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Thermal perception, adaptation and attendance in a public square in hot and humid regions

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ABSTRACT

Highly relevant to an individual's thermal perception, the thermal environment in outdoor public spaces impacts the use of such spaces. Thermal adaptation, which involves physiological, psychological and behavioral factors, also plays an important role in assessment of thermal environments by users. Given that these issues have rarely been addressed for outdoor environments in hot and humid regions, this study examines user thermal comfort in a public square in Taiwan. Physical measurements were taken and a questionnaire survey was used to assess the thermal comfort of subjects. The number of people visiting the square was also counted. Analytical results indicate that the thermal comfort range and neutral temperature of subjects was higher than those of people in a temperate region. Additionally, local subjects preferred a cool temperature and weak sunlight, and adapted to thermal environments by seeking shelter outdoors. Analytical results confirm the existence of thermal adaptation and illustrate the characteristics of, and variances in, thermal adaptation. During the cool season, the number of people visiting the square increased as the thermal index value increased. However, the number of people frequenting the square decreased as the thermal index increased during the hot season. These experimental results were compared with those for temperate regions, indicating that the human energy balance model cannot fully explain the influence of climate on use of public spaces; that is, psychological and behavioral factors also play important roles in outdoor thermal comfort. Study findings also elucidate design of outdoor public spaces in hot and humid regions.

1. Introduction

Weather can significantly impact mood and behavior. With sufficient exposure, pleasant weather can improve mood and enhance cognition [1]. Due to the need for leisure and recreation, people are often directly exposed to weather when visiting outdoor urban spaces. Therefore, a comfortable thermal environment is extremely important to the enjoyment of public spaces.

Some studies have examined thermal comfort in outdoor environments. Compared with indoor thermal comfort, outdoor thermal comfort and thermal acceptable range should differ due to psychological and behavioral factors [2–6], i.e., thermal adaptation.

Adaptation is the gradual decrease in an organism's response to repeated environmental stimulation, such that an organism adapts to survive in a given environment [7]. Thermal adaptation has become an important issue in studies of indoor and outdoor thermal environments. Many studies have indicated that occupant perceptions and preferences for thermal environments vary markedly due to differences in behavioral adjustments, physiological adaptation to a climate, and psychological habituation or expectations. Physiological adaptation to a climate is generally slow and has not been a focus of thermal comfort studies. Conversely, the impacts of psychological adaptation and behavioral adjustment on thermal comfort are significant [3,7–10].

Some studies investigating thermal adaptation have examined how psychological factors influence thermal comfort, indicating that individuals residing in hot and humid regions have better tolerance for high temperatures than those residing in temperate regions [11–13]. Expectations [6,14], perceived control [8,15] and cultural characteristics [16] markedly impact thermal comfort. People typically adopt different behaviors when adjusting to indoor thermal environments; these behaviors also affect their degrees of thermal acceptance [17].

The success of a public space can be based on the number of people who use that space [18]. Therefore, to determine whether perception of a thermal environment affects space usage, Nikolopoulou et al. [2] proposed that the easiest method is to estimate the number of individuals using a public space. Some studies of semi-outdoor spaces [5],

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parks and public squares [2,19–21] examined whether the number of people and thermal environment were correlated, and demonstrated that the number of people using a space increased as air temperature (Ta) or mean radiant temperature (Tmrt) increased in public spaces in temperate regions.

However, most studies on outdoor thermal comfort have been conducted in temperate climate countries. Although thermal adaptation to ventilated indoor spaces in hot and humid regions has been thoroughly elucidated, few studies have focused on thermal adaptation to outdoor environments in hot and humid regions. According to case studies in temperate regions, as outdoor Ta increased from winter (roughly 1 °C) to summer (29 °C), the temperature at which people feel comfortable, i.e., neutral temperature, increased from roughly 8 °C to 28 °C [2]. This study investigates whether such a drastic change also occurs in hot and humid regions. No study has determined whether the number of people visiting an outdoor public space and its thermal environment are correlated in a hot and humid region. Other issues addressed are whether observations vary among seasons and whether thermal adaptation affects the willingness of people to visit outdoor public spaces in Taiwan.

Conducted in Taiwan, which has a hot and humid climate, this study purpose examines outdoor thermal comfort, verifies the existence of thermal adaptation and explores issues associated with public square utilization and thermal environment. By comparing study results with those obtained for different regions, this study sheds light on outdoor thermal comfort and public square utilization in a hot and humid region, and identifies design practices mitigating microclimate condition.

2. Method

2.1. Study area

The study square is located in Taichung City (120°40' E, 24°08' N, at an altitude of 26 m), central Taiwan. Fig. 1 shows the average, maximum and minimum air temperatures (Ta) and average relative humidity (RH) in Taichung City in 1971–2000. Average Ta is highest in July at 28.5 °C (maximum temperature, 33 °C), and average Ta is coldest in January at 16.2 °C (minimum temperature, 12.4 °C). Average RH during a year is 70–80%. Meteorological data show that summers in Taichung City are hot and winters are mild. Since low Ta only exist from December to February, this study defines this period as the "cool season" and the remaining months (March to November) as the "hot season".

The investigation site is the public square in front of the National Taiwan Museum of Fine Arts (NTMOFA), Taichung City. The square encompasses 102,000 m^2. This rectangular public square has 1300 m^2 located directly in front of the NTMOFA. People typically walk, relax, attend activities, take photos, and paint in this public square.

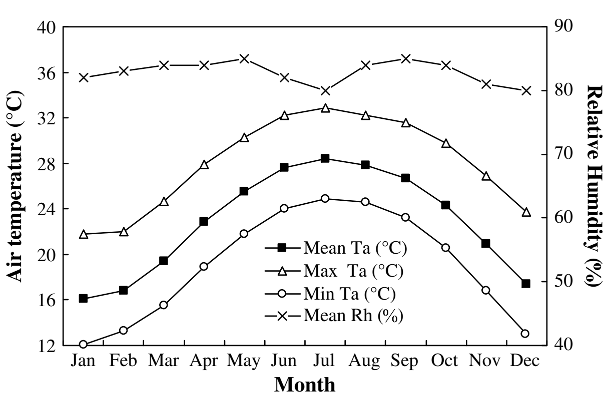

Fig. 1. Monthly mean/maximum/minimum air temperatures and mean relative humidity in central Taiwan (1971–2000). Source: Central Weather Bureau, Taiwan.

2.2. Physical measurements

This study measured Ta, RH, global radiation (G), wind speed (v) and globe temperature (Tg). All instruments are compliant with the ISO 7726 [22] standard and placed at a height of 1.1 m above ground on tripods in the middle of the square. On the measurement day, data were acquired at 1 min intervals from 13:00 to 18:00, when the square is used most. Other climate parameters, such as cloud condition, water vapor pressure and sun duration, were obtained from the Taichung Weather Station, located 1 km from the NTMOFA.

2.3. Thermal comfort indices

Several indices based on the energy balance of the human body were applied to assess outdoor thermal comfort, e.g., predicted mean vote (PMV) [23], effective temperature (ET*), standard effective temperature (SET*) [24], OUT_SET* [4,25] and physiologically equivalent temperature (PET) [26]. The PMV, ET*, and SET* indices have a solid basis for indoor use, whereas the OUT_SET* and PET indices have been primarily designed for outdoor use [4]. Notably, SET* is defined as the air temperature at which an individual in a reference environment (Ta = Tmrt, RH = 50%, v = 0.15 m/s) wearing 0.6 clo with a metabolic rate of 1.2 mets has the same mean skin temperature and skin wettedness as the individual in the complex environment [24]. The OUT_SET* was developed to adapt SET* to outdoor conditions. Similarly, PET is defined as the air temperature at which, in a typical indoor setting (Ta = Tmrt, water vapor pressure = 12 hPa, v = 0.1 m/s), the heat budget of the human body is balanced with the same core and skin temperature as those under complex outdoor conditions. Thus, PET enables a layperson to compare the integral effects of complex thermal conditions outside with his or her own experience indoors [27].

Because both the PET and OUT_SET* indices were developed by considering the effects of short- and long-wave radiation fluxes in outdoor environments on the human energy balance, they are both appropriate for outdoor assessing thermal comfort. Using the PET index in outdoor environments has some benefits. First, PET is already included in German VDI 3787 [26] for human biometeorological evaluation of climate in urban and regional planning. Second, PET can be estimated using free software packages (e.g., RayMan) [28]. In addition to the factors need to calculate PET in the RayMan model, such as air temperature, air humidity, wind speed, human clothing and activity, Tmrt, can be estimated by importing the observed value of global radiation or by importing cloud cover, time of year and surrounding obstacles (e.g., fisheye photos). Furthermore, parameters such as albedo, the Bowen ratio of the ground surface and Linke turbidity of air can be also adjusted using RayMan. In this manner, the evaluation of PET using the RayMan model is very flexible and practical. Third, PET has been used in urban built-up area with complex shading patterns and generated accurate predictions of thermal environments [21,29,30]. Therefore, PET was chosen as the primary thermal index in this study.

2.4. Questionnaire survey

A questionnaire survey was administered during field measurements. The first part of the questionnaire collected demographic information (e.g., age and sex) and data for activity