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Comparisons of Respondent Thermal Perceptions in Underneath-elevated-building (UEB) Areas and Direct-radiated (DR) Areas

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Abstract

Outdoor activities are believed to provide citizens with various benefits, including stress reduction, livability improvement and energy conservation. Encouraging outdoor activity becomes an effective way to evocate positive emotions. Thus, numerous studies were established to enhance respondent outdoor thermal comfort by investigating landscape design and building morphology. Yet, studies on the outdoor microclimate and thermal comfort in the underneath-elevated-building (UEB) area were scarce. In this study, on-site measurements and questionnaire surveys were conducted from March to December in 2016. Comparisons of meteorological parameters and respondent thermal perceptions between the underneath-elevated-building area and the direct-radiated (DR) area were presented. Results indicated that occupants were more comfortable in UEB area. It appeared that solar radiation and wind speed were two major issues affecting respondent outdoor thermal comfort and highly relative to occupants' thermal sensation, which can be helpful references for urban planners to optimize outdoor microclimates by altering building designs.

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Keywords: *Outdoor thermal comfort; Underneath-elevated-building area; Direct-radiated area; On-site measurement; Questionnaire survey*

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1. Introduction

Citizens are in need of a livable lifestyle. Compared to the regular indoor activities, outdoor activities are more desirable due to their diverse advantages, such as relieving stress [1], evocating positive emotions [2] and reducing energy consumptions from relevant indoor facilities. However, residents' enthusiasm for going outside is often hindered by the terrible meteorological conditions. To resolve this, great effort was put into the research of optimizing urban microclimate by altering building morphology and landscape. Typical approaches were street canyons [3], shelters [4] and green infrastructures [5]. It is widely acknowledged that the alterations of building and landscape design can be beneficial for enhancing urban microclimate as well as outdoor thermal comfort at precinct scale.

The elevated building design, utilizing the first floor as stilt floor to create open ground, was studied by a few studies [6,7] and proved to have great impacts on pedestrian-level wind and thermal environment. The wind amplifications and shading shelters provided by the elevated building designs are also desirable in the regions with hot and humid climate. However, the respondent thermal perceptions and thermal comfort conditions in the underneath-elevated-building (UEB) remain unexplored. This study aimed to study the occupants' actual responses to the thermal environment in the UEB area, compared with those in the direct-radiated (DR) area. Comparisons of meteorological parameters, respondent thermal sensation and thermal comfort were presented by means of questionnaire surveys and on-site measurements at selected locations in a university campus in Hong Kong.

2. Methodologies

2.1. On-site measurement

Six sites were selected for on-site measurements, including three UEB sites and three DR sites. The UEB sites are corridors beneath the elevated building blocks with two sides open, allowing incoming wind to flow though. These UEB sites receive no direct solar radiation for most of the daytime due to the shading shelters. The DR sites are generally open ground spaces with several sides obstructed by building blocks. These sites receive both direct and reflected solar radiation. From empirical observations, wind speed in these DR sites were relatively low owing to the surrounding obstacles. A mini meteorological station was adopted to meteorological parameters measurements, including air temperature, wind speed, relative humidity, globe temperature and directional radiation. The data logging interval was set to 10s and the logged data was the average value of the parameters in the last ten seconds. The instrument sensors station were all mounted at about 1.5m above ground level, indicating pedestrian level. The instruments were compliant with ISO standard 7726 [8] for physical quantities measurements and calibrated before each experiment. Specifications of the measurement instruments included in the mini meteorological station are summarized in Table 1.

Table 1. Specifications of measurement instruments

Meteorological parameter	Sensor	Measuring Range	Accuracy
Air temperature (T_a)	R.M.YOUNG 41382	-50 ~ 50 (℃)	±0.3℃
Relative humidity (RH)		0 ~ 100 (%)	±1%
Wind speed (V_a)	R.M.YOUNG 81000	0 ~ 40 (ms^{-1})	±0.05 ms^{-1}
Globe temperature (T_g)	TJHY HQZY-1	-40 ~ 60 (℃)	±0.3℃

2.2. Questionnaire survey

The questionnaire survey was designed to investigate the thermal perceptions of the occupants during measurement periods and also to collect the relevant clothing and activity information of the participants. It comprised four major sections: personal information, sunlight perception, wind perception and the overall thermal perception. Subjects were wearing their own clothes during each experiment and the information about clothing and activity level were collected by converting quantitatively to clothing insulation and metabolic rate values according to ASHRAE standard 55 [9] and ISO standard 7730 [10]. The evaluation of thermal sensation vote (TSV) adopted ASHARE 7-point scale [11]. The information of thermal comfort vote (TCV) followed a 5-point scale: very uncomfortable, comfortable, neutral, comfortable and very comfortable. The measurement and survey method is to let participants stay in three of the above-mentioned sites for 15 minutes in turn, while conducting mild activities such as sitting, standing and walking. The subjects were asked to finish the questionnaire after each 15-minute adaptation.

2.3. Thermal comfort index

Physiological Equivalent Temperature (PET) was adopted as the thermal comfort assessing index in the present study. It is defined as the equivalent temperature at which the heat balance of human body can be maintained and the human's core and skin temperature equals in both the assessed environment and an imaginary typical indoor situation. For any given combinations of meteorological parameters and human behavior information, human core and skin temperature can be calculated according to MEMI. By comparing core and skin temperature to the calculated values in MEMI, the equivalent air temperature of the above-mentioned indoor setting can be obtained. This equivalent air temperature is equals to PET. In this study, PET was calculated using Rayman 1.2 [12] with free access to PET by inputting the required parameters including Air temperature, relative humidity, wind speed, mean radiant temperature, metabolic rate, clothing insulation, height, weight, age and gender. All parameters mentioned above can be collected or calculated from the on-site measurements and surveys.

3. Results

3.1. Meteorological parameters

A comparison of the basic meteorological parameters in the some of the measurement days were summarized in Table 2, including air temperature (Ta), relative humidity (RH), wind speed (Va) and globe temperature (Tg). DR site 5 and UEB site 6 were selected for comparison. Maximum, minimum and average values of each meteorological parameters were illustrated. The measurements in both sites were conducted simultaneously in the afternoon.

Table 2. Summary of meteorological parameters

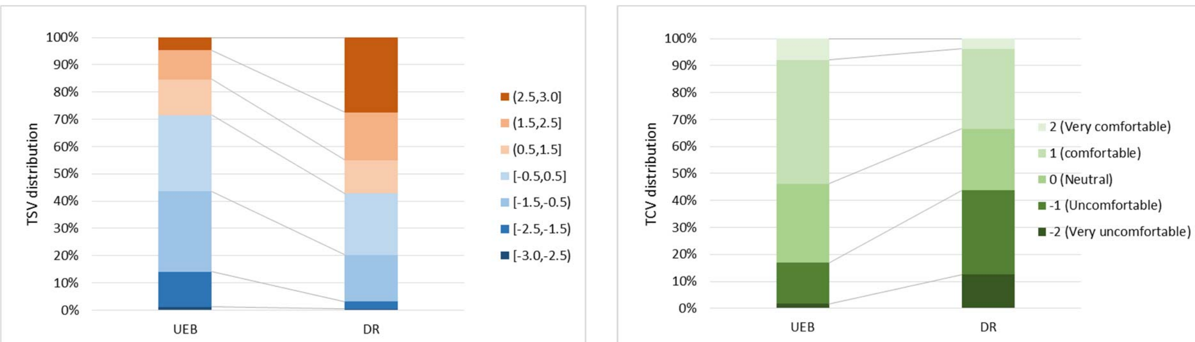
			Experiment date									
			28/6	**15/7**	**17/7**	**1/8**	**22/8**	**26/8**	**21/11**	**5/12**	**6/12**	**12/12**
T_a (℃)	**Site 5 (DR)**	Max	30.6	32.1	32.5	31.6	33.5	34.6	25.4	27.1	23.3	25.8
		Min	30.4	31.6	31.9	31.5	32.4	33.1	25.3	26.7	22.6	24.4
		Avg	**30.5**	**31.8**	**32.2**	**31.5**	**32.8**	**33.7**	**25.4**	**26.9**	**22.9**	**25.4**
	Site 6 (UEB)	Max	30.8	31.9	33.6	31.5	31.9	33.4	25.3	26.7	22.2	24.8
		Min	30.5	31.7	33.0	31.4	30.8	32.7	25.0	24.7	21.9	23.3
		Avg	**30.7**	**31.8**	**33.5**	**31.4**	**31.1**	**33.0**	**25.1**	**25.1**	**22.0**	**23.6**
RH (%)	**Site 5 (DR)**	Max	77.0	72.0	69.0	77.0	88.8	69.0	80.0	65.0	41.0	58.0
		Min	75.0	69.0	66.0	69.0	80.0	66.0	78.0	62.0	39.0	54.0
		Avg	**76.2**	**70.6**	**67.8**	**73.5**	**86.7**	**67.9**	**78.9**	**63.6**	**40.0**	**55.2**
	Site 6 (UEB)	Max	76.0	71.0	64.0	75.0	88.0	73.0	81.0	73.0	41.0	63.0
		Min	73.0	70.0	61.0	67.0	78.0	71.0	80.0	64.0	40.0	57.0
		Avg	**75.0**	**70.8**	**61.8**	**70.6**	**83.0**	**72.1**	**80.6**	**70.4**	**40.9**	**61.1**
Va (ms^{-1})	**Site 5 (DR)**	Max	1.2	3.5	2.4	2.0	1.0	2.7	2.1	1.0	2.9	1.6
		Min	0.2	0.5	0.3	0.5	0.0	0.3	0.0	0.0	0.5	0.1
		Avg	**0.7**	**1.7**	**1.2**	**1.3**	**0.5**	**1.1**	**0.7**	**0.4**	**1.5**	**0.6**

	Site 6 (UEB)	Max	1.8	2.5	1.5	2.5	5.2	2.9	5.9	3.4	2.7	4.3
		Min	0.4	0.2	0.2	0.6	1.9	0.9	0.9	0.7	0.8	0.5
		Avg	**0.8**	**1.2**	**0.9**	**1.4**	**2.9**	**1.7**	**2.7**	**2.1**	**1.8**	**2.6**
T_g (℃)	**Site 5 (DR)**	Max	35.9	36.1	42.3	32.2	46.1	43.4	25.7	34.7	24.5	32.5
		Min	31.5	33.2	36.3	32.0	40.7	40.0	25.4	32.2	23.4	29.8
		Avg	**32.9**	**35.0**	**40.6**	**32.1**	**43.8**	**41.9**	**25.6**	**33.9**	**23.8**	**32.0**
	Site 6 (UEB)	Max	32.8	32.5	34.6	31.7	32.7	35.5	25.3	26.4	23.0	24.4
		Min	31.9	32.0	33.4	31.6	31.0	33.4	25.1	24.8	22.3	23.3
		Avg	**32.6**	**32.3**	**33.9**	**31.7**	**31.3**	**33.9**	**25.2**	**25.2**	**22.8**	**23.6**

It can be observed that variations of air temperature and relative humidity are 0 to 2°C and 2 to 10% respectively for both sites, which are nearly negligible. Average air temperature in DR site is generally 2°C higher than UEB site, which is possibly caused by radiation. Difference in relative humidity of both sites are also subtle with less than 7% in average value. However, variations of wind speed and globe temperature for site 5 and site 6 are much more obvious than air temperature and relative humidity. Range of wind speed in DR site and UEB site can reach to 3.0 ms^{-1} and 5.0 ms^{-1} respectively. Solar radiation in DR site is obviously higher than UEB site from the comparison of globe temperature. In the comparison between both sites' average wind speed and globe temperature, UEB site has a generally stronger wind and weaker radiation than the DR site, due to the obstructions to wind from surrounding buildings blocks and the shading shelters. In general, difference of both air temperature and relative humidity between the selected sites are small. The major differences in meteorological parameters between UEB and DR sites are wind speed and solar radiation.

3.2. Thermal perceptions

Fig. 1 illustrates the distributions of thermal sensation votes (TSV) and thermal comfort votes (TCV) in both UEB and DR areas from all questionnaire surveys. The TSV scale in this study follows the ASHRAE 7-point scale and the descriptions of thermal sensation was represented quantitatively. The value +3 denotes 'hot' while -3 denotes 'cold'. Results indicated that 57% of the occupants felt warm or hot in DR area while the percentage is less than 30% in UEB area. 46% of the occupants expressed their discomfort in DR area and only 17% of them felt uncomfortable or very uncomfortable in UEB area. It is clear that the 'lift-up' design provides the occupants with cooler and more comfortable microclimate, which can be highly desirable by the people staying outdoor, especially in the hot and humid climate.



(a) (b)

Fig. 1. Distributions of thermal sensation votes (TSV) and thermal comfort votes (TCV) in UEB and DR areas: (a) TSV; (b) TCV.

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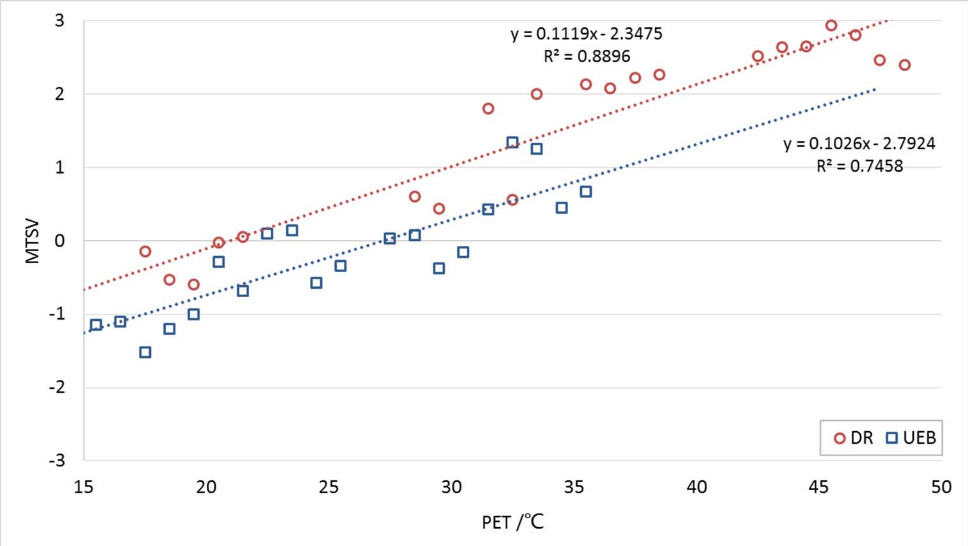

Fig. 2. Linear regressions between Mean Thermal Sensation Votes (MTSV) and PET

For a clear comparison on the occupants’ thermal sensation in certain thermal stress, thermal sensation votes were correlated with physiological equivalent temperature, shown in Fig. 2. The one-degree average method was adopted. Each point shown in the figure represents the average thermal sensation vote value, i.e. mean thermal sensation vote (MSTV), in the nearby 1 °C PET bin. The data points with sample size less than 4 were deleted to avoid errors.

It is observed that MTSV correlates well with PET for both DR and UEB conditions, for the R2 values for both conditions are high in the linear regressions. Slopes of both regression lines are similar, indicating the occupants are equally sensitive to the changes of thermal stress in both DR and UEB areas. On the other hand, the regression line for the DR area is higher than that for the UEB area. This indicates that occupants feel hotter in DR area rather than in UEB area even with the same degree of thermal stress, which is represented by PET. Considering the major differences appearing in wind and radiation for the DR and UEB areas, it is possible that the strong solar radiation and the still wind in the DR areas lead to a hotter thermal perception.

3.3. Radiation and wind perceptions

The correlations between respondent radiation/wind perceptions and thermal sensation votes were presented in Fig. 3. Data of radiation/wind perceptions were collected from questionnaire surveys. For the evaluations of sunlight and wind level, a 7-point scale were adopted with a range from -3 to +3, indicating ‘too strong’, ‘strong’, ‘slightly strong’, ‘neutral’, ‘slightly weak’, ‘strong’ and ‘too weak’. For sunlight and wind improvement, subjects were asked if they needed improvement for the sunlight or wind condition and three options were provided: ‘less sunlight/wind’, ‘no change needed’, ‘more sunlight/wind’, indicating the values -1, 0 and +1, respectively. The average value of radiation/wind perceptions were plotted for each TSV range. The bubbles (points) in the figures denote the sample size. Bubbles with less than 10 samples were deleted to avoid accidental errors.

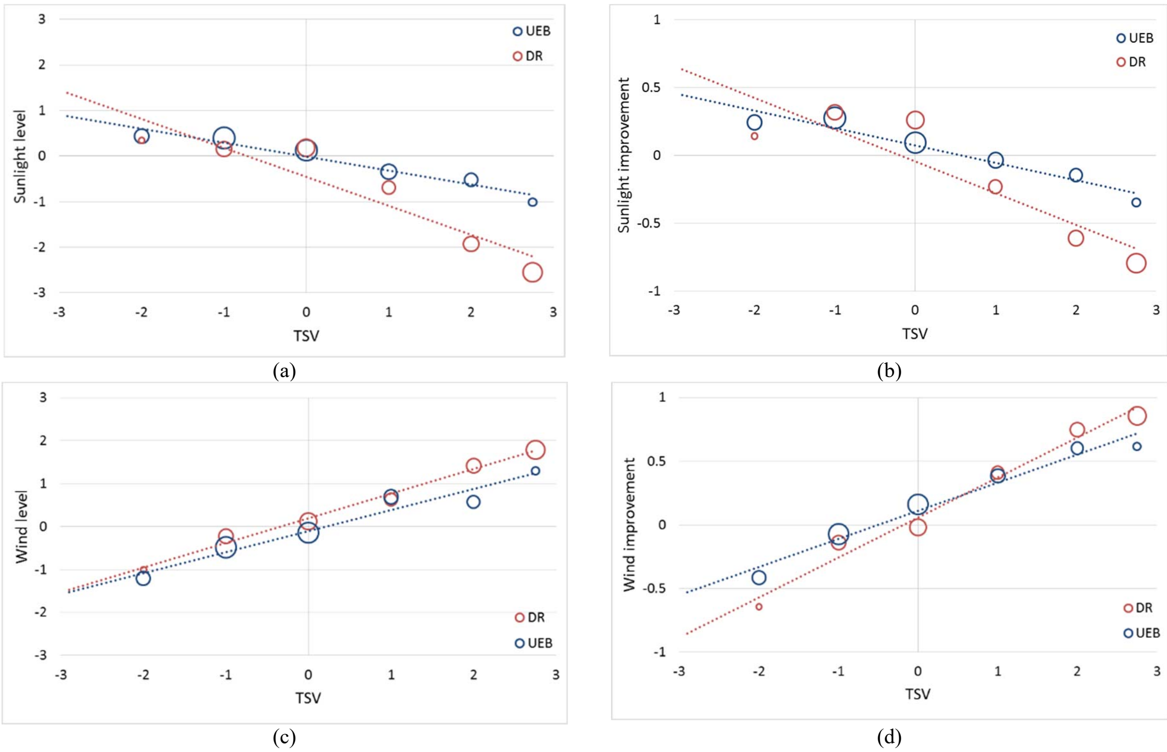

Fig. 3. Correlations between radiation/wind perceptions and TSV:
(a) Sunlight level v.s. TSV; (b) Sunlight improvement v.s. TSV; (c) Wind level v.s. TSV; (d) wind improvement v.s. TSV.

Trends in Fig. 3 clearly indicate that occupants' radiation or wind perceptions are closely related to their thermal sensations. Obvious negative correlations were observed between sunlight level/improvement and TSV, while the correlations between wind level/improvement and TSV appeared to be positive. This means changes of wind and solar radiation can oppositely affect occupants' thermal sensation. Subjects tend to feel hot in strong sunlight and cold in strong wind. The radiation/wind level variation trends are similar for both DR and UEB area. But in hot conditions, sunlight level in DR area tend to drop more rapidly than in UEB area, while wind level for both areas have similar trend of variation. The same goes to sunlight/win improvement. This indicates that wind condition equally affects occupants' thermal sensation in both DR and UEB areas, but sunlight condition has a stronger impacts on the respondent thermal sensation in DR area, especially in hot weather.

4. Conclusions

The case study has demonstrated the differences in meteorological parameters, thermal perceptions and radiation/wind perceptions between UEB and DR areas. The major distinctions in meteorology between DR and UEB area appeared in solar radiation and wind speed. The occupants felt generally cooler and more comfortable in while staying in the UEB area, even with the same degree of thermal stress. Further investigations revealed that respondent thermal perceptions closely related to the subjects' perceptions upon solar radiation and wind speed. Restricting radiation and amplifying wind flow can be effective approaches to a more comfortable thermal state, especially in the hot climate. This indicates that the UEB area can be a more favorable and appealing place for occupants to conduct outdoor activities, due to its capability to providing shading shelters and wind amplifications. The present study serves as a preliminary investigation on the respondent thermal perceptions in two typical building morphologies. It also provides references for urban planners to take account the benefits of the 'lift-up' design for the promotions of urban microclimate and the livability of city residents.

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