Assessment of overhead environments on pedestrian thermal comfort in a dense urban district

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Abstract. Outdoor thermal comfort in urban environmental settings is often investigated at a small scale, e.g., in street canyons. Yet, pedestrian thermal comfort in a district is scarcely assessed, especially in terms of the comprehensive overhead environments such as sky openness, green coverage, and sun exposure. This study provides a systematic methodology to quantify the district-scale pedestrian thermal comfort performance considering overhead environments. Mobile transects were designed for data collection during peak hot hours within a medium-scale district. A portable weather station was used to measure outdoor thermal environments and a fisheye lens was to capture hemispherical images of overhead environments. A universal thermal comfort index, Physiological Equivalent Temperature (PET), was subsequently calculated with the collected thermal environment data. Meanwhile, hemispherical images were segmented into areas of visible sky, overhead greenery, and sun, which were further weighed into corresponding view factors. Eventually, a multiple regression model was developed between PET and view factors together with meteorological variables. The results showed that a decrease in the sky view factor of 0.17 or an increase in the green view factor of 0.21 could reduce PET by 0.5°C. The findings scientifically support resilient urban planning in greening and cooling urban dense spaces for comfortable and liveable environments.

1 Introduction

In the context of global warming, heat waves occur frequently and intensively in cities worldwide [1]. In this regard, urban outdoor thermal environments are increasingly receiving attention, and sustainable and performance-driven urban planning and development are gradually engaged to limit temperature rise within 1.5°C by 2050 [2]. The urban district functions as a vibrant space for city dwellers to work, live and socialize. A thermally comfortable outdoor space provides pedestrians with high-quality urban living [3] and enhanced walkability [4], reversely improving human health.

Pedestrian thermal comfort in an urban district is highly affected by surrounding environmental conditions, e.g., air temperature, humidity, wind speed, sun position, and shade [5]. Apart from these conditions, radiant temperature also correlates with thermal comfort [6]. With the environmental conditions surveyed, a universal index, physiological equivalent temperature (PET), can be used to estimate thermal comfort [7]. PET is derived by solving the heat balance between the human core and human skin. It can be estimated using the RayMan model [8] based on the meteorological variables, human activity level and human clothing. In this regard, it is necessary to sense these environmental conditions to better understand their impacts on pedestrian thermal comfort.

To sense real urban outdoor environments, field survey is commonly carried out in two ways, stationary measurement and mobile measurement. Stationary measurement is conducted at pre-selected locations to collect and record environmental data for a certain duration [9]. These collected time series datasets are further analysed to gain insight into the temporality of urban heat environments. Yet, the survey locations are constrained due to the high cost of sensing instruments. Mobile measurement is conducted at a designed transect to cover more locations. These collected spatial datasets benefit the better understanding of spatial variability and can be used for urban heat mapping to support sustainable and resilient urban planning [10]. Most existing studies use stationary measurement at a small scale such as street canyons [11, 12]. Only a few studies use mobile measurement to investigate urban thermal environments at a medium scale such as an urban district [10, 13]. However, these mobile measurements rarely consider the complexity of the overhead physical environments affecting pedestrian thermal comfort.

This study aims to assess the impacts of overhead environments on pedestrian thermal comfort in a dense urban district. The novelty of this study lies in two aspects: 1) thermal environments and view factors are comprehensively assessed at a district scale; 2) a multiple regression model between the thermal comfort index (PET) and view factors together with meteorological variables is proposed for districts in tropical Singapore. This model can support urban planning by evaluating pedestrian thermal comfort in given thermal and overhead environments.

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2 Methodology

2.1 Study area

Singapore is a city-state island located in a tropical rainforest climate. As a well-known garden city with extensive dense and green urban settings, Singapore has both high temperature and high humidity throughout the year. The maximum diurnal temperature varies from 26 to 33°C and the mean annual relative humidity is as high as 84% [14]. The present study site is located in one-north, a 200-hectare research and business park close to the south of Singapore, as shown in Fig. 1. It is considered a sustainable integrated district with innovative solutions and urban systems, which leverages integrated spatial, social, and environmental strategies for high urban vibrancy.

2.2 Data collection

Field measurements were performed during 12:30 - 15:30 pm (local solar time) on 11 August 2022 to capture outdoor weather conditions at peak hot hours along sidewalks. One bike with common instruments was used for mobile data collection, as shown in Fig. 2. Descriptions of the used instruments are presented as follows.

2.2.1 Portable weather station

The Kestrel 5400 heat stress tracker [15] was used as a portable weather station. It was placed 1.5 m above the ground level, to monitor outdoor weather conditions. Air temperature, relative humidity, globe temperature, and wind speed were measured and recorded every 2 s. These weather parameters were further used to estimate the mean radiant temperature and physiological equivalent temperature (PET).

2.2.2 Smartphone

The smartphone used was the iPhone 12 model, of which the camera system has a 0.5x zoom out to capture the full circle of a hemispherical fisheye image.

2.2.3 Fisheye lens

The 180° fisheye lens combined with the smartphone was used to sense overhead environments. It was vertically placed 1.5 m above the ground level to capture hemispherical images every ~5 s. A remote shutter was connected to the smartphone and each click of the shutter took one fisheye image, including the timestamp and GPS info. Besides, continuous double clicks with a short interval (less than 1 s) marked where the wind speed was measured. Each fisheye image was further decoded into three indexes, i.e., sky view factor, greenery view factor, and sun ratio.

2.2.4 GPS tracker

The GPS tracker (named myTracks) installed in the smartphone was used to record the coordinates along survey routes. Each GPS tracker was set up for recording every 1 s. The timestamp info of each coordinate can therefore be obtained upon when to start mobile measurement.

2.3 Design of mobile survey routes

The mobile survey routes were designed to cover key sidewalks considering their intense and frequent usage, as shown in Fig. 3(a). It is worth noting the constrained survey window during peak hot hours (12:30 - 15:30 pm), which remained at a relatively high temperature. In this survey window, the key tradeoff considered was between measuring sufficient sidewalks and maintaining a low cycling speed and stops. A low cycling speed can stabilize instruments for accurate measurement, while stops are necessary to accurately measure the wind speed. Specifically, the cycling speed was set as ~8km/hr. Each stop took at least 10 s to record wind speeds. The sidewalks were labelled according to street directions, as shown in Fig. 3(b). Among these sidewalks, there are two major categories, the park area (S18_B, S19_B, S20_B, S21_B, S22_B, S25_B, and S26_B in Fig. 3(b)) and non-park area (the remaining sidewalks).
The globe sensitivity is 0.95, and the globe diameter equals 0.15 m. The globe temperature is estimated using Eq. (1) [18], based on measurements of the globe temperature, air temperature, and wind speed.

\[
T_{\text{g}} = T_{\text{a}} + \frac{U}{0.15} + \frac{U^3}{0.15^3 \cdot 0.95} \cdot \left( T_{\text{g}} - T_{\text{a}} \right) - 273.15
\]

where \( T_{\text{g}} \) is the globe temperature (°C), \( T_{\text{a}} \) is the air temperature (°C), \( U \) is the wind speed (m/s), \( \varepsilon \) is the globe sensitivity (=0.95), and \( D \) is the globe diameter (m). It is worth noting that even though human clothing and activity levels were set fixed for calculating PET, its applicability was not essentially restricted [7, 14].

2.4.2 Thermal comfort index

Physiological equivalent temperature (PET) was estimated for a standardized pedestrian (age: 35 years, weight: 75 kg, height: 1.5 m) [21]. Moreover, the pedestrian was assumed to be standing (equivalent metabolic rate of 1.4 met) with walking shorts and a short-sleeve shirt (equivalent clothing value of 0.36 clo). The PET calculation procedure is illustrated in Eq. (2) [19, 20].

\[
\text{PET} = T_{\text{mrt}} + \frac{0.35 \cdot (U - 0.3)}{0.5 + \frac{T_{\text{mrt}} - T_{\text{a}}}{10}}
\]

The physiological equivalent temperature (PET) was partitioned into an individual index, i.e., sky view factor, green view factor, and sun ratio through hemispherical fisheye images. The fisheye image was first segmented into the areas of sky, greenery, and sun based on their respective colour channel [22]. Subsequently, each segmented area was weighted through pixel counting.

The sky view factor (SVF) is calculated using the modified version of the manual Steyn-method, as given by Eq. (2) [23]. Basically, the fisheye image was partitioned into \( n \) annuli and the SVF is then calculated by summing up the contribution from each annular.

\[
\text{SVF} = \frac{2}{\pi} \sum_{i=1}^{n} \sin \left( \frac{\pi(2i-1)}{2n} \right) \left( \frac{sp_i}{ti} \right)
\]

where \( i \) is the \( i \)th annular ring, \( sp_i \) is the globe temperature, \( n \) is the total number of annular rings (= 36), and \( sp_i \) and \( ti \) are the number of sky pixels and the total number of pixels in the \( i \)th ring, respectively.

The green view factor (GVF) is calculated in a similar way as SVF. The difference lies that only green pixels are counted, as illustrated in Eq. (3). Where \( gpi \) is the number of green pixels in the \( i \)th ring.

\[
\text{GVF} = \frac{2}{\pi} \sum_{i=1}^{n} \sin \left( \frac{\pi(2i-1)}{2n} \right) \left( \frac{gpi}{ti} \right)
\]

The sun ratio is calculated as the ratio between the sun area \((sa)\) and the full-circle sun area \((sa_{full})\) in a fisheye image, as given by Eq. (4).
importance. It estimates the contribution of independent variables to the R² averaged over rankings [26] using the ‘relaimpo’ package in R software. The datasets used for regression analysis were those only in the non-park area. Furthermore, non-park datasets were further refined to remove those with GVF less than 0.1. Because the green areas of the fisheye images with GVF under 0.1 were mostly not centred in the image, which means the overhead greenery was far away from the measurement location. After removal, the dataset size for regression analysis was 51.

### 3 Results and discussion

The measurements of all the aforementioned indexes in the study site were summarized in Table 1. The mean air temperature was 32.2°C with a slight variation (Std 0.58) and the mean relative humidity was 63.7%. The mean wind speed calculated was 1.1 m/s. The mean globe temperature was 38.7°C, with a high variation (Std 2.53). This might derive from the heterogeneity of urban environmental settings such as sky visibility and greenery coverage. The sky view factor varied from 0 to 0.94, reflecting that some locations were fully shaded (SVF = 0) and some were almost fully exposed (SVF = 0.94) to the sky. Green view factor (GVF) ranged from 0 to 0.88, indicating that some locations were with no tree crowns (GVF = 0) over 1.5m and some with dense tree crowns (GVF = 0.88). The sun ratio (SR) varied from 0 to 1, indicating that the sun was sometimes fully blocked (SR = 0) due to high-rise buildings and fully visible (SR = 1) in open areas.

Table 1. Statistics of the thermal environment, thermal comfort and overhead environment indexes.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>T&lt;sub&gt;a&lt;/sub&gt; (°C)</td>
<td>32.2</td>
<td>0.58</td>
<td>30.9</td>
<td>34.4</td>
</tr>
<tr>
<td>T&lt;sub&gt;g&lt;/sub&gt; (°C)</td>
<td>38.7</td>
<td>2.53</td>
<td>34.2</td>
<td>44.4</td>
</tr>
<tr>
<td>RH (%)</td>
<td>63.7</td>
<td>1.63</td>
<td>59.6</td>
<td>68.0</td>
</tr>
<tr>
<td>U (m/s)</td>
<td>1.1</td>
<td>0.83</td>
<td>0.1</td>
<td>5.6</td>
</tr>
<tr>
<td>PET (°C)</td>
<td>37.8</td>
<td>2.66</td>
<td>32.3</td>
<td>43.2</td>
</tr>
<tr>
<td>SVF</td>
<td>0.41</td>
<td>0.24</td>
<td>0.002</td>
<td>0.94</td>
</tr>
<tr>
<td>GVF</td>
<td>0.23</td>
<td>0.24</td>
<td>0.002</td>
<td>0.94</td>
</tr>
<tr>
<td>SR</td>
<td>0.38</td>
<td>0.39</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Notes: T<sub>a</sub>, T<sub>g</sub>, RH, U, PET, SVF, GVF, and SR are short for air temperature, globe temperature, relative humidity, wind speed, physiological equivalent temperature, sky view factor, green view factor, and sun ratio, respectively.

More statistics on thermal environment and thermal comfort indexes were illustrated in Fig. 4. The majority of measured air temperatures ranged from 31.5 to 33°C. The relative humidity mainly ranged between 61 and 66%. Most wind speeds were less than 2 m/s. The globe temperature displayed a wide range between 34 and 44°C. With these thermal environment variables in different ranges, the calculated PETs were various and classified into four thermal perceptions contextualized in Singapore [27]. Over half of the investigated locations were not hot (PET < 39°C), while a tiny percentage of locations was very hot (PET > 43°C).

3.1 Linear regression between PET and view factors

The linear regressions between PET and each of the three view factors are shown in Fig. 5. The sky view factor and sun ratio displayed positive linear relationships with PET, while the green view factor showed a negative relationship with PET. Even though the low R² values of the three linear models showed weak linear relationships, the directions of the identified relationships were plausible.
3.2 Multiple regression between PET and view factors

The relative importance of each independent variable on PET was calculated and listed in Table 2. Wind speed contributed little importance to thermal comfort (PET) in the study site. In this regard, it was not included in multiple regression analysis. Globe temperature was excluded even though it was of the most importance. The objective was to apply the multiple regression model to commonly accessible meteorological data. This model estimated PET due to air temperature, relative humidity, sky view factor, green view factor, and sun ratio (R2 = 0.455), as shown in Fig. 6.

Table 2. The relative importance of each independent variable on PET.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Relative Importance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_a</td>
<td>80.9</td>
</tr>
<tr>
<td>RH</td>
<td>5.6</td>
</tr>
<tr>
<td>GVF</td>
<td>4.7</td>
</tr>
<tr>
<td>T_s</td>
<td>3.6</td>
</tr>
<tr>
<td>SVF</td>
<td>2.0</td>
</tr>
<tr>
<td>U</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Fig. 6. Estimated variations of PET due to overhead environments: a) sky view factor, b) green view factor and c) sun ratio when keeping other variables as constants. T_a, RH, SVF, GVF, and SR are short for air temperature, relative humidity, sky view factor, green view factor, and sun ratio, respectively.

Three typical scenarios were analysed to demonstrate the effect of each view factor on PET with the other variables kept as constants, as shown in Fig. 6. Specifically, the other variables were set as respective mean values in Table 2. In the sky view factor scenario, PET was predicted with the change of SVF under three typical hot temperatures (31, 32 and 33°C), as shown in Fig. 6 (a). A decrease in SVF of 0.17 could reduce PET by 0.5°C. An SVF of 0.84 was predicted to determine the boundary between ‘warm’ and ‘hot’ heat perception at 32°C air temperature, and an SVF of 0.16 differentiated ‘warm’ and ‘hot’ at 33°C air temperature. In the green view factor scenario, PET was estimated with the change of GVF under three typical hot temperatures, as shown in Fig. 6 (b). An increase in GVF of 0.21 could reduce PET by 0.5°C. A GVF of 0.50 differentiated ‘warm’ and ‘hot’ at 33°C air temperature, and a GVF of 0.54 differentiated ‘slightly warm’ and ‘warm’ at 31°C air temperature. In the sun ratio scenario, PET was estimated with the change of SR under three typical hot temperatures, as shown in Fig. 6(c). PET would not significantly change with the variation of SR. PET with different SRs was predicted as ‘hot’ thermal perception at 33°C air temperature, while it was ‘warm’ at both 31 and 32°C air temperatures.

4 Conclusions

This study employed a mobile method to survey the thermal environments and overhead environments in a dense district during the typical peak hot hours in tropical Singapore. A multiple regression model was developed between the thermal comfort index (PET) and interpreted view factors together with meteorological variables. This model revealed that a decrease in the sky view factor (SVF) of 0.17 or an increase in the green view factor (GVF) of 0.21 could reduce PET by 0.5°C. In practice, it is killing two birds with one stone when increasing tree canopy covers for shade, which addresses both SVF and GVF. The proposed model can be a useful tool to guide urban planners to improve outdoor thermal comfort and reduce urban heat risks in a dense district. Future studies could benefit from the modification of the proposed systematic approach. The limitation lies in the limited datasets used for statistical analysis. In the future, more data will be collected and provide higher confidence in the multiple regression model.

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5 References