the evaluation of environmental perception should be conducted in order to identify specific causes for the increase in thermal tolerance by psychological adaptation.

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