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Outdoor thermal comfort and outdoor activities: A review of research in the past decade

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ABSTRACT

Outdoor spaces are important to sustainable cities because they accommodate pedestrian traffic and outdoor activities, and contribute greatly to urban livability and vitality. In the global context of climate change, outdoor spaces that provide a pleasurable thermal comfort experience for pedestrians effectively improve the quality of urban living. The influence of thermal comfort on outdoor activities is a complex issue comprising both climatic and behavioral aspects; however, current investigations lack a general framework for assessment. This paper presents a review of research over the past decade on the behavioral aspects of outdoor thermal comfort. The article focuses on perceptions of outdoor thermal comfort and the use of outdoor space in the context of urban planning. We further discuss a general framework for assessing outdoor thermal comfort based on behavioral aspects and the need for predicting tools in the design and planning of outdoor thermal comfort.

Introduction

Outdoor spaces are important to sustainable cities because they accommodate daily pedestrian traffic and various outdoor activities and contribute greatly to urban livability and vitality. Encouraging more people on the streets and in outdoor spaces will benefit cities from various perspectives, including physical, environmental, economical, and social aspects (Hakim et al., 1998; Hass-Klau, 1993; Jacobs, 1972; Whyte, 1988). With more than half of the world's population now living in cities (Population Reference Bureau, 2009), downtown areas are particularly vulnerable to extreme weather conditions in the global context of climate change. Under these circumstances, ensuring that pedestrians are well served by outdoor spaces is essential to high-quality urban living. Over the past few decades, making outdoor spaces attractive to people, and ultimately used by them, has been increasingly recognized as a goal in urban planning and design (Carr, Francis, Rivlin, & Stone, 1993; Gehl & Gemzøe, 2004; Marcus & Francis, 1998; Maruani & Amit-Cohen, 2007).

Among many factors that determine the quality of outdoor spaces, the outdoor microclimate is an important issue. In contrast with car commuters, pedestrians are directly exposed to their immediate environment in terms of variations of sun and shade, changes in wind speed, and other characteristics. Thus, people's sensation of thermal comfort is greatly affected by the local microclimate. The microclimate also influences decisions on whether to use the space. For example, in his seminal work, "Life Between Buildings: Using Public Space," Gehl (1971) first studied the influence of microclimate on outdoor activities by counting people sitting on sunny and shady benches. He showed that local sunny or shady conditions significantly impact the desire of people to either stay or leave. In the past decade, broad applications in urban studies of concepts and equipment used in biometeorology and urban climatology have yielded a vast number of research projects on outdoor thermal comfort in various climates around the world (Ahmed, 2003; Ali-Toudert & Mayer, 2006; Cheng & Ng, 2006; Cheng, Ng, Chan, & Givoni, 2010; Givoni et al., 2003; Gulyas, Unger, & Matzarakis, 2006; Höppe, 2002; Nikolopoulou & Lykoudis, 2006; Spagnolo & De Dear, 2003; Stathopoulos, Wu, & Zacharias, 2004; Tseliou, Tsiros, Lykoudis, & Nikolopoulou, 2009). Some studies have focused on modeling and assessment methods from a thermophysiological perspective (e.g., Gulyas et al., 2006; Höppe, 2002), whereas others have conducted detailed investigations of the climatic parameters that determine the thermal comfort level of humans (e.g., Cheng & Ng, 2006; Spagnolo & De Dear, 2003). In the context of urban planning, how the thermal sensations of people influence their behavior and use of outdoor spaces is of utmost interest. Given the range of literature along these lines, a general framework for assessing the behavioral aspects of outdoor thermal comfort conditions will be beneficial for both researchers and planning practitioners. Such a framework has yet to be discussed in great depth.

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The focus of this review is twofold. First, we provide a brief introduction to the most widely used models and indicators in outdoor thermal comfort assessment. Second, we present a comprehensive literature review of outdoor thermal comfort research over the past decade from a behavioral perspective, with a focus on the link between outdoor thermal comfort and outdoor activity and the use of outdoor space in the context of urban planning. Subsequently, we discuss a general framework for assessing the behavioral aspects of outdoor thermal comfort and identify the need for predicting tools in design and planning that address outdoor thermal comfort.

An introduction to outdoor thermal comfort assessment methods

Steady-state assessment methods

A number of biometeorological indices have been developed to describe human thermal comfort level by linking local microclimatic condition and human thermal sensation (Task Committee on Outdoor Human Comfort of the Aerodynamics, 2004). A major group of such indices are the so-called steady-state models. These models are based on the assumption that people's exposure to an ambient climatic environment has, over time, enabled them to reach thermal equilibrium, and they provide numerical solutions to the energy balance equations governing thermoregulation. Nagano and Horikoshi (2011) provided a good summary of indices in this category. One of the most widely used indices is the Predicted Mean Vote Index (PMV) (Fanger, 1982), which predicts the mean thermal response of a large population of people. It is often measured on a seven-point scale (+3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, −1 = slightly cool, −2 = cool, −3 = cold). In practice, PMV is also commonly interpreted by the Predicted Percentage Dissatisfied Index (PPD), which is defined as the quantitative prediction of the percentage of thermally dissatisfied people at each PMV value. PMV has been included in the International Organization for Standardization ISO standard (ISO, 1994). Originally developed as an indoor thermal comfort index, PMV has also been commonly adopted in outdoor thermal comfort studies in which large groups of people are being surveyed (Cheng et al., 2010; Nikolopoulou, Baker, & Steemers, 2001; Thorsson, Lindqvist, & Lindqvist, 2004).

The Physiological Equivalent Temperature (PET) (Mayer & Höppe, 1987) is another notable example of a steady-state model. PET is a temperature dimension index measured in degrees Celsius (°C), making its interpretation comprehensible to people without a great deal of knowledge about meteorology. PET is based on the Munich Energy-balance Model for Individuals (MEMI) (Höppe, 1984) and is defined as the air temperature at which, in a typical indoor setting, the human energy budget is maintained by the skin temperature, core temperature, and sweat rate equal to those under the conditions to be assessed (Höppe, 1999). PET is particularly suitable for outdoor thermal comfort analysis in that it translates the evaluation of a complex outdoor climatic environment to a simple indoor scenario on a physiologically equivalent basis that can be easily understood and interpreted. PET has been widely applied in areas with various climatic conditions (Ali-Toudert & Mayer, 2006; Cheng et al., 2010; Lin, 2009; Matzarakis, Mayer, & Iziomon, 1999; Thorsson, Honjo, Lindberg, Eliasson, & Lim, 2007).

Other steady-state evaluation methods include the Index of Thermal Stress (ITS) (Givoni, 1976), the fuzzy-PMV (Hamdi, Lachiver, & Michaud, 1999), the OUT-SET* (Pickup & De Dear, 1999), and the COMFA outdoor thermal comfort model (Kenny, Warland, Brown, & Gillespie, 2009). These all serve as analytical tools to assess human thermal responses to the local thermal environment.

Non-steady-state assessment methods

The problem with steady-state methods is that they cannot effectively account for the dynamic aspects of the course of human thermal adaptation. For example, Höppe (2002) explicitly showed the difference between the dynamic thermal adaptation process of a pedestrian and the steady-state condition using a simple "sunny street segment" simulation case (Fig. 1). A similar analysis was conducted by Bruse (2005). As opposed to the various indicators developed to assess steady-state thermal comfort, the methodologies for dynamic assessment show a scattered picture. Höppe stated as early as 2002, "The problem we face today is that there are no internationally accepted non-steady-state indices for the solution of this problem. (p. 664)" The picture remains unchanged today. Most methods for assessing human dynamic thermal adaptation are based on the Pierce Two-Node model (Gagge, Fobelets, & Berglund, 1986; Gagge, Stolwijk, & Nishi, 1971). As the name implies, this model treats the human body as two isothermal parts, skin and core, based on which thermoregulation (i.e., heat exchange equations) is constructed for the passive state. Effectively, core temperature, skin temperature, and mean body temperature can all be derived by their deviation from the set points. Other thermoregulatory indicators such as sweating rate and skin blood flow can also be calculated accordingly.

Although these assessment methods can provide detailed investigations of the dynamic course of human thermal adaptation, they have two major drawbacks when applied in outdoor thermal comfort studies. First, the indicators used, such as skin temperature, require extensive monitoring of human subjects, which is hardly feasible and practical in outdoor cases. Therefore, the current studies are restricted mainly to indoor cases (Foda & Sirén, 2010; Zhang, Huizenga, Arens, & Wang, 2004) or simulation cases in the virtual world (Bruse, 2005; Havenith, 2001; Huizenga, Zhang, & Arens, 2001). Second, these indicators require domain knowledge in biometeorology and physiology and are not informative enough to provide useful implications for planning practice. Nevertheless, the assessment of unsteady outdoor thermal comfort

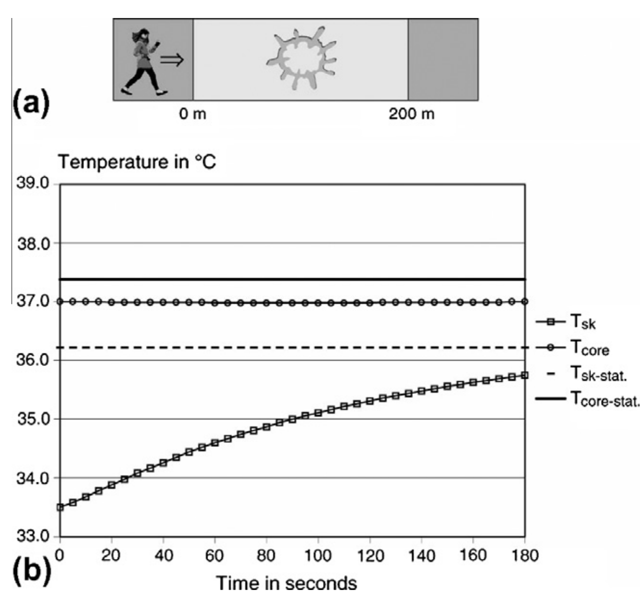

Fig. 1. An illustration showing the difference between a dynamic thermal adaptation process of a pedestrian and its steady-state condition: (a) scenario "sunny street segment"; (b) temporal variation of a pedestrian's physiological conditions, described by skin temperature (T_{skin}) and core temperature (T_{core}). T_{skin}-stat. and T_{core}-stat. are steady-state skin temperature and core temperature, respectively. Source: Höppe (2002).

conditions remains an active area of thermal comfort research, and constant efforts are being made for model development and field study (Fiala, Lomas, & Stohrer, 2001; Jendritzky, Maarouf, & Staiger, 2001; Shimazaki et al., 2011; Tokunaga & Shukuya, 2011).

Recent research on the behavioral aspects of outdoor thermal comfort

Although preliminary studies have been conducted on the relationship between outdoor thermal comfort and outdoor activity (Li, 1994; Nagara, Shimoda, & Mizuno, 1996), detailed microclimatic analysis and thermal comfort assessments have been included in these studies only in the last decade because of the advances in techniques in the fields of urban climatology and biometeorology. This section provides a comprehensive review of research in this domain. Table 1 shows a summary of the reviewed studies.

The work by Nikolopoulou et al. (2001) (Table 1) is one of the first outdoor thermal comfort studies to address people's behavior. Its research framework and analysis procedures have greatly influenced subsequent studies in this area. In their study, Nikolopoulou et al. (2001) investigated thermal comfort conditions of urban open space as resting areas in a British city (Cambridge). They interviewed people on their subjective evaluations of thermal sensation, given in a five-point scale varying from too cold to too hot. They also considered environmental characteristics (air temperature, solar radiation, etc.) and individual characteristics (age, sex, clothing, etc.). Although the authors observed that the finding of comfort conditions generally implied that more people used the space, the most important finding of their study was the large discrepancy between the actual thermal comfort sensation of the interviewees as described by the Actual Sensation Vote (ASV) (described as *subjective* data) and the theoretically predicted thermal comfort condition as described by PMV (described as *objective* data). Only 35% of the interviewees were within acceptable theoretical comfort conditions, whereas the majority was within either the too hot or the too cold condition (Fig. 2). The authors concluded that a physiological approach alone is not sufficient to evaluate the thermal comfort condition for outdoor spaces and therefore suggested the importance of "thermal history" and "memory and expectation".

Accordingly, in a later discussion using the same case study, Nikolopoulou and Steemers (2003) further formalized this idea as three levels of thermal adaptation: *physical*, *physiological*, and *psychological*. They discussed this concept from a design perspective with an emphasis on psychological adaptation. In their paper, the authors demonstrated through regression analyses that only approximately 50% of the variance between objective and subjective comfort evaluations could be explained by physical and physiological conditions. They speculated that the difference was attributable to psychological factors such as naturalness, past experience, perceived control, time of exposure, environmental stimulation, and expectations. The authors developed a network demonstrating the interrelationships among various influencing parameters of psychological adaptation (Fig. 3). In terms of implications for planning, the authors discussed design considerations in microclimatic planning to increase use of outdoor spaces and argued that the understanding of these influencing factors would not restrict design solutions but would rather complement their role in the design. Although the concept is generally tempting, as the authors admitted, no quantified relationship in terms of the effectiveness of a design alternative had been determined to that point because of the complexity of the interrelationship among the various factors (Fig. 3).

From an urban design perspective, Zacharias, Stathopoulos, and Wu (2001) attempted to form a quantitative link between microclimate and use of urban open spaces. In their study, seven corporate plazas and public squares in the downtown area of a North American city (Montreal) were examined to discover the relationship between local microclimate and usage level, which was measured as presence levels of people and three types of activities, namely, sitting, standing, and smoking. Through multiple regression analyses and ANOVA tests, the authors demonstrated that microclimatic variables, preponderantly temperature and sun, account for about 12% of the presence variance in studied

Table 1
Review of outdoor thermal comfort studies from behavioral aspects in the last decade.

City and climate	Urban area	Season	Survey method	Thermal comfort assessment	Analysis method	Behaviors	Factors determining comfort	Levels of consideration	Source
Cambridge, UK; Temperate	Open spaces	Spring, summer, winter	Interview, attendance counting	PMV/PPD	Regression, frequency distribution	Attendance	Environmental stimulation, thermal history	Physical, physiological, psychological	Nikolopoulou, Baker, and Steemers (2001)
Montreal, Canada; Temperate	Plazas, public squares	Spring, summer, autumn	Observation, presence counting	No	Multiple regression, ANOVA test	Sitting, standing, smoking	Temperature, sun	Climatic	Zacharias, Stathopoulos, and Wu (2001)
Gothenburg, Sweden; Temperate	Urban park	Summer, autumn	Interview, questionnaires, vote	PMV	Regression, frequency distribution	Stay and rest	Microclimatic condition, thermal expectation	Physical, physiological, psychological	Thorsson, Lindqvist, and Lindqvist (2004)
Kassel, Germany; Temperate	Open spaces near a bistro	Spring, summer	Observation, presence counting	PET	Regression	Attendance	Temperature, solar radiation, wind speed, expectation	Physiological, expectation	Katzschner (2006)
Satellite city of Tokyo, Japan; Temperate	Park, square	Spring	Interview, questionnaires, unobtrusive observation	PET	Frequency distribution, regression	Various	Weak relation	Physiological, social	Thorsson et al. (2007)
Athens, Greece; Temperate	Neighborhood square, seashore place	Four seasons	Interview, questionnaires, observation	No	Regression	Presence, sitting	Temperature, solar radiation	Meteorological, social,	Nikolopoulou and Lykoudis (2007)
Gothenburg, Sweden; Temperate	Square, park, courtyard, plaza	Four seasons	Observation, interview	No	Multiple regression	Attendance, various behaviors	Clearness, temperature, wind speed	Meteorological, functional, psychological	Eliasson et al. (2007)
Taichung, Taiwan; Subtropical	Public square	Four seasons	Observation, questionnaires	PET	Regression	Attendance	Temperature, solar radiation	Physiological, psychological, behavioral	Lin (2009)

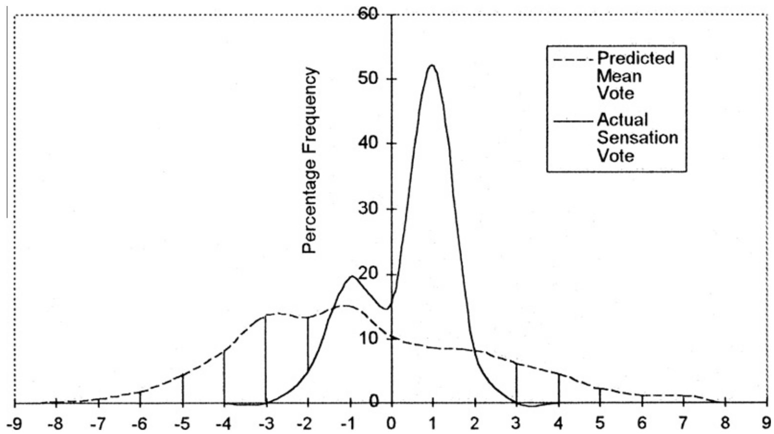

Fig. 2. Percentage frequency distribution for Predicted Mean Vote and Actual Sensation Vote. Source: Nikolopoulou et al. (2001).

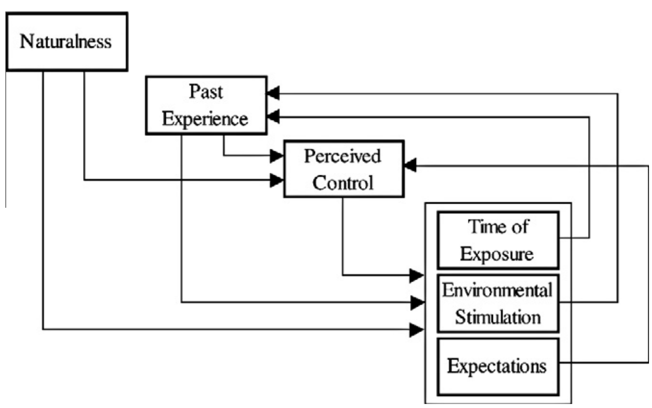

Fig. 3. Network demonstrating the interrelationships between the various parameters of psychological adaptation in outdoor thermal comfort studies. Source: Nikolopoulou and Steemers (2003).

open spaces, whereas place and time of day account for 38% and 7%, respectively. There was also a strong linear relationship between sitting behavior and air temperature ($r = 0.920$). Notably, the authors anticipated the usefulness of microclimatic considerations in predicting the presence of people in site planning processes for projects in built-up urban areas. However, they also noted that presence of people does not necessarily imply their satisfaction and suggested that the perception of comfort, as complementary to the levels of presence and activity type, should be considered if refinements of space design standards are to be achieved. In this regard, the major drawback of their study is the lack of a physiological analysis of the thermal sensational responses of the subjects.

Thorsson et al. (2004) also studied the influence of thermal bioclimatic conditions on behavioral patterns of people in an urban park as a resting area, but in a Swedish city (Gothenburg). Their study took a survey approach in which they interviewed approximately 280 people and used questionnaires to collect their reasons for visiting the park and their opinions on the design of the park. Their interviewees' subjective thermal sensations, as described by ASV, were also evaluated by means of a seven-point psychophysical scale. The objective thermal comfort index of PMV was calculated and compared to that of ASV. Similar to the findings of Nikolopoulou et al. (2001) (Fig. 2), the comparison showed a distinct discrepancy between ASV and PMV; that is, 59% of the interviewees found warm or hot conditions, whereas PMV gave a prediction of 23%; also, 38% of the interviewees found acceptable comfort conditions, whereas the PMV prediction was only 26%. The fact that the PMV curve was skewed toward the warm zone indicated that people visiting the park voluntarily exposed themselves to sunny areas that were well outside the theoretically acceptable thermal comfort range. The two major findings of this study are as follows: (1) transient exposure and thermal expectations may have a major influence on subjective assessment and satisfaction, and (2) steady-state models such as PMV may not be appropriate for the assessment of short-term outdoor thermal comfort. Preliminary planning recommendations were also made, such as creating microclimate diversity to increase both the physical and psychological adaptations of people and therefore their use of outdoor spaces.

The work by Katzschner (2006) in Kassel, Germany, is another noteworthy example of the effect of outdoor thermal comfort on outdoor activities. The study was in line with the EU RUROS Project (Rediscovering the Urban Realm and Open Spaces) (Nikolopoulou & Lykoudis, 2006), which aimed to provide measurement techniques and evaluation methods that are easy to use in urban planning. The temperature dimension index of PET was used to assess outdoor thermal comfort, and a PET range of 18–21 °C was found to be neutral. Simple microclimatic measurement routines were designed to measure and calculate solar radiation and PET. The use of open spaces near a small bistro was observed and compared to the calculated PET. The finding was generally in accordance with the study by Thorsson et al. (2004); that is, the behavior of people is dependent on outdoor thermal conditions but is also influenced by individual expectations. For example, people coming out of air-conditioned buildings still seek sunshine outside even when the objective PET evaluation exceeds neutral conditions. The use of PET makes the evaluation result informative and assessable for planners and decision makers.

Thorsson et al. (2007) studied the subjective outdoor thermal comfort and human activity in an urban environment that is much more densely built up than North American and European cases. They conducted case studies in a park and a square in a satellite city of Tokyo in Japan. The PET index was also used for quantifying people's objective thermal condition, and a PET value of approximately 20 °C was considered to be comfortable. In parallel, a nine-point scale was used to evaluate the subjective thermal sensations of 1192 people through the use of questionnaires. The two sets of data were compared, and similar to Nikolopoulou et al. (2001) and Thorsson et al. (2004), the PET curve was also skewed toward the warm zone. An important finding is that people tended to stay longer (19–21 min on average) when their perception of thermal conditions was within the acceptable comfort zone than when their perception was outside of the zone (11 min on average). Human activities in terms of attendance and behavior in relation to sunlit and shaded patterns were observed unobtrusively; a total of 7304 people were recorded. In contrast with previous studies, the result showed that the effect of the thermal environment on the use of the sites, as described by total attendance, was generally insignificant. For example, regression analyses showed that the correlation between total attendance and PET was very weak, with R^2 on the order of 0.001 for the square and 0.24 for the park. This inconsistency was explained by the authors in another paper as caused by cultural and climatic differences (Knez & Thorsson, 2006). As the correlation showed, the use of the park was more influenced by microclimate than the use of the square, which was attributed by the authors to the different functions of the sites. Although their paper uncovered other interesting findings, such as a difference in attitudes toward sun and shade between Japanese and Swedish people, the role of the social function of urban space in climate- and behavior-related research is more noteworthy.

Nikolopoulou and Lykoudis (2007) took a step further by explicitly integrating social and environmental objectives in their investigation of the diurnal usage pattern of outdoor spaces in a Mediterranean city (Athens). In their study, a neighborhood square and a resting area near the sea with very different characteristics were examined. The social characteristics of people (e.g., age, sex, whether working or retired) were also considered. Through observations and interviews of 1503 individuals, the spatial distribution of usage was derived. The authors notably considered the socio-economic characteristics of "popular locations" in interpreting usage variations (e.g., distinctions among kiosk, coffee shop, and playground). Using a statistical approach, the use of space was presented as a function of various meteorological parameters; air temperature and solar radiation were found to be the dominant factors in affecting the use of space. The downside of the analysis is the generally low correlation (with R^2 lower than 0.1 for most cases), which is in accordance with the common wisdom regarding the complex and conflicting nature of people's responses. Nonetheless, what is interesting is the distinguishable pattern of the influence of microclimate on sites with different functions (e.g., the presence of people in relation to the sun).

The function of urban space was extended to more diverse cases in the study by Eliasson, Knez, Westerberg, Thorsson, and Lindberg (2007). Four urban public spaces in a Nordic city (Gothenburg) (i.e., square, park, courtyard, and waterfront plaza) were examined. A total of 1379 people were interviewed. Human perception of the urban environment was categorized into functional and psychological evaluations, which were measured by total attendance and emotional satisfaction, respectively. Thermal comfort was surveyed based on a nine-point scale ranging from very cold to very hot in relation to the emotional states of the participants. Multiple regression analyses showed that clearness index, air temperature, and wind speed accounted for more than 50% of variance in place-related attendance, suggesting that the three climatic factors had a significant influence on the behavioral assessment of people. Although the study revealed distinct aesthetical evaluations of the waterfront plaza and the square in terms of feelings of beauty and pleasantness, social functions were not considered, at least explicitly, in relation to behavior assessment and usage variation. Nevertheless, the importance of climate-sensitive planning in urban design and planning projects was substantially confirmed by the study.

The studies discussed above were all conducted in regions with moderate climates, where warm conditions and sunlight are positive factors that affect the use of outdoor spaces among people. In contrast, Lin (2009) studied thermal perception and adaptation in relation to the use of a square in a hot and humid subtropical climate in Taichung City, Taiwan. For the study, a year is divided into a "cool season" (December to February) and a "hot season" (March to November). Physical measurements for both seasons were conducted, and the biometeorological index of PET was used. A total of 505 people were interviewed on their Thermal Sensation Vote (TSV) as given in an ASHRAE seven-point scale. Meanwhile, high-resolution photographs were used to count the number of people in the square. An important finding was that the thermal acceptable range for an entire year was 21.3–28.5 °C PET, which was significantly higher than the European scale of 18–23 °C PET, indicating that people living in different climates have different thermal preferences. Consequently, Lin's study showed that, as opposed to a temperate climate environment, cool temperature and weak sunlight are generally desirable during the hot season in a subtropical climate. For example, the field survey showed that more than 90% of people visiting the public square in the summer chose to stay under shade trees or in building shelters, indicating the importance of shade in outdoor environments. On this basis, the author proposed preliminary design strategies, such as adding trees and shelters, to achieve a higher level of thermal comfort and encourage a higher usage rate of outdoor spaces in hot and humid regions. However, the effectiveness of the general design requirements was not determined in any great depth.

From the examples above, it can be seen that microclimate indeed has a significant influence on the use of outdoor spaces in cities. Temperature, solar radiation, and wind speed are shown to be the most significant factors. Therefore, understanding the relationship among building form, thermal sensation, and human behavior is expected to provide guidelines and implications for urban design and planning practices. In fact, as early as 1985, the city of San Francisco established design requirements to control for the effect of a new building on the local microclimatic environment of public space, including limiting wind speed and controlling shadows cast by new construction (City & County of San Francisco, 1985). These regulations have been discussed in both legal and research literature (Bosselmann et al., 1988; Vettel, 1985) and copied in many other North American cities, such as Montreal and New York.

Summary and prospects for future research

Assessment of thermal perception from a behavioral perspective: a general framework

According to the literature reviewed above, outdoor spaces are important in promoting the quality of life in cities. However, outdoor thermal comfort in an urban environment is a complex issue with multiple layers of concern. The environmental stimulus (i.e., the local microclimatic condition) is the most important factor in affecting the thermal sensations and comfort assessments of people. These assessments are both dynamic and subjective: dynamic in the sense that adaptation to an ambient thermal condition is progressive, and that thermal sensation is primarily affected by previous experience, and subjective in the sense that the evaluation of a thermal comfort condition is not always consistent with the objective climatic or biometeorological condition. In addition to the climatic aspects of thermal comfort, a variety of physical and social factors that influence perceptions of urban space come into play when people are outdoors. For example, they are often engaged in activities, either alone or with other people, and those activities might be associated with physical amenities such as street furniture, shelter, seating, or kiosk stands. Thus, the use of outdoor space is determined not only by the "state of body" but also by the "state of mind." This suggests that, to assess the perception of outdoor thermal comfort in terms of behavioral aspects, an assessment framework should work on at least four levels: *physical*, *physiological*, *psychological*, and *social/behavioral* (Fig. 4).

This framework should allow the local microclimatic condition to be linked with human sensations as well as with the use of space in both spatial and temporal terms. In other words, static and objective aspects (i.e., physical and physiological characteristics) should be measured and modeled effectively to provide "climatic knowledge," and dynamic and subjective aspects (i.e., psychological and social/behavioral characteristics) require comprehensive field interviews and observations to provide "human knowledge."

The need for a predicting tool

Although people's subjective perceptions and responses to the urban environment are various and not yet well understood, simulation and scenario-testing tools are always of particular importance in an assessment framework because they provide a platform for the integration of knowledge from various perspectives and comparisons of various design scenarios. Givoni et al. (2003) addressed the need for "predicting tools" in the research for how changes in design details influence outdoor thermal comfort. As they put it, "In order to evaluate the importance of modifying the outdoor climate in a particular direction by specific design details it would be helpful if the designer would have some means for 'predicting' the effect of a particular change in a climatic element on the comfort of persons staying outdoor. (p. 77)" The statement applies with equal force to the more general context of research in this area, which is how urban design can influence the microclimate of an urban environment and people's outdoor thermal comfort and, in turn, how people's thermal comfort can influence their use of outdoor urban spaces. Design regulations and guidelines in this respect require comprehensive assessment before they are adopted.

The study of Zacharias, Stathopoulos, and Wu (2004) provides a good lesson. These authors had the opportunity to study a site that underwent a major design transformation intended to promote public use. They observed human behavior in a plaza before and after the design changes. Although the redesign was a standard solution for bringing more people into the plaza by providing seating provisions, their analysis revealed that the amount of seating had a modest effect on the presence of people and could even be considered as insignificant in affecting plaza use. In contrast, the quality and location of seating, which are affected by the principal climatic factors of temperature and sunlight, were shown to have a dominant effect in determining whether the seating was used. In this sense, the design solution failed to meet expectations because the decision was not informed by knowledge about which factors matter to people and design alternatives addressing possible outcomes.

Town planners and decision makers, when faced with the task of designing urban spaces that are desirable and thus used rather than abandoned, will be better informed with a predicting tool that allows various design alternatives to be compared and tested in terms of attractiveness and effectiveness. In particular, a testing tool is needed that can provide both quantitative and qualitative understanding of the relationships among microclimatic environment, subjective thermal assessment, and social behavior. Such a tool should have the ability to process detailed environmental information according to time and location variations and to generate analytical results to reveal the relationship. Environmental modeling tools such as ENVI-met (Bruse, 2010; Bruse & Fleer, 1998), TownScope (Teller & Azar, 2001), Rayman (Matzarakis, 2007), and SOLWEIG (Lindberg, Holmer, & Thorsson, 2008) can provide an understanding of climatic conditions, and human physiological modeling tools such as those by Huizenga et al. (2001) and Bruse (2005) can provide assessment of human thermal comfort.

The predicting tool should also be able to represent the individual characteristics of people and also the dynamic aspects of their behaviors in the assessment. Multi-agent-based simulation systems, such as BOTworld (Bruse, 2007, 2009), and the integration with geographical information system (GIS) techniques (Kántor &

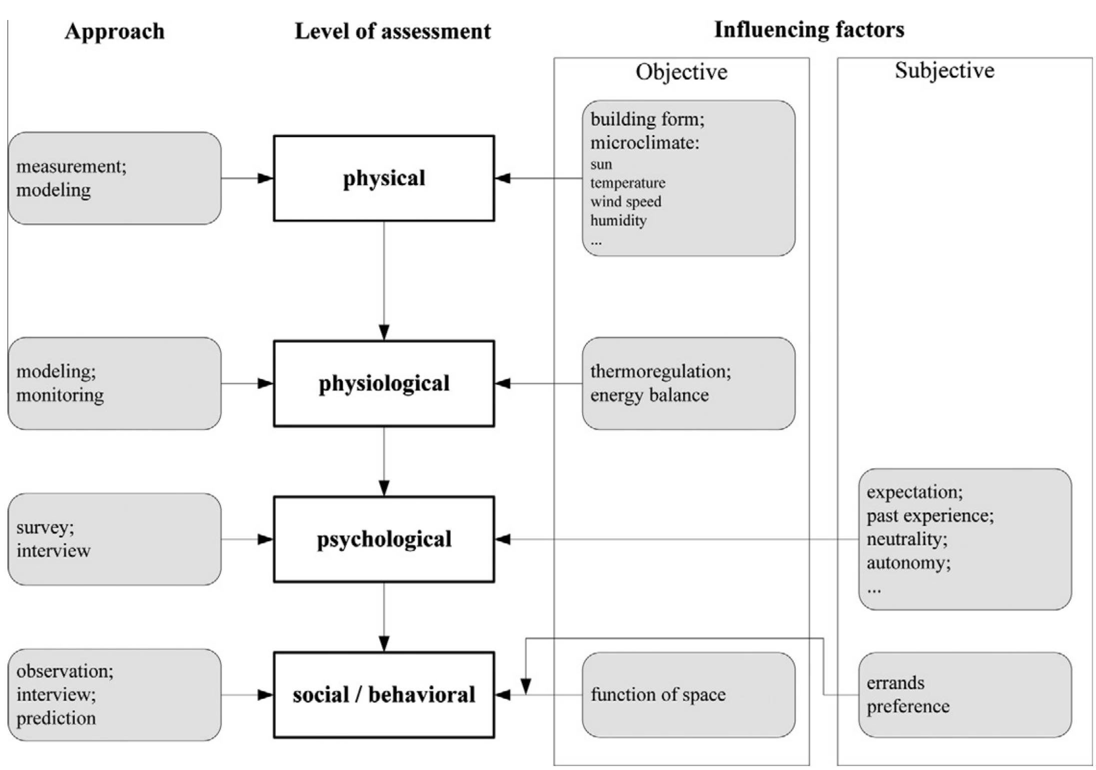

Fig. 4. A general framework for outdoor thermal comfort assessment based on behavioral aspects.

Unger, 2010) are expected to provide new approaches to understanding the influences of the outdoor thermal environment on human activity and people's use of outdoor space and the planning implications.

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