Building and Environment 59 (2013) 426–435

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Thermal comfort in outdoor urban spaces in Singapore

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ARTICLE INFO

Article history:
Received 25 June 2012
Received in revised form
14 September 2012
Accepted 14 September 2012

Keywords:
Thermal comfort
Outdoor urban spaces
Acceptable operative temperature range
Correlation analysis
Thermal adaptation

ABSTRACT

A thermal comfort study has been carried out in outdoor urban spaces in Singapore. The field study was carried out from August 2010 to May 2011. There were 2059 respondents from 13 different outdoor spaces participated in this study and 2036 effective questionnaire responses were collected. Thermal comfort perceptions and preferences were analyzed in this study. The neutral operative temperature occurred at 28.7 °C and preferred temperature was found to be 26.5 °C. Thermal acceptability analysis shows the acceptable operative temperature range was 26.3–31.7 °C in outdoor urban spaces in Singapore. Correlation analysis indicates that sun sensation/solar radiation has the most significant influence on human thermal sensation in outdoor spaces. This study also explores the impact of thermal adaptation on human thermal sensation in outdoor spaces, which could be useful for future researchers. Comparative analysis shows that people may expect a higher temperature in outdoor conditions than in semi-outdoor or indoor conditions in Singapore, suggesting that people in outdoor conditions could be more tolerant with the heat stress than people in indoor conditions in tropical climate.

1. Introduction

Singapore is commonly known as the 'Garden City' and 50% of the country is covered by greenery. However, urbanization has resulted in the disappearance of most primary rainforest in Singapore, which in turn has modified the local climate condition. One of best known effects is the urban heat island, which is the phenomenon that urban air temperature is higher than that of the surrounding rural environment [1]. One study indicated the presence of urban heat island effect and observed a maximum temperature difference of 4.01 °C between well planted area and the central business district area in Singapore [1]. Apart from urbanization, global warming is also a factor contributing to warmer climate in Singapore. The mean yearly temperature for Singapore for the period 1948–2008 shows an increase of 0.25 °C per decade [2]. The warmer urban climate may have some negative impacts on outdoor thermal comfort of people in Singapore. How does the outdoor thermal environment affect human thermal comfort perception in Singapore? And which climatic variable has the most significant influence on human thermal sensation? Understanding the characteristics of urban outdoor microclimate and the comfort implications for the people using them opens up new possibilities for the development of urban spaces [3].

Over the years, many field studies on thermal comfort have been conducted in different outdoor spaces and under different climatic conditions [3–10], which provided valuable information on understanding the effects of outdoor climatic conditions on people's thermal sensation as well as the use of outdoor spaces. However, outdoor thermal comfort in urban spaces is a complex issue and has become an increasingly prominent and hotly debated topic as reflected in the literature [11]. Empirical data from field surveys on the subjective human perception in the outdoor context is still needed, as this would provide a broader perspective from which to view comfort in urban spaces [3]. Based on the above review, it can be seen that most of the outdoor thermal comfort studies were conducted in temperate and cold climates and some of the studies were conducted in subtropical humid climate such as Hong Kong and Taiwan, but relatively little research has been conducted in the context of Singapore. Thus, it is worth to carry out a field study to evaluate the outdoor thermal environment conditions and human thermal comfort perceptions in Singapore.

Outdoor thermal comfort studies have revealed that a purely physiological approach is inadequate to characterize thermal comfort conditions outdoors, and thermal adaptation, which involves behavior adjustment (personal, environmental, technological or cultural), physiological factor (genetic adaptation or acclimatization) and psychological factor (habituation or expectation),

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http://dx.doi.org/10.1016/j.buildenv.2012.09.008

plays an important role in the assessment of thermal environments [5,8,12–15]. Although thermal adaptation has been the focus of many thermal comfort studies in both indoor and outdoor conditions, few evidence of thermal adaptation has been explored and most of the evidences investigated focused on behavior adjustment [3,15] and the difference between air conditioned (AC) and naturally ventilated (NV) spaces [10,12,16]. Thus, it is necessary to explore some other aspects of thermal adaptation besides behavior adjustment and differences between AC and NV environment.

Another important issue of thermal comfort study is the differences between indoor, semi-outdoor and outdoor conditions and only a few attempts have been made to understand the differences. Höppe P mentioned that the physiological and psychological factors needed to be considered and different approaches were necessary for assessing indoor or outdoor thermal comfort [17]. Hwang and Lin conducted a study to investigate thermal comfort requirement for occupants of semi-outdoor and outdoor environments and the results indicated that occupants of semi-outdoor and outdoor environments were more tolerant regarding thermal comfort than occupants of indoor environments [18]. Since several thermal comfort studies under indoor conditions [19,20] and semi-outdoor conditions [21] have been conducted in Singapore, it would be interesting to compare the human thermal sensation in outdoor condition with those in indoor and semi-outdoor conditions.

Given all of this, this study is expected to produce relevant and most recent data to provide a better understanding of the general thermal environment and occupants' thermal comfort perceptions in outdoor urban spaces in Singapore. The main objectives of this study are as follows:

1. To investigate the thermal comfort perception and preference of people in outdoor urban spaces in Singapore, and compare the results with previous indoor and semi-outdoor studies conducted in Singapore.
2. To investigate the impact of thermal adaptation on human thermal sensation in outdoor spaces.

2. Methods

2.1. Study areas

The field study was conducted in 13 different outdoor spaces in Singapore. Singapore is situated between 103°36′E–104°25′E longitude and 1°09′N–1°29′N latitude and has a tropical monsoon climate with uniformly high temperatures, high humidity and abundant rainfall throughout the year. The field surveys were carried out from August 2010 to May 2011. Each study area was carefully selected in order to represent different microclimatic conditions, functions and locations in the city. Thus, the data obtained from the survey can represent the thermal environment conditions that people may encounter in their daily life in urban Singapore. The study areas are typical resting-places which people visit to relax, meet friends, have a picnic, sunbathe, and play outdoor games. A total of 2036 sets of effective questionnaire were collected during the survey. The summary of data sample is presented in Table 1.

2.2. Data collection

Data collection includes physical measurement and subjective assessment. Each site was visited two or three times, trying to obtain different weather conditions (sunny/cloudy). All the field surveys were carried out on days with suitable weather, to avoid windy or rainy days. To account for the daily changing climatic conditions, the survey was conducted in four sections a day: morning (9–11am), midday (12–2pm), afternoon (3–5pm) and evening (8–10pm).

Table 1
Summary of the sample.

Sample size		2036
Gender	Male	1008
	Female	1028
Age (year)	Mean	30.1
	SD	14.9
	Minimum	10
	Maximum	72
Length of time living in Singapore (years)	Mean	7.8
	SD	14.7
	Minimum	0.5
	Maximum	46
CLO	Mean	0.30
	SD	0.06
	Minimum	0.15
	Maximum	0.56

The physical measurement aimed to collect the microclimatic parameters such as air temperature, globe temperature, relative humidity, wind speed and global radiation. The former four environmental parameters were measured by Testo 445, a system for flexible measurement of different measurement data, and the CM6B Pyranometer tracked global radiation, which is a combination of direct and diffuse solar radiation and the radiation emitted from the surroundings. The accuracy of the instrument conformed to ISO 7726 [22]. The measurement height was 1.1 m, corresponding to the average height of the centre of gravity for adults [23]. The objective physical measurements for each visit lasted 15–20 min. The average value of each measured variable was used for subsequent analysis.

The subjective assessment was based on responses to a questionnaire survey, which was administered simultaneously with physical measurement during each survey. The scope of the questionnaire was based on several preceding studies with special reference to the one used in the RUROS project in Europe [3], the ASHRAE standard questionnaire for indoor thermal comfort study [24] and some previous thermal comfort field studies [6,16,19,25]. The questionnaire comprised three sections. The first section asked the respondents to assess thermal sensation, thermal preference and thermal acceptability. The thermal sensation scale was the traditional ASHRAE 7-point scale (TSV, −3 cold, −2 cool, −1 slightly cool, 0 neutrality, 1 slightly warm, 2 warm and 3 hot). The thermal preference was the 3-point McIntyre preference scale (prefer warmer, no change and cooler). The thermal acceptability used direct assessment (acceptable, unacceptable). The respondents were also asked to indicate their sensation of the air humidity, wind speed and solar radiation intensity based on a 5-point scale and their preference based on a 3-point scale (humidity sensation vote HSV, −2 too dry, −1 dry, 0 ok, 1 humid, 2 very humid; wind speed sensation vote WSV, −2 stale, −1 little wind, 0 ok, 1 windy, 2 too much wind; sun sensation vote SSV, −2 too weak, −1 little weak, 0 ok, 1 little strong, 2 too strong). The second section of the questionnaire asked some questions relevant to thermal adaptation of the respondents. The third section dealt with demographic information such as age and gender, length of time living in Singapore, activity levels, and the clothes respondents were wearing.

Metabolic rate and clothing insulation were estimated in accordance with ASHRAE standard 55-2004 [24]. The standard provided a checklist of typical activities and their corresponding metabolic rates. As only respondents who were sitting and standing