Comfort in Urban Public Spaces

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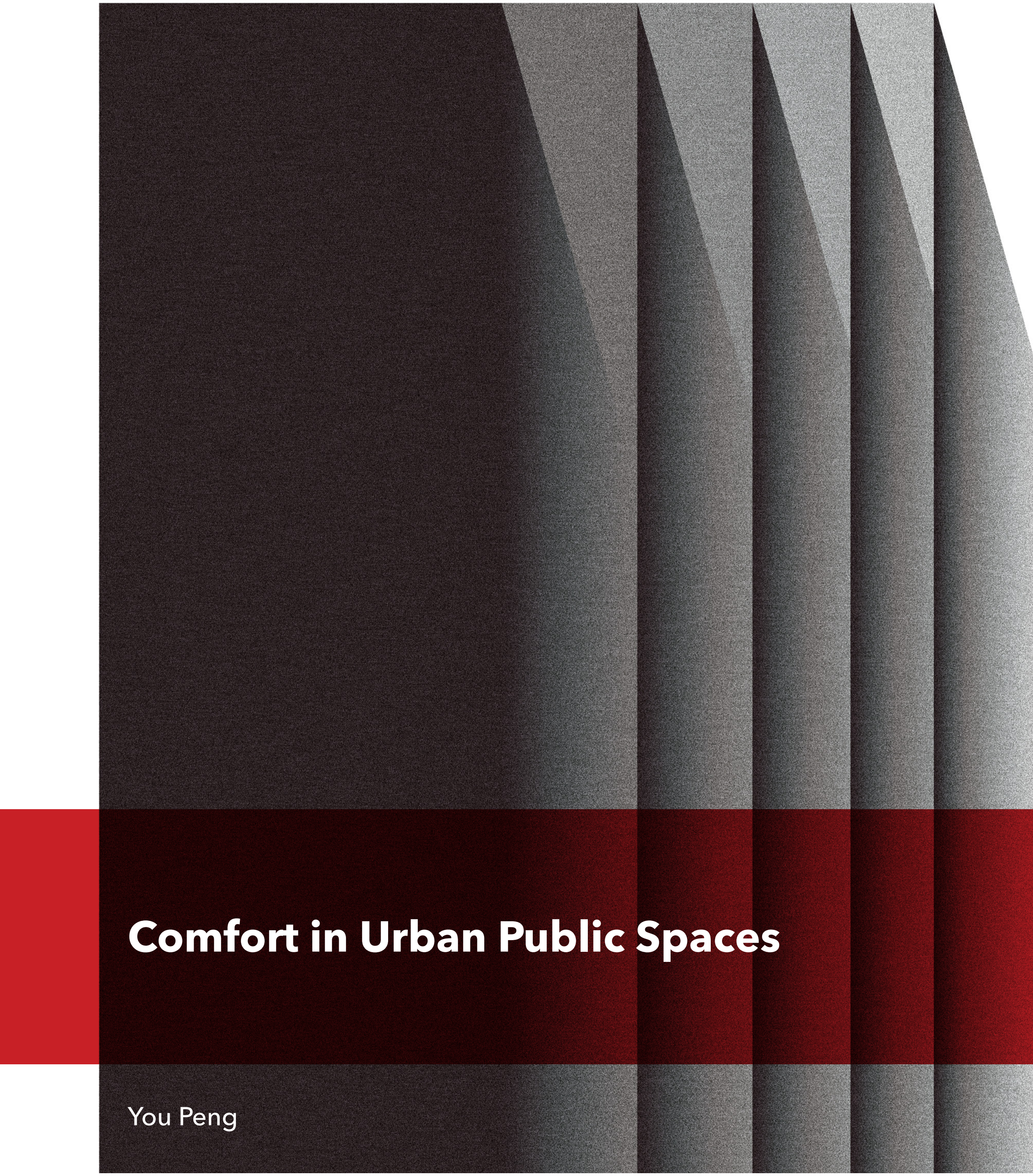

Comfort in Urban Public Spaces

You Peng

Bouwstenen 332

Comfort in Urban Public Spaces

PROEFSCHRIFT

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Zwei Dinge erfüllen das Gemüt mit immer neuer und zunehmender Bewunderung und Ehrfurcht, je öfter und anhaltender sich das Nachdenken damit beschäftigt: Der bestirnte Himmel über mir und das moralische Gesetz in mir.

Two things fill the mind with ever new and increasing admiration and awe, the more often and steadily we reflect upon them: the starry heavens above me and the moral law within me.

--- by Immanuel Kant

Preface

The completion of this dissertation means the long journey of my PhD study in the Netherlands is coming to an end. This experience shaped much of my current professional and academic pursuits. During this challenging trip, with ups and downs, fortunately, I was not alone. I would like to take this opportunity to offer my profound gratitude to everyone who helped me all the time along the way.

There are no proper words to convey my sincere appreciation and respect for my first promotor, prof. dr. Harry Timmermans. He offered me the opportunity to pursue my doctoral degree and broaden my horizon. I have benefited a lot from his broad knowledge and superb guidance. His flexibility, patience, and concern contribute to our excellent working relationship and the accomplishment of my PhD research. His comments and suggestions on methodology and writing in a scientific way have improved the quality of our publications and this dissertation to a higher level.

My deepest gratitude goes to my second promotor and daily supervisor, prof. dr. Tao Feng, who always helped me at the crucial time. He spent considerable time and effort on my work and guided me to the right track of doing research. He enlightened me to formulate the modeling approaches and put them into practice.

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I would also like to acknowledge the committee members, prof. dr. Theo Arentze, dr. ir. Twan van Hooff, and prof. dr. Yingxin Zhu for their valuable time and effort spent in reviewing my dissertation and their insightful and motivational comments.

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If the course of PhD research is like a trip, living abroad for a few years is more than just a trip. The real life is always far more complicated, and full of unexpected setbacks. Fortunately, I harvest friendship and knowledge. A special thanks owes to Bo, Dujuan, Feixiong, Hao, Kang, Nan, Rui, Tian, Xinfeng, Yang, Yi and Zhiqiang. I enjoy the way of life in the Netherlands and feel a pleasure of sharing my happiness with them.

Most importantly, I would like to thank my dear family for their help, patience and trust without any premise and condition. Despite the unexpected difficulties during these years, I have always been committed. Their care and concern always brighten and encourage me to finalize the relatively long process of PhD study and this dissertation.

You Peng

Eindhoven, April 2022

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1.

Introduction

1.1 Background and motivation

Humanity is experiencing a dramatic shift towards urban living (Grimm et al., 2008). Since 2007, more than half of the world population lives in cities. As the rapid urbanization seems unstoppable, the urban population is projected to reach 68% by 2050 (Cohen, 2003; United Nations, 2018). The increase of people residing in urban areas obviously increases pressure on land and public infrastructure. It leads to urban sprawl, due to the expanding demand for living and working space. Meanwhile, the concentration of population and industry in urban areas implies a higher consumption of energy, massive congestion, air pollution and significant change of the urban morphology, which contribute to climatic change and the degradation of environmental quality in city regions (Kalnay and Cai, 2003; Mills et al., 2010; Scheuer et al., 2017). More specifically, the anthropogenic activities have increased the global temperature and there is a high probability of a further increase if the current carbon emissions are unmanaged (IPCC, 2019). Urban life is facing a host of difficult challenges, including potential heat waves, cold spells, droughts and extreme rainfall that are projected to be more frequent, more severe, and of longer duration (Grimm et al., 2008; Wilson et al., 2008; Gao et al., 2015; IPCC, 2019). These prominent urban problems prompt solutions for anticipating and designing for uncertain, perhaps rapidly varying, microclimatic conditions (Chappells and Shove, 2005).

The outdoor thermal environment is complex due to the constantly changing environmental conditions and the interplay between the human body and the ambient environment. People are directly exposed to dynamic and non-uniform microclimates and environmental conditions when conducting daily activities. The abovementioned consequences of climate change and urban growth stimulated a growing concern about sustainable and climate-sensitive adaptation strategies and their implications for improved urban environmental quality, and research interests to overcome the adverse effects on comfort, health, and well-being of urban residents, especially among urban planning and policy making professionals (Lenzholzer et al., 2020). The experience of urban public space is highly dependent on microclimate conditions (Nikolopoulou et al., 2001; Zacharias et al., 2001; Eliasson et al., 2007; Gehl, 2011; Chen and Ng, 2012; Lai et al., 2014; Coccolo et al., 2016). Thermal comfort plays an indispensable role in the evaluation of urban microclimatic conditions and environment quality (Rupp et al., 2015).

In recent years, intense changes in urban microclimates and morphologies have endangered urban ecosystems (Gao et al., 2015). The fast pace of urban development has caused the replacement of dense greeneries with impermeable pavements and buildings which leads to high albedo and lack of natural ventilation (Kondo et al., 2001). Unlike the native vegetation counterparts in rural areas, the physical properties of urban materials with relatively high volumetric heat capacity generate higher heat storage and temperatures (Arnfield, 2003). In addition, urban geometry modifies the radiations and wind speed and turbulence which intensifies the heat emission in the urban canopy layer and induces thermal stress in outdoor public spaces, so that urban areas experience a substantially different meteorology than their rural counterparts (Oke, 1982, 1988; Heusinkveld et al., 2014). It has been confirmed that, as a downside to urbanization, the land cover of city centers brings more thermal discomfort when compared with peripheral and rural areas (Johansson and Emmanuel, 2006). In particular, the threat of pronounced additional warming of built-up areas has been well documented, which is known as the urban heat island (UHI). This phenomenon was reported not only in cities with high radiation, but also in cities of high latitudes characterized by warm or cold summers (Peng et al., 2012; Stewart and Oke, 2012; Santamouris, 2020). Urban public spaces are vulnerable to UHI and other possible adverse effects of extreme biometeorological conditions (Höppe, 2002). Due to the accelerating replacements of plants with impervious surfaces in urban growth, a thermal stress of higher temperature and less natural ventilation exist in urban areas compared with rural environments, which deteriorate the livability and vitality of urban spaces and impede sustainable development (Fong et al., 2019).

Residents in cities of developed countries stay most of the time in indoor environments. On average, individuals spend less than 20% of their time outdoors (Klepeis et al., 2001). The air-conditioned spaces are intensively used by the urban population to meet their thermal comfort requirements by skipping the natural wind and sunshine, adapting to avoid the increased vulnerability to climatic challenges in outdoor environments (Niu et al., 2015; Golasi et al., 2018). The sedentary lifestyle not only harms the health of people but also considerably increases energy consumption (Kumar and Sharma, 2020). However, it has been evidenced that physiological and psychological health and well-being of people depend on outdoor physical and recreational activities such as walking, jogging, and cycling. As a salient component of urban systems, where spontaneous and unexpected social interactions take place, outdoor public spaces can promote an active lifestyle by accommodating urban residents' daily traffic and outdoor activities (Spagnolo and de Dear, 2003a), and at the same time, contribute to energy efficiency of surrounding buildings (Yang et al., 2014).

People in outdoor urban environments are often directly exposed to their immediate non-uniform microclimatic conditions with variations of sun and shade, and changes in wind speed. As an essential factor to quantify the perceived environment, thermal comfort may influence people's usage patterns of urban public space (Nikolopoulou et al., 2001; Nikolopoulou and Lykoudis, 2007; Aljawabra and Nikolopoulou, 2010; Rupp et al., 2015; Shooshtarian et al., 2020). It has long been recognized that comfortable outdoor conditions meeting the occupants' expectations can attract a greater number of people to spend more time in urban public spaces, thus facilitate people's environmental and social interactions and reduce anthropogenic energy consumption of air conditioning and lighting in buildings (Nikolopoulou and Lykoudis, 2007; Krüger et al., 2013; Lai et al., 2014; Li et al., 2016). Although the impact of everyday comfort conditions on daily life is less noticeable, the variation throughout an entire year may significantly influence residents' outdoor behavioral patterns. Ensuring provision of high-quality and comfortable outdoor environments contributes to promoting an active lifestyle by providing spaces for outdoor recreational, commercial, social, and cultural activities (Chen and Ng, 2012; Shooshtarian, Rajagopalan, and Sagoo, 2018; Weijs-Perrée et al., 2019). Therefore, it is important that urban planners and researchers understand human comfort in outdoor spaces.

The objective of creating comfortable outdoor environment has several dimensions, from mitigation of adverse microclimatic and environmental effects and reduction of urban energy consumption to the improvement of public health and well-being as the ultimate goal (Nicol and Roaf, 2017). Applicable outdoor comfort evaluation is of great importance to implement adaptation strategies to mitigate adverse effects of climate change and ameliorate the microclimate in urban public spaces with respect to meeting residents' everyday demands with thermally comfortable conditions, which can provide critical and valuable information for urban planners and policy makers (Nikolopoulou and Steemers, 2003; Blocken et al., 2012; Shooshtarian et al, 2018). Taking outdoor comfort into account in urban planning and design practice can lead to a more holistic view of sustainable urban development. Urban design and planning professionals, therefore, have been directed to take microclimatic information into consideration for ensuring the provision of comfortable outdoor environments. However, the reconciliation of comfort determinants within design and planning processes is lacking a full understanding of human comfort.

In the past, human thermal comfort in outdoor places was generally not an issue in urban design, which is regarded as a neglect and indicates the increased possibility of problematic effects of discomfort in urban life (Lenzholzer, 2012). New knowledge on comfort assessments in outdoor public spaces that can serve as a basis for urban spatial design has been lacking (Lenzholzer and Koh, 2010). Addressing outdoor comfort has now become a prevalent focus in urban planning and design. Urban planners have become increasingly aware of the biometeorological consequences of planning and design practice (Lenzholzer et al., 2020). As a decisive indicator, human comfort requires a more comprehensive, structural, and analytical investigation.

1.2 Problem statement

Against this background, over the last two decades, an ever-increasing research interest in assessing comfort in outdoor urban environments has brought about an expedient use of approaches based on rational thermal indices, developed specifically for steady-state and uniform indoor settings (Johansson et al., 2014; Coccolo et al., 2016). However, real-world public spaces within cities are often highly heterogenous with regard to alterations in land cover, vegetation, facilities, geometry, and size. Therefore, the application of rational thermal indices alone is challenged because the steady state is hardly ever reached (Höppe, 2002). According to the recent literature, many empirical investigations have been conducted to develop predictive modeling approaches for understanding individual assessment of outdoor thermal comfort in different regions (Potchter et al., 2018). The direct use of existing rational indices alone has been shown inapplicable for outdoor comfort assessment since the non-thermal conditions influences human adaptation (Nikolopoulou et al., 2001; Höppe, 2002; Nikolopoulou and Lykoudis, 2006). It remains a challenge how to quantitatively describe human comfort due to the large number of influences given by the variability in urban microclimate, especially wind and solar radiation (Blocken and Carmeliet, 2004; Hondula et al., 2017).

Previous studies on outdoor comfort modeling mainly focused on objective meteorological conditions, the mechanism of heat exchange between human body and the ambient environment, and human physiological thermoregulatory responses (Katić et al., 2016).The active role of human adaptation and the relating individuals' socio-demographic, behavioral and psychological factors have been largely ignored. The nature and strength of the relationships between comfort assessment and these potential influences cannot be fully captured by considering the objective meteorological variables related to thermal conditions alone. In addition, the manners of influences on subjective comfort and the reason for different assessment under the similar conditions, need to be addressed and examined using a different methodology.

The characteristics of the human body vary individually, which implies that the standardized methods relying on the heat balance model are insufficient in representing the full range of contextual and personal determinants of human outdoor comfort assessment (Coccolo et al., 2016). People with different socio-demographic characteristics are likely to experience the same environments differently (Saarloos et al., 2009). The thermal sensation predicted by rational thermal indices tends to be inconsistent with respondents' actual thermal sensations in urban public spaces, (Nikolopoulou et al., 2001; Nikolopoulou and Steemers, 2003; Thorsson et al., 2004; Knez and Thorsson, 2006; Pantavou et al., 2013). The general applicability of rational indices has been questioned in previous empirical investigations since it was very difficult to conclude that the thermal neutrality of human body under the assumption of steady state equals to achieving subjective thermal comfort in complex urban microclimates (Nikolopoulou et al., 2001; Lin, 2009). As a rational experience, thermal sensation is directed towards an objective world in terms of cold and warm, while thermal comfort is an emotional experience and relative to expectations (Hensen, 1990). The heat balance model might not adequately reflect individuals' actual comfort assessments of outdoor urban environments due to a lacking consideration of high variability of individuals' preferences pertaining to the microclimate and the atmospheric environment (Höppe, 2002; Spagnolo and de Dear, 2003b; Knez and Thorsson, 2006; Nikolopoulou and Lykoudis, 2006; Oliveira and Andrade, 2007; Lin, 2009).

1.3 Research objectives

Many municipal authorities recognize the importance of outdoor comfort and require pertinent studies before planning and granting decisions about the development of new urban areas. The motivation to improve the quality of urban public spaces and making them more comfortable has been driven by escalating needs of sustainable urban development and high quality of city life that are difficult to ignore. The Netherlands is a densely populated country, with most of population and economic activities concentrated in urban areas. Due to UHI being intensified recently, Dutch cities experience more days of thermal stress than the countryside (van Hove et al., 2015). In the second half of 2010, a research program called Climate Proof Cities (CPC) was launched in the Netherlands intending to strengthen the adaptive capacity of cities and to reduce the vulnerability of the urban system against climate change by developing strategies and policy instruments for adapting cities and buildings (Albers et al., 2015). At that time, the climate-responsive and adaptation strategies in urban planning and policy making were emerging topics in the Netherlands. To support decision makers, the CPC program has addressed numerous possible adaptation measures with respect to applicability in various urban situations. Furthermore, measurements, numerical simulations and street surveys have been conducted to gain insight into the effectiveness of individuals' adaptation measures and combinations of measures for different spatial scales (Albers et al., 2015).

Comfortable urban public spaces improve citizen's quality of life by accommodating encounters with fellow citizens, offering recreational opportunities and are of considerable social and commercial value (Spagnolo and de Dear, 2003a). The comfort that people experience when participating in activities in outdoor environments affects their use patterns and the acceptance of the places (Zacharias et al., 2001; Givoni et al., 2003; Thorsson et al., 2004; Eliasson et al., 2007; Walton et al., 2007; Tseliou et al., 2010; Gehl, 2011; Lenzholzer, 2012). Despite extensive theoretical and empirical studies on indoor thermal comfort over the last century and the serious challenges of climate change and urbanization, research on human comfort in outdoor urban spaces has received less attention over the last two decades, although a substantial increase in the number of publications can be observed in recent years. From the basic needs and requirements of the urban population to a wide range of policy objectives, the study on outdoor comfort can provide climate-responsive strategies and guidelines for urban planning and municipal policy practices to facilitate sustainable development and residents' well-being.

Two typical genres of theoretical models dominate comfort research, namely the heat-balance model (Fanger, 1970; Höppe, 1999; Jendritzky et al., 2001; Bröde et al., 2012) and the adaptive model (de Dear and Brager, 1998; Nicol and Humphreys, 2002), which provide a theoretical basis for in-depth studies. State-of-the-art outdoor comfort modeling defines the objective thermal conditions by rational indices and unravels contextualized human adaptation through surveyed subjective thermal sensations, considering human psychological factors pertaining to assessments and preferences of meteorological conditions (Auliciems, 1981; de Dear and Brager, 1998; Potchter et al., 2018; de Dear et al., 2020). The last decade has witnessed a rapid growth of the number of in-situ field studies carried out in different geographical regions with distinct climates for calibrating rational indices based on the heat balance model and developing new comfort models for applications in outdoor urban spaces by considering subjective thermal sensation caused by context-based human adaptations (Kumar and Sharma, 2020).

Yet, the dominant comprehensive conceptual framework considering contextual influences and the active role of individuals still remains weak. Previous empirical investigations have mainly calibrated and localized the heat balance indices based on the subjective comfort assessments stemming from local sample population. The systematic understanding on how individuals' socio-demographic, behavioral, and psychological differences influence subjective comfort assessments requires more quantitative analyses of the pertinent influential factors and the way they affect comfort assessment. This PhD study examines relationships between human comfort assessment and an expanded set of influential factors. In light of related theoretical models (Knez et al., 2009; Lenzholzer and de Vries, 2019; Shooshtarian, 2019), the main objective of this dissertation is developing a comprehensive understanding of subjective outdoor comfort through:

- Examining the nature and strength of potential nonlinear relationships between subjective comfort assessment and an expanded set of influential factors.
- Exploring the functional structure of exogenous and endogenous variables with direct and indirect effects on human comfort assessment in urban public spaces instead of the straightforward pathway of causal effects.
- Introducing and verifying heterogeneity in individuals' comfort assessments by allowing variations in individuals' preferences, expectations, and adaptations instead of generalizing outdoor assessments for the "average person" across all conditions.

1.4 Outline of the dissertation

This dissertation consists of eight chapters. The outline of the contents is depicted in Figure 1.1. The details of each chapter are as follows.

Having presented in this chapter a brief discussion of the background, motivation, problem statement, and research objectives of this doctoral research project, the next chapter provides a literature review, which summarizes the development of outdoor comfort assessment modeling. A general overview is given with respect to the concept of comfort, the difference between indoor and outdoor applications, the development of modeling methodology and field studies in different climate zones all over the world. The main gaps in this literature are identified, which constitute the starting point for this PhD study.

A comprehensive conceptual framework is proposed in Chapter 3 with a broader range of influential factors which includes both microclimatic and environmental variables and individuals' socio-demographic characteristics, behavioral patterns, and psychological factors.

Chapter 4 introduces the data collection, including study location selection, questionnaire design, fieldwork of in-situ measurement and questionnaire-based survey. In addition, the results of descriptive statistical analysis on the dataset are presented about respondents' socio-demographic characteristics and behavioral factors related to visiting of the study location.

Chapter 5 explores the relationships between human comfort and the expanded set of influential factors, including both meteorological and environmental variables, and human factors. The relationships between outdoor comfort assessment and influential variables are examined using linear and nonlinear regression models.

In Chapter 6, a path model is introduced to explore the direct and indirect effects of various factors on outdoor comfort assessment. Compared with the linear regression model, the path model provides more details of the patterns of how the exogenous and endogenous variables impact human comfort assessment

Chapter 7 studies heterogeneity between different groups of people in terms of comfort assessment. The latent classes are identified based on their path structure.

Finally, Chapter 8 concludes the thesis with a summary of the main findings and conclusions. The chapter also discusses the implications and limitations of this study. Further, directios for future studies are indicated in this chapter.

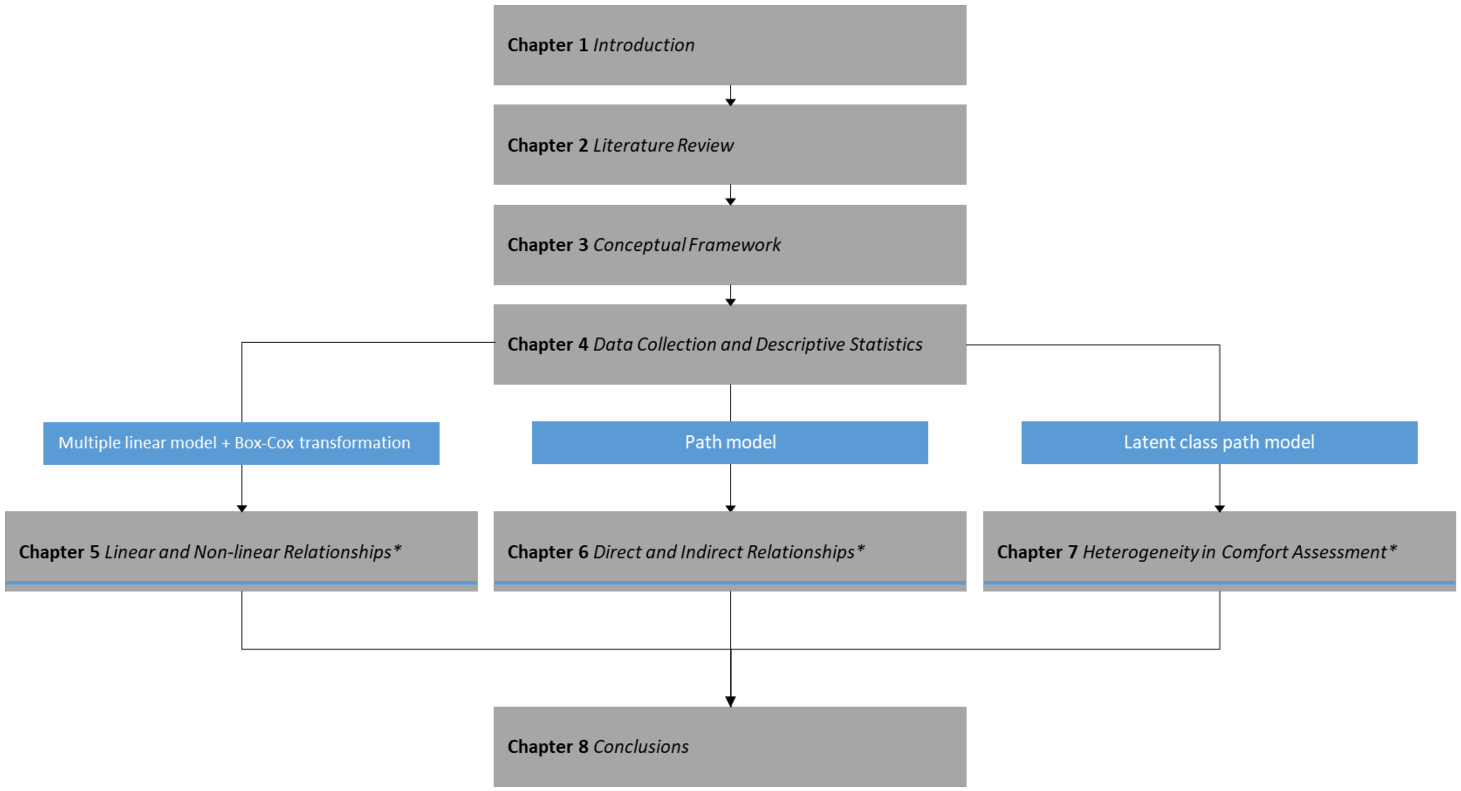

Chapter 1 *Introduction*
Chapter 2 *Literature Review*
Chapter 3 *Conceptual Framework*
Chapter 4 *Data Collection and Descriptive Statistics*
Multiple linear model + Box-Cox transformation
Path model
Latent class path model
Chapter 5 *Linear and Non-linear Relationships**
Chapter 6 *Direct and Indirect Relationships**
Chapter 7 *Heterogeneity in Comfort Assessment**
Chapter 8 *Conclusions*

Figure 1.1 Outline of the dissertation

2.

Literature Review

2.1 Introduction

As mentioned in the introduction, urban residents are vulnerable to the adverse effects in terms of thermal stress, extreme weather and environmental health risks when exposed to outdoor urban environments (Kovats and Hajat, 2008; Steeneveld et al., 2011). Given the rapid urbanization, on the other hand, the associated serious degradation of environmental quality and significant decrease in thermal comfort levels have a great influence on the number of visitors and activities in urban public spaces (Aljawabra and Nikolopoulou, 2010; Fong et al., 2019). Comfortable outdoor spaces become a valuable resource and are essential for urban livability and vitality (Mills et al., 2010; Chen and Ng, 2012).

Unlike indoor settings, outdoor urban spaces are dynamic and non-uniform, in which microclimatic and environmental conditions, especially wind speed, solar radiation, sound pressure level and air quality, vary substantially (Höppe, 2002). For many years, outdoor thermal comfort has been examined by various thermal indices focusing on aggregated thermal effects related to physical and physiological aspects (de Freitas and Grigorieva, 2015, 2017; Coccolo et al., 2016; Potchter et al., 2018). In parallel, significant differences between objective prediction by rational indices and subjective assessments obtained through questionnaire-based surveys on outdoor comfort were found in different regions around the world (Potchter et al., 2018). In fact, perceived comfort is more than neutral thermal sensation based on heat balance. It is a cognitive process involving many factors in terms of physical, physiological, psychological, and other processes (ASHRAE, 2017; Binarti et al., 2020). When simulating thermal sensation and assessing thermal comfort in urban outdoor environments, the predations using thermal indices alone become problematic (Nikolopoulou et al., 2001; Nikolopoulou and Steemers, 2003; Knez and Thorsson, 2006, 2008; Nikolopoulou and Lykoudis, 2006; Eliasson et al., 2007; Thorsson et al., 2007; Klemm et al., 2015; Lenzholzer and de Vries, 2019).

In recent years, searching for the most suitable approach to predict outdoor thermal comfort in a certain climate zone has become a research trend (Johansson et al., 2014; Pantavou et al., 2014; Coccolo et al., 2016; Potchter et al., 2018). Field investigations have been conducted to define the localized outdoor thermal comfort boundaries for improving the local applicability of the rational index and to elaborate the urban environments in reference to individuals' comfort assessment (Johansson et al., 2014;

Lam et al., 2018; Potchter et al., 2018; Shooshtarian et al., 2018; Baruti et al., 2019; Dunjić, 2019; Shooshtarian, 2019). Hence, it is generally admitted that defining human outdoor comfort need to take both microclimatic variables and context-based human factors into account (Becker et al., 2003; Givoni et al., 2003; Nikolopoulou and Lykoudis, 2006; Kántor et al., 2012).

During the last two decades, research on outdoor comfort modeling has significantly increased, which is mainly due to the response to the increasing urban environmental stress and heat load (Spagnolo and de Dear, 2003a; Johansson et al., 2014). Since the early 2000s, the concerns over climate change and environment matters have been widespread to outdoor thermal comfort. Research has been steadily increasing until 2010 when the number of outdoor comfort studies was exploding (Potchter et al., 2018). The field studies using rational indices coupled with surveys of subjective thermal sensation and comfort assessment have been extensively documented and reviewed with an aim to improve the feasibility of rational thermal indices in outdoor environments (Brager and de Dear, 1998; Chen and Ng, 2012; Rupp et al., 2015; Coccolo et al., 2016; Potchter et al., 2018; Dunjić, 2019; Elnabawi and Hamza, 2019; Binarti et al., 2020; Shooshtarian et al., 2020). Because neutral or preferred thermal sensation have a varying ranges, the effects of human adaptation have been conceived as depending on geographical and seasonal contexts and person-related factors, such as individuals' age, gender, health, socio-cultural backgrounds, experiences, and expectations (Andrade et al., 2011; Lin, et al., 2013; Pantavou et al., 2013; Potchter et al., 2018; Kumar and Sharma, 2020)

This chapter reviews the well-known thermal indices and a chronological series of empirical outdoor comfort research related to human factors (e.g., age, gender, body build, clothing, activity, perceptions, and preferences related to thermal condition) and in different regions with diverse climatic and cultural contexts. A substantive overview of the research articles pertaining to the development of methodologies in modeling outdoor comfort through field studies will be reviewed.

The reminder of this chapter first presents the development of different outdoor thermal comfort indices. Then, adaptive models are introduced, which is allocated to the key concepts of human thermal adaptation including three dimensions: physiological acclimatization, behavioral adjustment, and psychological adaptation. To provide the information on how to specify thermal comfort condition using two approaches, the heat balance model and adaptive model, comfort studies using a context-based adaptive approach are reviewed. This review reveals the applicability of existing approaches to assessing outdoor comfort and the challenges faced, which leads to the important role of human and contextual factors in the development of outdoor comfort modeling.

2.2 Outdoor thermal comfort indices

According to the classic or deterministic understanding, thermal comfort is driven exclusively by physics of the body's heat exchange with its immediate environment (de Dear et al., 2016). Up to now, more than 165 objective thermal indices have been developed to assess thermal conditions of the environment, to define human thermal comfort and to rank thermal stress (de Freitas and Grigorieva, 2015, 2017). Thermal indices have been primarily applied to evaluate thermal sensation and thermal comfort in various climatic regions (Singh et al., 2011). Thermal indices can be divided into (1) direct index – directly derived from environmental variables, (2) rational index – based on the human heat balance model considering meteorological variables along with metabolic rate and clothing insulation, and (3) empirical index – define human comfort in a specific microclimate, formulated as regressions (linear/ nonlinear) based on data observed from the field studies including onsite measurements on meteorological variables and questionnaire-based surveys on subjective assessment and human factors (Coccolo et al., 2016; de Freitas and Grigorieva, 2017; Dunjić, 2019; Binarti et al., 2020).

2.2.1 Direct index

The collective effects of meteorological variables, such as air temperature, humidity, wind speed and solar radiation, were used to define thermal comfort level in the form of direct indices with simplified formulae. Initially, the direct indices were applied for in industries and the military applications with extreme weather conditions that might negatively influence people's productivity, efficiency and even their survival (Epstein and Moran, 2006). Since then, the Wet Bulb Globe Temperature (WBGT) was proposed as an international standard (Yaglou and Minaed, 1957). The heat index (HI) was designed for warm environment and wind chill index (WCI) was designed for cold environment (Steadman, 1979a). Several direct indices have been introduced to calculate thermal comfort level in various climatic conditions (Coccolo et al., 2016; Sen and Nag, 2019).

2.2.1.1 Wet Bulb Globe Temperature

WBGT is a type of apparent temperature applied to estimate the effect of thermal stress in direct sunlight, which takes air temperature, humidity, wind speed and visible and infrared radiation. WBGT was used to define appropriate exposure levels to high temperatures in different applications, such as sporting events and the military. WBGT for the outdoor environment is defined as (ISO 7243, 1989; Budd, 2008):

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_a \tag{2.1}$$

where T_g is globe temperature, T_a is dry-bulb air temperature, while T_w is the natural wet-bulb temperature.

2.2.1.2 Heat Index

HI combines the effects of air temperature and relative humidity (Steadman, 1979b) and is derived from a multiple regression model (Błażejczyk et al., 2012) expressed as:

$$\begin{aligned} HI = {} & -0.8784695 + 1.61139411 \cdot T + 2.338549 \cdot RH - 0.14611605 \cdot T \cdot R \\ & -0.012308094 \cdot T^2 - 0.016424828 \cdot RH^2 + 0.02211732 \cdot T^2 \cdot R \\ & +0.00072546 \cdot T \cdot RH^2 - 0.000003582 \cdot T^2 \cdot RH^2 \end{aligned} \tag{2.2}$$

where T is the air temperature (℃) and RH is the relative humidity (%). The neutal sensation is defined as HI > 27℃.

2.2.1.3 Wind Chill Index

WCI measures how cold people feel when staying in outdoor environments. WCI is based on the rate of heat loss from exposed skin caused by wind and cold. Wind draws heat from the human body, which drives down skin temperature and eventually the internal body temperature. Thus, a new WCI, namely Wind Chill Temperature (WCT) (OFCM, 2003), was developed, which improves the previous WCI with progresses in knowledge of heat exchange. WCT is defined with a thermal scale from “comfortable” (>0℃) to “extreme cold risk” (<55℃) and expressed as:

$$WCT = 13.12 + 0.6215T - 11.37v_{10}^{0.16} + 0.3965Tv_{10}^{0.16} \tag{2.3}$$

where T is the air temperature (℃) and v_{10} is the wind speed at 10m of height (km/h).

2.2.2 Rational index

In recent decades, a number of thermal indices based on energy transfer mechanisms and the heat balance between human body and environment have been developed to assess thermal comfort in outdoor spaces. Fanger (1970) initially proposed a model for computing the heat gain and loss of human body in a steady state and uniform thermal condition. Since then, the principles of thermodynamics of the Pierce two-node model were introduced for predicting thermal comfort condition (Gagge, 1936; Gagge et al., 1986). For two-node model, it simplifies the human body into a two-layer structure with skin and core, which is represented by a concentric cylinder. Later, an increasing number of segments of human thermoregulatory model was developed which determine the prediction accuracy, since the anatomical structure of human body significantly influence the heat exchange between the body and the ambience (Katić et al., 2016). The multiple segment model abstracts the human body into multiple segments, and each segment is divided into skin, fat, muscle, bone, and other layers. Each layer in each segment is regarded as a heat transfer node with thermal physiological parameters and is controlled by energy and mass conservation equations.

With the progress in knowledge on the physics regarding mechanism of energy exchange between human body (represented by physiological thermoregulatory system of manikin model) and immediate ambient environment as well as the understanding of personal factors in terms of clothing level and metabolic rate (Katić et al., 2016), most of heat balance-based thermal indices were developed under steady state conditions or equivalent temperatures transferred from indoor to outdoor with the equilibrium of the thermo-regulation system (Błażejczyk et al., 2012). Multiple segment models have been developed to tackle the challenge when outdoor thermal comfort assessment requires the simulation of asymmetric boundary thermal conditions and transient environments. The apparent limitation of direct indices was improved by the heat balance model that have been developed to describe the relationship between thermal environment, personal factors, and human thermal sensation. However, the original heat balance model is only applicable in the steady-state environments, while the modified rational thermal indices based on heat balance models are feasible in the nonuniform and transient environments (Katić et al., 2016).

Since the last two decades, various indices grounded on the heat balance theory have been used for linking human thermal comfort assessment to meteorological variables in outdoor environment (de Freitas and Grigorieva, 2015, 2017; Binarti et al., 2020).

According to an examination of thermal indices (de Freitas and Grigorieva, 2017; Potchter et al., 2018), Predicted Mean Vote (PMV) (Fanger, 1970), Physiological Equivalent Temperature (PET) (Höppe, 1999), Standard Effective Temperature (SET*) (Gagge et al., 1986) and the version for outdoor application (OUT_SET*) (Pickup and de Dear, 2000), and Universal Thermal Climate Index (UTCI) (Jendritzky et al., 2001) account for most of applications in previous investigations on outdoor thermal comfort. Specifically, among others, PET, UTCI, OUT_SET* are designed for outdoor applications.

2.2.2.1 Predicted Mean Vote

PMV is a well-known thermal index which is based on one-node human thermoregulatory model and defined by six variables, such as air temperature, relative humidity, radiation, wind velocity, metabolic rate and clothing insulation (Fanger, 1970; Potchter et al., 2018). PMV is represented by the average value of people's thermal sensation vote with 7-point scale (-3 = very cold to +3 = very hot). In addition, the Predicted Percentage of Dissatisfied (PPD) was presented to describe the ratio of the unsatisfied sample with the studied thermal conditions. The detailed interpretation of PMV is given in ISO 7730 (ISO 7730, 2005). The neutral thermal sensation can be archived when the heat produced by metabolism equals the heat exchanged to the environment through skin and respiration.

PMV was derived statistically from thermal sensation votes of subjects in a climate chamber with steady-state thermal condition. Hence, PMV-PPD was initially applied for assessing indoor thermal comfort. PMV is limited to give a realistic prediction on thermal condition of human body since the mean skin temperature and sweat rate are dependent on human activity alone, not on climatic conditions (Gagge et al., 1986). Later on, "Klima-Michel-Modell" (KMM) was introduced in PMV for outdoor applications by using easily obtainable meteorological data as inputs and adding the variables regarding short and long wave radiations (Jendritzky and Nübler, 1981). KMM stems from the thermo-physiological assessment conducted for a 35 years old male with 1.75m height and 75kg weight, assuming 172.5W work load corresponds to walking at 4km/h (Kim et al., 2009). A calculation program of PMV-PPD is described in ISO7730 (ISO 7730, 2005).

2.2.2.2 New Standard Effective Temperature

As an improvement of the Effective Temperature (ET*), SET* was proposed based on two-node model, covering heat exchange through radiation, convection and evaporation, and considering clothing insulation and metabolic rate (Gagge et al., 1986). SET* is defined as the equivalent temperature of an isothermal environment, in which relative humidity is 50%, wind speed is lower than 1.5m/s, and air temperature equals to mean radiant temperature. In this isothermal environment, the human body with standard clothing based on the metabolic activity would have the same heat stress and thermo-regulatory strain as in the actual environment. For outdoor applications, SET* has been extended to OUT_SET*, which adds the mean radiant temperature as an important influential variable.

2.2.2.3 Physiological Equivalent Temperature

PET is a widely and frequently used thermal index specially for outdoor applications (Johansson et al., 2014; Coccolo et al., 2016). Based on the Munich Energy-Balance Model for Individuals (MEMI), PET is defined as the air temperature at which the heat balance of the human body is maintained with core and skin temperature equal to those under the conditions being assessed (Höppe, 1999). The equation based on heat balance theory is expressed as:

$$M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \tag{2.4}$$

where M is the metabolic rate, W is the physical work output, R is the net radiation of the human body, C is the convective heat flow, E_D is the latent heat flow to evaporate water into water vapor diffusing through the skin, E_{Re} is the sum of heat flow for heating and humidifying the inspired air, E_{Sw} is the heat flow due to evaporation of sweat and S is the storage heat flow for heating and cooling the body mass. The unit of all heat flows is the *watt*. The individual terms have positive signs in this equation if they result in heat gain for the human body, or they have negative signs in the case of heat loss (Höppe, 1999). From the literature, the neutral PET of individuals varies in different climatic and cultural contexts (Lin and Matzarakis, 2008; Lin et al., 2010; Cohen et al., 2013). In addition, the modified PET (mPET) has been developed based on a multi-segment human thermoregulatory model and a multi-layer clothing model, which improves original PET to react to the variation of relative humidity and clothing insulation (Chen and Matzarakis, 2014).

2.2.2.4 Universal Thermal Climate Index

The newly developed UTCI appeared in 1999 and since then its use has constantly increased (Coccolo et al., 2016). Defined as the air temperature of reference environment given the combination of meteorological variables (air temperature equals to mean radiant temperature, wind velocity equals 0.5m/s at the height of 10m, relative humidity equals 50% but up to vapor pressure of 20hPa, and metabolic rate equals 135 W/m^2), UTCI aims at reflecting the human physiological response to the multi-dimensionally defined actual outdoor thermal environment with a one-dimensional quantity. The 10-point scale denotes the thermal sensation from -40˚C (extreme cold stress) to +46˚C (extreme hot stress) and the neutral sensation falls in the range between 9˚C and 26˚C (Bröde et al., 2012).

UTCI is based on the multi-node dynamic thermo-physiological UTCI-Fiala model (Fiala et al., 2012) which is regarded as the most advanced thermoregulatory model with both passive and active systems. The passive thermo-physiological system of human body is comprised of 15 cylindrical body elements in 3 categories in terms of anterior, posterior, and inferior. Each element consists of 7 different concentric tissue material layers including brain, lung, bone, muscle, viscera, fat, and skin. Furthermore, the skin is divided into inner and outer layers. The passive thermo-physiological system of UTCI-Fiala model embraces the bio-heat transfer, metabolic heat generation, and blood circulation. The heat exchange between human body and environment in the manner of convection, evaporation, radiation, and respiration. The thermoregulatory responses of the central nervous system, such as vasoconstriction and dilation of the cutaneous blood flow, shivering and sweating. The calculation equation of UTCI (Bröde et al., 2012) is expressed as:

$$UTCI(T_a, T_{mrt}, v, pa) = T_a + Offset(T_a, T_{mrt}, v, pa) \tag{2.5}$$

where T_a denotes the air temperature (℃), T_{mrt} denotes the mean radiant temperature (℃), v is the wind speed (m/s), pa is the water vapor pressure (hPa) and $Offset$ denotes the deviation from air temperature.

Clothing insulation is determined as a function of the air temperature and wind speed in real-world conditions using an adaptive clothing model (Fiala et al., 2012). UTCI is applicable in all climates with the acclimatizing clothing model (Błażejczyk et al., 2012).

2.2.3 Empirical indices

Based on psychological thermal comfort definition given by ASHRAE (ASHRAE, 2017), empirical indices have been developed for assessing the human comfort in a certain microclimate which expresses thermal comfort condition based on the formula of explanatory variables derived from onsite monitoring and surveys (Coccolo et al., 2016). The procedures are specifically applied for the selected locations, where the empirical indices are defined and validated. The famous empirical indices are Actual Sensation Vote (ASV) (Nikolopoulou et al., 2001), Thermal Sensation Vote (TSV) (Givoni et al., 2006; Lai et al., 2014).

2.2.3.1 Actual Sensation Vote

ASV was firstly employed in European project "RUROS", which is expressed as a linear equation based on onsite measurements of meteorological variables (air temperature, global radiation, wind speed and relative humidity, which represent the microclimate) and questionnaires of subjective comfort assessment in seven different European cities (Nikolopoulou et al., 2001; Nikolopoulou and Lykoudis, 2006). The ASV equation (Nikolopoulou, 2004) is expressed as:

$$ASV = a \cdot T_a + b \cdot S + c \cdot V + d \cdot RH + \varepsilon \tag{2.6}$$

where T_a is the dry bulb air temperature (℃), S is the global solar radiation (W/m^2), V is the wind speed (m/s), and RH is the relative humidity (%). a, b, c and d are the coefficients, and ε denotes the error term, which are different corresponding to different climatic zones.

2.2.3.2 Thermal Sensation Vote

TSV is an empirical index generated by multiple regression with explanatory variables derived from onsite measurements and questionnaire-based surveys. The explanatory variables include air temperature, wind speed, relative humidity, horizontal solar irradiation, and ground temperature. The collective impacts of these meteorological variables are formulated with a linear equation and the sensation scale is different for each study location (Givoni et al., 2006; Hwang and Lin, 2007; Krüger and Rossi, 2011; Lai et al., 2014; Villadiego and Velay-Dabat, 2014; Ye et al., 2015; Amindeldar et al., 2017;

Hou et al., 2017; Krüger et al., 2017; Krüger et al., 2017). The formula of TSV is written as:

$$TSV = a \cdot T_a + b \cdot R + c \cdot V + d \cdot H + \varepsilon \qquad (2.7)$$

where T_a is the dry bulb air temperature (℃), R is the global radiation (W/m^2) or the solar radiation (W/m^2), V is the wind speed (m/s), and H is the absolute humidity (g/kg air) or relative humidity (%). a, b, c and d are the coefficients, and ε denotes the error term.

2.3 Adaptive model

As an alternative to the rational thermal indices-based comfort modeling, an adaptive comfort model has been proposed to overcome the limitation of static heat balance models. Adaptive model accommodates the role of human adaptation in indoor thermal comfort assessment and posits the comfort within a framework of contextualized perceptual relativism (Nicol and Humphreys, 1973; de Dear and Brager, 1998; de Dear et al., 2020). Similarly, in outdoor environment which is radically unlike the steady state of the controlled indoor setting, the approach using thermal index alone is inadequate to assess thermal comfort since it fails to account for the human adaptation (Lin, 2009; Chen and Ng, 2012). Beyond physical and physiological dimensions, some non-thermal factors were addressed to interact with comfort assessment including regional contexts and individuals' socio-demographics and cognition (de Dear and Brager, 1998). It is widely acknowledged that people expected warmer condition in the summer season (or hot climate zones), or cooler condition in winter (or cold climate zones) (de Dear and Brager, 1998; Nicol and Humphreys, 2002; Lin, 2009).

However, the adaptive models for indoor setting are too simple to apply in outdoor conditions. Recent studies on outdoor comfort have been driven by the failure of "one size fits all" approaches based on rational indices and inspired by adaptive models. Hence, it is more applicable and efficient to define human comfort and discomfort based on unified standards and indices while taking local thermal adaptation into account (Nikolopoulou and Lykoudis, 2006; Lin, 2009; Kántor et al., 2012). Due to a wide range of urban microclimates in urban outdoor spaces, the subjective response to thermal condition in outdoor environment may involve more extensive determinants, which is obviously different from the response to indoor thermal condition (Höppe, 2002; Reiter and De Herde, 2003). Nevertheless, the adaptive approach has been employed in the non-steady state of outdoor environments, with combined objective thermal factors and non-thermal factors pertaining to human behavioral adjustment, and physiological and psychological adaptations. More realistic modeling of human comfort in outdoor environment related to a certain context and the corresponding human expectations and behaviors has been proposed (Oliveira and Andrade, 2007; Lin, 2009; Johansson et al., 2018; Heng and Chow, 2019). The adaptive approach was applied to explain the varying range of neutral or comfortable temperature between cities with similar weather conditions, as well as different locations in the same city.

Human adaptation is the key concept in adaptive approaches and plays an important role in outdoor comfort assessment (Brager and de Dear, 1998). To meet reconciliation between the environment and comfort requirements, three assumptions in which people adapt themselves to the environment are commonly made, involving (1) physiological adaptation, (2) behavioral adjustment, and (3) psychological adaptation (Höppe, 2002; Nikolopoulou and Lykoudis, 2006). The role of physiological adaptation to the thermal effects has shown a gradual decreasing response resulted from a repeated exposure to the environmental and meteorological stimuli (Nikolopoulou and Steemers, 2003; Reiter and De Herde, 2003). Behavioral adjustment implies an active role of individual people in managing the comfort level by physical actions. Psychological adaptation refers to an altered perception of sensory information due to experiences and expectations.

2.3.1 Physiological acclimatization

Physiological acclimatization includes all changes of physiological responses stimulated by exposure to meteorological factors related to thermal conditions, which causes a gradual diminution in the strain induced by such exposure (Brager and de Dear, 1998). The physiological response of the human body to a periodical exposure in a certain thermal condition, within a couple of days, would change for tolerance with the given stimuli. The physiological acclimatization is based on two principles: genetic adaptation and acclimatization. The genetic adaptation is related to the genetic adaptability to the prevailing climate rather than acquired adaptation. Acclimatization is defined as the changes in the settings of the physiological thermoregulation system over a period of days or weeks in response to single or a combination of thermal stimuli.

2.3.2 Behavioral adjustment

Behavioral adjustment is related to all modifications that people undertake consciously or unconsciously to avoid discomfort thermal condition by modifying heat and mass fluxes influencing thermal balance between the body and ambient environment. Brager and de Dear (1998) defined behavioral adjustment in terms of three categories, including (1) personal adjustment: adjusting to the surroundings by changing personal variables, such as clothing, activity, posture, eating food, drinking hot or cold beverages, and moving to a different location, (2) environmental adjustment: modifying the environments, when control is available, such as opening or closing windows, staying in shades, etc., and (3) cultural adjustment, including scheduling activities, adapting dress codes, etc. Behavioral adjustment potentially offers an opportunity for people to play an active role in maintaining their own comfort.

2.3.3 Psychological adaptation

Psychological adaptation encompasses the effects of cognitive and cultural variables and describes the extent to which habituation and expectation change one's perception of and reaction to sensory information (Brager and de Dear, 1998). The repeated or chronic exposure to an environmental stressor leads to a diminution of the triggered intensity of sensation. It was pointed out that people's reaction to a thermal condition which is less than perfect will depend very much on their expectation, personality and what else they are doing at that time (McIntyre, 1981). The psychological adaptation was acknowledged to largely account for the discrepancy between surveyed and predicted thermal sensation (Nikolopoulou et al., 2001; Nikolopoulou and Steemers, 2003; Lenzholzer and Koh, 2010).

2.4 Context-based adaptive approach

From the view of adaptive theory, people living in different climates and cultures would have different long-term thermal backgrounds and environmental attitudes, which may influence their psychological evaluation of comfort in urban spaces despite similar thermal conditions (Knez and Thorsson, 2006; Lenzholzer and de Vries, 2019). No real fixed universal boundaries of comfortable microclimate exist since the range of comfortable condition shifts depending on the geographical and seasonal contexts (Lin and Matzarakis, 2008; Cohen et al., 2013). In hot climate, a comfort range may tend to be on a warmer side, while in cold climate it approaches to the cooler side than in the hot climate. The similar tendency is also found that the comfortable setting during winter lies a little cooler than in the summer. Various lifestyles, behaviors, socio-economic states, cultural backgrounds, thermal experiences, thermal tolerances, and adaptation may result in diverse comfort assessments (Li and Liu, 2020).

The criticism on existing approaches based on rational indices alone, therefore, was addressed which led to the research interest in the calibration of thermal comfort scale of different rational indices based on subjective thermal perceptions and preferences to fulfill the different requirements for various climatic and cultural contexts by taking human adaptation into account (Lin et al., 2015; Lucchese and Andreasi, 2017). The range of thermal comfort for different rational indices were examined through comparison between the predictions by rational indices and the subjective thermal comfort assessments (e.g., Thermal Sensation Votes and Actual Comfort Votes) derived from questionnaire-based surveys.

The outdoor comfort studies should be reviewed for various climate zones since researchers have been dedicated to defining the local boundaries of neutral thermal sensation or thermal comfort scale for different thermal indices. The fieldwork of most cases may take place within several days, months or different seasons, which are accompanied by physical measurements and questionnaire-based surveys (Johansson et al., 2014). The procedures can be elaborated as (1) Real-time meteorological data are measured and input to thermal indices calculations; (2) The questionnaire data are collected to determine the subjective thermal sensation, thermal comfort, and preference on overall thermal conditions and single meteorological variables. In some cases, more detailed information of respondents is required such as socio-demographics, body build, moods, activity, purpose, time of stay, etc.; (3) Regression analysis is applied to reveal the relationship between objective thermal indices and subjective comfort evaluations in different study areas. Based on the influence of human adaptation, the local neutral or preferred range of thermal indices are calibrated. As shown in Table 2.1, up to 151 field studies on outdoor thermal comfort have been carried out in different climatic zones from 2001 to 2019, according to Köppen-Geiger climate classification. Research interest continues to grow with a considerable boost in the number of recent publications (Potchter et al., 2018). Almost all field investigations employed questionnaire-based surveys in combination with simultaneous onsite measurements.

From the literature, the psychological adaptation is regarded as significantly influencing human outdoor thermal comfort, in addition to the microclimatic variables. The human factors related to socio-demographic characteristics, clothing insulation, activity, purpose, duration of stay, thermal history and experiences, preferences and expectations on overall thermal conditions and single meteorological and environmental variables were proposed to offset the regional deviations (Lin, 2009).

2.5 Conclusions

This chapter summarized the literature on the development of existing mainstream outdoor comfort modeling methodologies and presented the state-of-the-art knowledge to bridge the gap between the objective thermal indices and subjective comfort evaluations based on an understanding of the active role of human adaptation and climatic and cultural contexts in a real-world situation. As presented, the direct indices based on the combined effect of meteorological variables were initially adopted as simplified approaches for assessing and predicting outdoor comfort and discomfort. Since then, with the progress in knowledge of human body's thermoregulation and mechanism of heat transfer and advancement of computation capability, rational indices dominate research on outdoor thermal comfort and related practices.

Since the heat balance-based thermal indices lack human specific inputs and contextual information, as well as designated thresholds for accurate prediction of human comfort assessment in outdoor complex environments, emphasis is placed on the differential contextual conditions and human adaptations, and the resulting impacts on outdoor comfort assessment. In recent years, more and more research attention and production have been focusing on the active role of human acclimatization and adaptation, which accounts for the varying outdoor comfort assessment in different geographical and seasonal contexts. Field studies have been carried out which is generally comprised of on-site field measurements to retrieve the meteorological variables and the surveys on subjective comfort votes.

The review of the mainstream of existing field studies on outdoor comfort indicates that an important future research avenue is the survey-based field investigation to link human physiology, psychology, and behavior to comfort assessment. Studies have evidenced that individuals' outdoor comfort assessments are strongly related to their past experiences and current behaviors. Nevertheless, the commonly used approaches for outdoor comfort assessment, e.g., the heat balance-based thermal index, the empirical adaptive approach, or the combination of both, have failed to provide realistic and context-specific dataset for analysis and modeling. A significant knowledge gap in the field of outdoor comfort assessment still exists. Few studies considered the environmental stimuli, such as noise, glare of sunlight and air quality in outdoor spaces. Although the subjective assessment is able to define human comfort beyond a “universal” neutral thermal sensation, which involves the human thermal preference and adaptation based on the regional climate and culture, and the human sensitivity to different meteorological and environmental conditions. People’s thermal experiences, expectations and perceptions have not been used as inputs in the measurement of outdoor comfort. From the adaptive theory point of view, the consideration of a complete interaction between human and environment through taking subjective sensation of abovementioned environmental stimuli into account in the quantification of overall outdoor comfort would potentially improve the reliability of modeling.

Although a few relevant studies can be found in the literature, the underlying variation in the mechanism of comfort assessment among surveyed population is not systematically understood and worth exploring (Krüger and Drach, 2017). Attempts to understand individual differences in comfort assessment require further elaborating the specific effects of human factors, such as socio-demographic characteristics, emotions, body build, activity, transport modes, purpose of using outdoor spaces, duration in outdoor spaces, etc. Accordingly, the following chapters in this dissertation are designed to expand our knowledge horizons on the comprehensive outdoor comfort modeling, offering insights on the perspectives of human socio-demographic backgrounds, behavior, and psychology.

Nomenclature

ASV	Actual Sensation Vote	HSV	Humidity sensation Vote
AT	Apparent Temperature	HTL	Human Thermal Load
ATSV	Actual Thermal Sensation Vote	ITS	Index of Thermal Stress
BMI	Body Mass Index	IZA	Thermal comfort Index for cities of Arid Zones
Clo	Clothing insulation	MBCMS	Bioclimatic Model for Subtropical Medium-Sized Cities
CV	Comfort Vote	Met	Metabolic rate
DI / ID	Thom’s Discomfort Index	MOCI	Mediterranean Outdoor Comfort Index
DTS	Dynamic Thermal Sensation	OBD	Olgyay’s Bioclimatic Diagram
EI	Empirical Index	OCV	Overall Comfort Vote
ET*	Effective Temperature	OUT_SET*	Outdoor Standard Effective Temperature
ETU	Universal Effective Temperature	PE	Vinje’s Comfort Index
GOCI	Global Outdoor Comfort Index	PET	Physiological Equivalent Temperature
HPV	Humidity Preference Vote	PMT	Perceived maximum temperature

Nomenclature

PMV	Predicted Mean Vote	TOCI	Turkish Outdoor Comfort Index
PT	Perceived Temperature	T_{op}	Operative Temperature
PTC	Perceived Thermal Comfort	TPV	Thermal Preference Vote
PTV	Percentage of Thermal Acceptability	TP	Thermal Perception
S(COMFA)	COMFA model’s energy balance	TS / TSI	Thermal Sensation Index
SET*	Standard Effective Temperature	TSV	Thermal Sensation Vote
SSV	Sun Sensation Vote	UCBTSV	Calculated thermal sensation vote by UCB model
STI	Subjective Temperature Index	UTCI	Universal Thermal Climate Index
TAV	Thermal Acceptability Vote	WBGT	Wet Bulb Globe Temperature
TCV	Thermal Comfort Vote	WPV	Wind Preference Vote
T_e	Equivalent Temperature	WSV	Wind Sensation Vote
THI	Temperature-Humidity Index	Y_{DS}	Sense of Thermal Comfort
TI	Terjung’s index		

Table 2.1 List of peer-reviewed field studies (based on Potchter et al., 2018)

No.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
1	Nikolopoulou et al., 2001	Cambridge, UK	Temperate oceanic (Cfb)	1431	PMV, ASV	Clo, Psychological adaptation
2	Ahmed, 2003	Dhaka, Bangladesh	Tropical wet savanna (Aw) Tropical dry savanna (As)	1500	CV	Met
3	Becker et al., 2003	Yotvata, Israel	Hot deserts (BWh)	36	PMV	N/A
4	Givoni et al., 2003	Tokyo, Japan Tel Aviv, Israel Mash'abei-Sadeh, Iseael	Humid subtropical (Cfa) Hot-summer Mediterranean (Csa) Hot deserts (BWh)	72 220 85	TSV	N/A N/A N/A
5	Spagnolo and de Dear, 2003	Sydney, Australia	Humid subtropical (Cfa)	1018	T_{op}, ET*, PET, PT, OUT_SET*	Clo, Gd
6	Gómez et al., 2004	Valencia, Spain	Hot-summer Mediterranean (Csa)	1500	ID, PE, WBGT, TI, OBD	N/A
7	Stathopoulos et al., 2004	Montreal, Canada	Humid continental (Dfb)	466	T_e	N/A
8	Thorsson et al., 2004	Göteborg, Sweden	Temperate oceanic (Cfb)	285	PMV	N/A
9	Knez and Thorsson, 2006	Tokyo, Japan Göteborg, Sweden	Humid subtropical (Cfa) Temperate oceanic (Cfb)	63 43	PET	N/A
10	Nikolopoulou and Lykoudis, 2006	Kassel, Germany Athens, Greece Thessaloniki, Greece Milan, Italy Fribourg, Swiss Cambridge, UK Sheffield, UK	Temperate oceanic (Cfb) Humid subtropical (Cfa) Hot-summer Mediterranean (Csa)	824 1503 1813 1173 1920 948 1008	ASV	Clo
11	Eliasson et al., 2007	Göteborg, Sweden	Temperate oceanic (Cfb)	1379	PET	N/A

Table 2.1 Continued

No.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
12	Hwang and Lin, 2007	Taichung, Taiwan Yunlin, Taiwan Chiayi, Taiwan	Monsson humid subtropical (Cwa)	3027	SET*, TSV, SSV, WSV	N/A
13	Oliveira and Andrade, 2007	Lisbon, Portugal	Hot-summer Mediterranean (Csa)	91	PET	Clo
14	Kántor et al., 2007	Szeged, Hungary	Temperate oceanic (Cfb)	844	PMV	N/A
15	Thorsson et al., 2007	Tokyo, Japan	Humid subtropical (Cfa)	1142	PET	N/A
16	Lin and Matzarakis, 2008	Sun Moon Lake, Taiwan	Monsson humid subtropical (Cwa)	1644	PET	N/A
17	Metje et al., 2008	Birmingham, UK	Temperate oceanic (Cfb)	451	PMV	N/A
18	Lin, 2009	Taichung, Taiwan	Monsson humid subtropical (Cwa)	505	PET	Clo
19	Aljawabra and Nikolopoulou, 2010	Marakech, Morocco Phoenix, USA	Hot semi-arid (BSh) Hot deserts (BWh)	303 126	PMV	N/A
20	Hwang et al., 2010	Taichung, Taiwan	Monsson humid subtropical (Cwa)	3837	T_{op}	Clo
21	Tseliou et al., 2010	Kassel, Germany Athens, Greece Thessaloniki, Greece Milan, Italy Fribourg, Swiss Cambridge, UK Sheffield, UK	Temperate oceanic (Cfb) Humid subtropical (Cfa) Hot-summer Mediterranean (Csa)	824 1503 1813 1173 1920 948 1008	PET, THI, WCI	N/A
22	Andrade et al., 2011	Lisbon, Portugal	Hot-summer Mediterranean (Csa)	91	PMV, SET*, PET, TPV, WPV	Age, Gd, Preference
23	Krüger and Rossi, 2011	Curitiba, Brazil	Temperate oceanic (Cfb)	1654	TSV	Age, Gd

Table 2.1 Continued

No.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
24	Lin et al., 2011	Taichung, Taiwan Yunlin, Taiwan Chiayi, Taiwan	Monsson humid subtropical (Cwa)	1644	SET*	Clo
25	Mahmoud, 2011	Cairo, Egypt	Hot deserts (BWh)	300	PET	N/A
26	Shimazaki et al., 2011	Osaka, Japan	Humid subtropical (Cfa)	57	PMV, SET*, HTL	N/A
27	Bröde et al., 2012	Curitiba, Brazil	Temperate oceanic (Cfb)	1654	UTCI	Clo
28	Cheng et al., 2012	Hong Kong	Monsson humid subtropical (Cwa)	286	PMV, PET	N/A
29	Kántor et al., 2012	Szeged, Hungary	Temperate oceanic (Cfb)	967	PET	N/A
30	Makaremi et al., 2012	Putrajaya, Malaysia	Tropical rainforest (Af)	200	PET	N/A
31	Nasir et al., 2012	Shah Alam Lake Garden, Malaysia	Tropical rainforest (Af)	292	PET, AT	N/A
32	Ng et al., 2012	Hong Kong	Monsson humid subtropical (Cwa)	2702	PET	N/A
33	Schnell et al., 2012	Tel Aviv, Israel	Hot-summer Mediterranean (Csa)	1457	PET	N/A
34	Xi et al., 2012	Guangzhou, China	Humid subtropical (Cfa)	114	SET*	N/A
35	Yin et al., 2012	Nanjing, China	Humid subtropical (Cfa)	205	PMT	Gd
36	Yahia and Johansson, 2013	Damascus, Syria	Cold semi-arid (BSk)	920	PMV, PET, ET*, OUT_SET*	Clo
37	Cohen et al., 2013	Tel Aviv, Israel	Hot-summer Mediterranean (Csa)	1731	PET	N/A
38	Krüger et al., 2013	Glasgow, UK	Temperate oceanic (Cfb)	567	PET	N/A

Table 2.1 Continued

No.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
39	Lin et al., 2013	Taichung, Taiwan	Monsson humid subtropical (Cwa)	759	WBGT	Clo, Met
40	Lindner-cendrowska, 2013	Warsaw, Poland	Warm-summer humid continental (Dfb)	553	UTCI, PET	Clo
41	Pantavou et al., 2013	Athens, Greece	Hot-summer Mediterranean (Csa)	1706	UTCI, TSV	Clo
42	Yang et al., 2013	Singapore	Tropical rainforest (Af)	2036	T_{op}	N/A
43	Yang et al., 2013	Singapore Changsha, China	Tropical rainforest (Af) Humid subtropical (Cfa)	2020 2052	PET	N/A
44	Zhou et al., 2013	Wuhan, China	Humid subtropical (Cfa)	386	SET*	N/A
45	Lai et al., 2014	Tianjin, China	Cold semi-arid (BSk)	1565	PMV, PET, UTCI	Age, Clo, Met
46	Lai et al., 2014	Wuhan, China	Humid subtropical (Cfa)	490	TSV	N/A
47	Pantavou et al., 2014	Athens, Greece	Hot-summer Mediterranean (Csa)	1706	UTCI, ASV, STI	N/A
48	Pearlmutter et al., 2014	Sede-Boqer, Israel	Hot deserts (BWh)	319	ITS, PET	N/A
49	Sangkertadi and Syafriny, 2014	Manado, Indonesia	Tropical rainforest (Af)	300	PMV, Y	N/A
50	Tsitoura et al., 2014	Crete, Greece	Hot-summer Mediterranean (Csa)	200	PMV, PET, WBGT, OUT_SET*, Comfort state	N/A
51	Tung et al., 2014	Taichung, Taiwan Yunlin, Taiwan Chiayi, Taiwan	Monsson humid subtropical (Cwa)	1644	PET	Gd
52	Villadiego and Velay-Dabat, 2014	Barranquilla, Colombia	Tropical wet savanna (Aw)	781	TSV	N/A

Table 2.1 Continued

No.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
53	Watanabe et al., 2014	Nagoya, Japan	Humid subtropical (Cfa)	42	ETU, UTCI, OUT_SET*	N/A
54	Chen et al., 2015	Shanghai, China	Humid subtropical (Cfa)	596	PET	N/A
55	da Silva and de Alvarez, 2015	Vitoria, Brazil	Tropical rainforest (Af)	841	PET	N/A
56	Saaroni et al., 2015	Tel Aviv, Israel	Hot-summer Mediterranean (Csa)	300	ITS	N/A
57	Lin et al., 2015	Keelung, Taiwan Taichung, Taiwan Tainan, Taiwan	Monsson humid subtropical (Cwa)	2071	PET	N/A
58	Ruiz and Correa, 2015a	Mendoza, Argentina	Cold desert (BWk)	622	THI, PE, TS, S (COMFA), PMV, PET, ASV	N/A
59	Ruiz and Correa, 2015b	Mendoza, Argentina	Cold desert (BWk)	622	IZA	N/A
60	Sharmin et al., 2015	Dhaka, Bangladesh	Tropical wet savanna (Aw)	700	ASV	N/A
61	Yoshida et al., 2015	Osaka, Japan	Humid subtropical (Cfa)	36	HTL	N/A
62	Rutty and Scott, 2015	Barbados, The Caribbean Islands Saint Lucia, The Caribbean Islands Tobago, The Caribbean Islands	Tropical wet savanna (Aw) Tropical monsoon (Am)	472	UTCI	Age, Gd
63	Ye et al., 2015	Wuhan, China	Humid subtropical (Cfa)	4712	TSV	Clo
64	Zeng and Dong, 2015	Chengdu, China	Monsson humid subtropical (Cwa)	255	PET	N/A
65	Salata et al., 2015	Rome, Italy	Hot-summer Mediterranean (Csa)	1565	PMV	N/A

Table 2.1 Continued

No.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
66	Klemm et al., 2015	Arnhem, Netherlands Utrecht, Netherlands Rotterdam, Netherlands	Temperate oceanic (Cfb)	184 181 194	PET, Perceived thermal comfort	N/A
67	Klemm et al., 2015	Utrecht, Netherlands	Temperate oceanic (Cfb)	108	CV	Age, Clo, Gd
68	Kariminia et al., 2016	Isfahan, Iran	Cold desert (BWk)	504	PMV, PET, SET*	N/A
69	Chow et al., 2016	Singapore	Tropical rainforest (Af)	1573	THI, WBGT, PET	N/A
70	Elnabawi et al., 2016	Cairo, Egypt	Hot deserts (BWh)	320	PET	N/A
71	Giannakis et al., 2016	Nicosia, Cyprus	Hot semi-arid (BSh)	305	DI	N/A
72	Hashim et al., 2016	Kota Damansara, Malaysia	Tropical rainforest (Af)	30	PMV	N/A
73	Hirashima et al., 2016	Belo Horizonte, Brazil	Tropical wet savanna (Aw)	1693	PET	N/A
74	Huang et al., 2016	Wuhan, China	Humid subtropical (Cfa)	1460	UTCI	Age, Gd, Activity
75	Jeong et al., 2016	Seoul, Korea	Monsson humid subtropical (Cwa)	790	PET, SET*, OUT_SET*	N/A
76	Kántor et al., 2016	Szeged, Hungary	Temperate oceanic (Cfb)	5805	PET	N/A
77	Kovács et al., 2016	Szeged, Hungary	Temperate oceanic (Cfb)	5128	PET	N/A
78	Kurazumi et al., 2016	Bangkok, Thailand	Tropical wet savanna (Aw)	34	ETFe	N/A
79	Li et al., 2016	Guangzhou, China	Humid subtropical (Cfa)	1005	PET	Clo
80	Liu et al., 2016	Changsha, China	Humid subtropical (Cfa)	7851	PET	N/A
81	Lucchese et al., 2016	Campo Grande, Brazil	Tropical wet savanna (Aw)	408	PMV, PET, UTCI, TEP, Y_{DS}	N/A

Table 2.1 Continued

No.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
82	Maras et al., 2016	Aachen, Germany	Temperate oceanic (Cfb)	138	UTCI	N/A
83	Salata et al., 2016	Rome, Italy	Hot-summer Mediterranean (Csa)	941	PET, MOCI	N/A
84	Schnell et al., 2016	Tel Aviv, Israel	Hot-summer Mediterranean (Csa)	26	DI	N/A
85	Shooshtarian and Ridley, 2016	Melbourne, Australia	Temperate oceanic (Cfb)	1023	PET	Age, Gd
86	Song and Jeong, 2016	Bucheon, Korea	Monsson humid subtropical (Cwa)	29	PMV, SET*, WBGT	N/A
87	Zhao et al., 2016	Guangzhou, China	Humid subtropical (Cfa)	1582	SET*	N/A
88	Middel et al., 2016	Tempe, USA	Hot deserts (BWh)	1284	PET	N/A
89	Golasi et al., 2016	Rome, Italy	Hot-summer Mediterranean (Csa)	592	PMV, PET, MOCI, ASV, ET	Body fat, Clo, Met
90	Amindeldar et al., 2017	Teheran, Iran	Cold semi-arid (BSk)	410	TSV	Age, Gd
91	Chan et al., 2017	Hong Kong	Monsson humid subtropical (Cwa)	1000	ASV	N/A
92	Heidari and Azizi, 2017	Kashan, Iran	Hot deserts (BWh)	295	ASV	Clo
93	Hou et al., 2017	Harbin, China	Monsoon humid continental (Dwa)	602	TSV	N/A
94	Huang et al., 2017	Hong Kong	Monsson humid subtropical (Cwa)	1107	PET, UTCI, UCBTSV	N/A
95	Kim and Macdonald, 2017	San Francisco, USA	Warm summer Mediterranean (Csb)	701	PET	N/A
96	Krüger et al., 2017	Rio de Janeiro, Brazil	Tropical wet savanna (Aw)	985	PET, UTCI	N/A
97	Krüger, 2017	Curitiba, Brazil	Temperate oceanic (Cfb)	1685	UTCI, DTS, TSV, TPV	N/A

Table 2.1 Continued

No.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
98	Lucchese and Andreasi, 2017	Campo Grande, Brazil	Tropical wet savanna (Aw)	524	PET	N/A
99	Krüger et al., 2017	Curitiba, Brazil Rio de Janeiro, Brazil Glasgow, UK	Temperate oceanic (Cfb) Tropical wet savanna (Aw)	1685 985 567	PMV, PET, TSV	Age, Gd, Body build
100	Nasrollahi et al., 2017	Isfahan, Iran	Cold desert (BWk)	291	PET	N/A
101	Ndetto and Matzarakis, 2017	Dar es Salaam, Tanzania	Tropical wet savanna (Aw)	606	PET	N/A
102	Nouri and Costa, 2017	Lisbon, Portugal	Hot-summer Mediterranean (Csa)	30	PET	N/A
103	Shih et al., 2017	Tainan, Taiwan	Tropical monsoon (Am)	164	PET	N/A
104	Shooshtarian and Rajagopalan, 2017	Melbourne, Australia	Temperate oceanic (Cfb)	1059	PET	N/A
105	Tseliou et al., 2017	Athens, Greece	Hot-summer Mediterranean (Csa)	2313	PET, ATSV	N/A
106	Vanos et al., 2017	Lubbock, USA	Cold semi-arid (BSk)	261	S (COMFA)	Age, Clo, Gd
107	Wang et al., 2017	Groningen, Netherlands	Temperate oceanic (Cfb)	389	PET, T_{op}	N/A
108	Yang et al., 2017	Umea, Sweden	Subarctic (Dfc)	525	PMV, PET, UTCI	Age, Gd
109	Chindapol et al., 2017	Chiangmai, Thailand	Tropical wet savanna (Aw)	135	UTCI, HSI, TSI, WBGT, DI, TSV, TCV	N/A
110	Lam et al., 2018	Melbourne, Australia	Temperate oceanic (Cfb)	3320	UTCI	Clo
111	Lam et al., 2018	Melbourne, Australia	Temperate oceanic (Cfb)	2198	AT	Age, Clo, Gd
112	Lamarca et al., 2018	Concepción, Chile	Warm summer Mediterranean (Csb)	301	ASV, PTCI	N/A

Table 2.1 Continued

NO.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
113	Fang et al., 2018	Guangzhou, China	Humid subtropical (Cfa)	2007	T_{op}, PET, UTCI	Clo, Met
114	Golasi et al., 2018	Rome, Italy	Hot-summer Mediterranean (Csa)	941	PET, MOCI, GOCI	N/A
115	Lindner-Cendrowska and Błażejczyk, 2018	Warsaw, Poland	Warm-summer humid continental (Dfb)	662	PET	Clo
116	Galindo and Hermida, 2018	Cuenca, Spain	Hot-summer Mediterranean (Csa)	2321	PET, TSV	Age, Gd, Clo
117	Cheung and Jim, 2018	Hong Kong	Monsson humid subtropical (Cwa)	427	PET, UTCI, TSV	Age, Clo, Gd, Preference, Acceptability
118	Lai et al., 2018	Tianjin, China	Cold semi-arid (BSk)	1549	TSV	Age, Clo, Gd, ACT
119	Aljawabra and Nikolopoulou, 2018	Marrakech, Morocco Phoenix, USA	Hot semi-arid (BSh) Hot deserts (BWh)	303 126	ASV	Clo, Changing place, Cold drinks, Socio-economic, Expectation, Experience
120	Lam and Lau, 2018	Melbourne, Australia Hong Kong	Temperate oceanic (Cfb) Monsson humid subtropical (Cwa)	2162 414	UTCI, DTS, TSV	Gd, Clo
121	Yao et al., 2018	Shanghai, China	Humid subtropical (Cfa)	1014	TSV	Clo, Activity, Use of air conditioner, Purpose
122	Johansson et al., 2018	Guayaquil, Ecuador	Tropical wet savanna (Aw)	343	PET, SET*	Clo, Activity, Previous air-conditioner usage, Purpose, Preference

Table 2.1 Continued

NO.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
123	Chen et al., 2018	Harbin, China	Monsoon humid continental (Dwa)	31	PET, TSV, TCV	Clo, Psychological adaptation, Preference
124	Salata et al., 2018	Rome, Italy	Hot-summer Mediterranean (Csa)	941	MOCI	Clo, Met
125	Ali and Patnaik, 2018	Bhopal, India	Hot-summer Mediterranean (Csa)	240	PET, ASV	Gd, Socio-economic class, Preference
126	Shooshtarian et al., 2018	Melbourne, Australia	Temperate oceanic (Cfb)	1059	PET	Frequency and purpose of visit, type of visitors, Length of stay outdoor, Activity, Thermal adaptive measures
127	Lim et al., 2018	Suwon, Korea	Monsson humid subtropical (Cwa)	20	SET*	N/A
128	Wang et al., 2018	Guangzhou, China	Humid subtropical (Cfa)	1006	T_{op}, PET, TSV, TCV, TPV, HSV, HPV, WSV, WPV	Thermal adaptive measures, Preference
129	Heng and Chow, 2019	Singapore	Tropical rainforest (Af)	1508	PET, TSV, HSV, WSV, SSV	N/A
130	Brychkov et al., 2018	Sede-Boqer, Israel	Hot deserts (BWh)	105+2055	CV	Thermal history, Preference, Acceptability
131	Xu et al., 2018	Xi’an, China	Humid subtropical (Cfa)	37	PET, UTCI, OCV, TSV	N/A

Table 2.1 Continued

NO.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
132	Liu et al., 2018	Shenzhen, China	Humid subtropical (Cfa)	1870	PET, OUT_SET*, UTCI, TSV, HSV, WSV, SSV	N/A
133	Piselli et al., 2018	Perugia, Italy	Hot-summer Mediterranean (Csa)	367	PET, MOCI	N/A
134	Kenawy and Elkadi, 2018	Melbourne, Australia	Temperate oceanic (Cfb)	2123	PET, TSV, TAV, TP, NPET	Thermal preference and acceptance
135	Gobo et al., 2019	Santa Maria, Brazil	Humid subtropical (Cfa)	864	EI, MBCMS	BMI
136	Yung et al., 2019a	Hong Kong	Monsson humid subtropical (Cwa)	454	PET	Age, Clo, Gd, Educational background, Reason to visit, Companionship, Thermal history, Length of staying, Shade preference
137	Hadianpour et al., 2019	Tehran, Iran	Cold semi-arid (BSk)	1008	PET, UTCI, TSV, WSV, WPV, HPV	Clo, Met
138	Lau et al., 2019	Hong Kong	Monsson humid subtropical (Cwa)	1917	PET, TSV, HSV, WSV, SSV	N/A
139	Lu et al., 2019	Harbin, China	Monsoon humid continental (Dwa)	886	ATSV, OCV	N/A
140	Sharmin et al., 2019	Dhaka, Bangladesh	Tropical wet savanna (Aw)	1286	TSV, PET	N/A
141	Xie et al., 2019	Hong Kong	Monsson humid subtropical (Cwa)	1600	T_{op}, PMV, PET, SET*, UTCI, TSV, TCV	N/A
142	Cohen et al., 2019	Beer Sheva, Israel	Hot deserts (BWh)	996	PET, TSV	Gd, Clo

Table 2. Continued

NO.	Reference	Location	Climatic zone	Sample	Index and vote	Human factor
143	Fang et al., 2019	Guangzhou, China	Humid subtropical (Cfa)	644	WBGT, PMV, SET*, PET, UTCI, TSV	Clo
144	Smith and Henríquez, 2019	Chillán, Chile	Warm summer Mediterranean (Csb)	362	ASV	Reason to use, Experience, Socio-economic level
145	Canan et al., 2019	Konya, Turkey	Cold semi-arid (BSk)	296	PET, TSV, TOCI, TPV	Age, BMI, Clo, Met, Time of exposure
146	Chan and Chau, 2019	Hong Kong	Monsson humid subtropical (Cwa)	1000	PMV, PET	Age, Clo, Purpose, Perception of environmental features
147	Zabetian and Kheyroddin, 2019	Tehran, Iran	Cold semi-arid (BSk)	200	PMV	Sense of place, Thermal adaptation, Activity
148	Cheung and Jim, 2019	Hong Kong	Monsson humid subtropical (Cwa)	830	PET, UTCI, TSV, TPV, TAV, 1-hour acceptable temperature ranges	Age, BMI, Gd, Exercise, Lifestyle, Residence length
149	Leng et al. 2019	Harbin, China	Monsoon humid continental (Dwa)	301+364	PET, TSV, TPV	Activity, Gd, Adaptive behavior, Use of spaces
150	Huang et al. 2019	Mianyang, China	Monsson humid subtropical (Cwa)	523	PET, TSV, TCV, TAV, PTV	Clo, Gd, Activity, Adaptive behavior

3.

Conceptual Framework

3.1 Introduction

Outdoor comfort is an interdisciplinary research subject, involving bioclimatology, urban physics, physiology, psychology, and social behavior (Nikolopoulou, 2011). As revealed in many empirical investigations, the subjective human perceptions of ambient environmental conditions are essential in their thermal sensation and overall comfort levels. However, two main theoretical models, namely heat balance model and adaptive model, that underpin the knowledge of outdoor comfort assessment are not able to account for the influences of human psychological perception and adaptation. The heat balance model based on the framework of heat exchange and human physiological thermoregulation in steady-state and uniform settings ignores the active role and reactions of human in response to the outdoor thermal conditions. Although, adaptive models based on the framework of perceptual temperature related to contextual thermal conditions considers the active role of individual subjects and their thermal history and experiences, the limited set of variables considered in the model constraints its application for systematically understanding comfort assessment in outdoor environments (Shooshtarian et al., 2020).

From the perspective of steady state settings, due to the large variability in urban microclimates, especially the fluctuating wind speed and solar radiation, the heat flow to and from human body cannot be balanced in the real-world dynamic and nonuniform outdoor situations (Höppe, 2002). Regardless theory and practice, the assessment of human comfort in outdoor urban environments is highly complicated. According to the numerous empirical investigations, the rational thermal indices are inadequate to understand and assess outdoor comfort alone. The most significant reason is that these approaches focus on the thermo-physiological component of comfort but ignore the subjective factors pertaining to the perception of environment (Spagnolo and de Dear, 2003a; Knez and Thorsson, 2006; Lin, 2009; Lenzholzer, 2010, 2012; Andrade et al., 2011). Moreover, the strong relationship between comfort and usage patterns in different outdoor public spaces has been well documented (Nikolopoulou et al., 2001; Zacharias et al., 2001, 2004; Thorsson et al., 2004; Aljawabra and Nikolopoulou, 2010; Yung et al., 2019b), which shed light on how behavioral factors influence outdoor comfort assessment.

The theory underlying the adaptive model significantly influenced research trends about outdoor comfort. Realizing the active role of humans in determining outdoor comfort, explorations on contextual and human factors have been extended to outdoor environments in various climatic zones (Potchter et al., 2018; Binarti et al., 2020; Kumar and Sharma, 2020; Li and Liu, 2020). Many trials were conducted in different locations for calibrating thermal indices based on surveyed human subjective perceptions and preferences. Apart from meteorological factors of urban microclimate, individual's behavioral, physiological and psychological adaptations play a significant role in thermal comfort assessment (Amindeldar et al., 2017). However, the shortcomings of outdoor comfort modeling will not be addressed if the conceptual framework of outdoor comfort assessment is not improved. Although several localized standards have been established for the evaluation of outdoor thermal comfort, the theoretical knowledge concerning human behavioral and psychological factors influencing comfort in outdoor environments is still limited. Although the importance of physical, physiological, and psychological aspects in comfort assessment has been stressed and retrieved through field studies, adequate consideration of human factors in comfort modeling is still lacking, which must be taken into account for the systematic understanding of comfort assessment (Chen and Ng, 2012).

This research brings about the necessity of a comprehensive conceptual framework with an expanded set of both contextual and human factors on comfort assessment in urban public spaces. The conceptual framework is proposed with the identification of knowledge gaps for exploring and examining (1) the hypothetical relationships between comfort assessment and an expanded set of explanatory variables including microclimatic and environmental stimuli and human socio-demographic, psychological and physiological factors, (2) the hypothetical nonlinear effects of various factors on outdoor comfort assessment, (3) the hypothetical intermediate effects of human psychological factors, and (4) the differences in the process of individuals' comfort assessment determined by socio-demographic and past behaviors and experiences, given the similar microclimatic and environmental conditions in urban public spaces.

The remainder of this chapter consists of three sections. Section 3.2 provides an overview of important concepts of outdoor comfort. These concepts induce the analytical evaluation of human and contextual factors in comfort modeling and enlightens the proposed conceptual framework with an expanded set of influential factors, which is introduced in section 3.3.

3.2 Concepts related to comfort

3.2.1 Thermal sensation and thermal neutrality

Thermal sensation refers to sensory unconscious acquiring of environmental stimuli by receptors in the skin, which is utilized by human body to obtain information concerning the thermal condition of external objects or the environment. Thermal sensation is conceptually different from thermal comfort which is the satisfied state of mind. Instead, thermal sensation represents the evaluation of immediate feeling which results from exposure to a thermal environment (Zhang and Zhao, 2009). Thermal sensation is normally evaluated by the ASHRAE 7-point scale (ASHRAE, 2017) which ranges from -3 to +3 (respectively represented by “cold”, “cool”, “slightly cool”, “neutral”, ”slightly warm”, “warm”, “hot”).

The primary objective in conventional outdoor comfort studies is to obtain thermal neutral temperature, which is assumed to equal to the temperature related to comfort. Thermal neutrality, as the mostly used definition of comfort, refers to the condition where more than 80% of the occupants feel neither cool nor hot (ASHRAE, 2017). Regression and probit analysis were applied to predict the neutral temperature in different regions based on surveyed subjective comfort assessment. The regression of mean thermal sensation over a range of temperatures defines the neutral temperature and average of thermal scale at each bin temperature (Humphreys and Nicol, 1998). The regression identifies the relationship between mean subjective thermal sensation and the predicted thermal comfort while the probit analysis predicts the neutral temperature based on respondents’ thermal preference, which is split into two categories: “warmer than neutral” and “cooler than neutral”. The neutral responses to thermal preference are evenly divided into the abovementioned two categories. The intersection between the two curves generated by probit analysis indicates a neutral temperature for the target population.

3.2.2 Thermal preference and preferred temperature

Thermal preference is a primary measure of thermal satisfaction and is normally evaluated with McIntyre preference scale (McIntyre, 1982). Three types of preferences have been applied, including “cooler”, “no change” and “warmer”. Thermal preference is related to human adaptation and is influenced by thermal experience and expectation.

Preferred temperature is a temperature of a thermal condition where most of occupants prefer no change in the surrounding environment. It is a criterion of the optimal thermal condition, which is also referred to as optimum temperature. In the case of probit analysis, the preferred temperature can be predicted according to surveyed thermal preference of respondents. A temperature at intersection between the curves of "preferring to higher temperature" and "preferring to lower temperature" is defined as the preferred temperature (McIntyre, 1978). Field investigations indicates the preferred temperature is a better representative of thermal satisfaction and acceptability (Cheung and Jim, 2018).

3.2.3 Overall comfort

The overall comfort can be assessed with the 7-point scale, which is similar with ASHRAE thermal sensation scale, from "very discomfortable" (-3), "discomfortable" (-2), and "slightly discomfortable" (-1) in the left side, "neutral or just right" (0) in the middle, to "slightly comfortable", "comfortable", and "very comfortable" in the right end.

3.2.4 Comfort zone

When defining people's thermal comfort, a single given temperature is not sufficient. Hence, the comfort zone, namely the acceptable thermal range, was introduced into comfort study and standards (ASHRAE, 2017). The thermal range in which at least 80% of occupants are thermally satisfied is assumed to be a comfort zone. To determine the comfort zone, two methods are applied, a direct approach and an indirect approach. In the direct approach, occupants are asked for their choices on whether accepting the thermal variables or not. In the indirect approach, comfort zone is calculated based on the three central categories of thermal sensation scales. The indirect approach is mostly used in outdoor comfort studies, however, its validity is challenged in outdoor empirical investigations since the meteorological and environmental variables are varying quickly and the interaction between human and environments is complex (Höppe, 2002; Lai et al., 2014; Huang et al., 2016).

3.3 The human factors

The physiological difference between comfort and thermal sensation was confirmed by experimental investigation a long time ago (Gagge et al., 1969). As a rational experience, thermal sensation is directed towards an objective world in terms of cold and warm;

thermal comfort, on the other hand, is an emotional experience and relative to expectation (Hensen, 1990). Instead of thermal neutrality, an individual's comfort emerges from a desired sensation or satisfaction (Humphreys and Hancock, 2007; Zhang and Zhao, 2009; Ning et al., 2016). In contrast to heat balance theory, the mainstreaming of adaptive comfort principles assumes that comfort will derive from the standpoint of adaptation, which is more than a derivative of neutrality state or an outcome of steady-state heat balance (Humphreys et al., 2007; Yang et al., 2014). Individuals have the ability to be more comfortable through access to opportunities to modify conditions such as changing clothing or activity level (Cole et al., 2008). The "average person" comfort has been specified individually and extended by taking into consideration dynamic, integrated and participatory aspects (Chappells and Shove, 2005; Cole et al., 2008; Nicol and Roaf, 2017). The postulation that comfort is the physical state of a passive individual recipient has been developed and advanced to the psychological perception derived from their experience, expectation, and reaction. The individual's role is gaining increasing importance, therefore drawing more and more attention within comfort modeling (Singh et al., 2011). In addition, comfort has been socially determined and defined by norms and expectations, shifting from one time, place, and season to the other. The context-based individual and social factors on thermal perception have been studied through investigation in outdoor spaces, which reveal the specific thermal requirements of the occupants and their relationship with the moderating factors (Aljawabra and Nikolopoulou, 2010; Shooshtarian and Ridley, 2017). Moreover, the culture and climate that people are used to, their emotional state, visiting purpose and their use of public spaces may potentially also link to individuals' subjective evaluation of outdoor comfort (Knez and Thorsson, 2006; Thorsson et al., 2007; Knez et al., 2009; Aljawabra and Nikolopoulou, 2010). The age, gender, metabolic rate, clothing insulation and body build were examined in previous studies (Thorsson et al., 2007; Andrade et al., 2011; Krüger and Rossi, 2011; Nasir et al., 2012; Lin et al., 2013; Pantavou et al., 2013; Lai et al., 2014; Tung et al., 2014; Lam et al., 2018). However, there is no consistency in the findings regarding the effects of age, gender, and body build. The socio-economic factors, including education, job and self-evaluation, were also investigated with respect to their influences on human outdoor behavior and thermal perception (Aljawabra and Nikolopoulou, 2010). More sensitive to prevailing outdoor climate was addressed among individuals with better education and economic status. Further, individuals with better economic status reduced their discomfort given the same thermal conditions (Maras et al., 2016).

The potential relationships between a wide range of individual factors and outdoor comfort are worthy to investigate. Compared with the individual's physiological and socio-economic factors, fewer investigations incorporated individuals' psychological and behavioral factors into numerical modeling. The research focus has shifted to human and contextual factors that are conductive to interpreting variations in individuals' subjective outdoor comfort assessments (Nikolopoulou et al., 2001; Nikolopoulou and Steemers, 2003; Knez and Thorsson, 2006, 2008; Lin, 2009; Lenzholzer and van der Wulp, 2010; Lam et al., 2018; Lam et al., 2020). The individuals' past thermal history has been hypothesized as influences on thermal expectations and thus their thermal comfort (Brager and de Dear, 1998). Previous studies scratched the surface of human adaptations by involving modified expectations as cognitive process directly interacting with environmental perceptions and outdoor comfort, which are evidenced at the mercy of change relying on variations in states of emotions (Knez and Thorsson, 2006; Lenzholzer, 2010). Thus, in this study, the effects of psychological and emotional factors are assumed to potentially change overall outdoor comfort. As an underpinning of the adaptive model, humans play an active role in thermal sensation and comfort assessment rather than being a passive recipient. Therefore, the active agent can modify the perception of comfort through adjustments in behavior, immediate environments, even social norms (Chappells and Shove, 2005).

3.4 Conceptual framework

From the perspective of engineering research, comfort assessment is a direct process of heat exchange between human body and physical environment. The research concerning physiological aspects of comfort indicates that thermal comfort is determined by three components, i.e., respondents' physiological condition, thermal attributes of the environment, and the mechanism of heat exchange. This conceptual framework is largely accepted and used in thermal comfort standards and modeling approaches to define what is a comfortable environment. In fact, especially in a real-world setting, a comfortable environment is not constrained to thermal attributes. Comfort is a complex subjective assessment closely associated with place-related and person-related factors in terms of physical, physiological, socio-demographic and psychological aspects, that are difficult to model and elaborate (Johansson et al., 2014; Shin, 2016). The acceptability and satisfaction of outdoor activities involve the subjective assessment of the quality of the given microclimate and environment, which indicates how much the outdoor condition fulfils the expectation and needs of the respondent.

From the literature, people's expectations and needs are highly relying on their socio-demographic background and past experiences, as well as the purpose of being in that outdoor environment.

Thermal comfort is defined as "the state of mind that expresses satisfaction with the thermal environment" by ASHRAE (ASHRAE, 2017). As the understanding of comfort is constantly evolving, there is more to comfort than physiological response to meteorological thermal conditions (Chappells and Shove, 2005). Beyond what is described in heat balance models, individuals' comfort assessment refers to the outcome of an interactive process between an individual and the environment. Evidence from field investigations prove that individuals' subjective assessments are much more elastic than the predictions of rational indices (Nikolopoulou and Steemers, 2003). Findings of previous studies have also acknowledged the role of contextual influences in terms of meteorological and socio-cultural conditions, and individual socio-demographic characteristics, psychological and behavioral factors in shaping the individuals' comfort expectations and perceptions (Brager and de Dear, 1998; Chappells and Shove, 2005; Lam et al., 2018). Assessing individuals' comfort responses to microclimate and environmental conditions of urban public spaces requires measurements of both physical conditions and individuals' assessments. However, no integrated conceptual frameworks yet exist to facilitate the implication of the holistic concept of comfort to coupled human-place systems (Shooshtarian et al., 2015). To this end, more efforts need to focus on conceiving a new conceptual framework of comfort assessment with an expanded set of determinants that involves socio-demographic, and behavioral and psychological factors apart from meteorological variables. Thereby, a human adaptive paradigm is expected to provide more psychological and behavioral insights into the process of outdoor comfort modeling. Although substituted by thermal neutrality in the heat balance model for engineering simplification, in this thesis, we consider human comfort as the research objective and focus on the linkage between outdoor comfort assessment in urban public spaces and its influential factors stemming from different contextual and individual dimensions.

Outdoor thermal comfort assessment is reduced to a simplified cause-effect process based on a direct relationship between the human body and physical surrounding environment. To undertake it, the thermal environment should be evaluated against the human thermoregulatory system by thermal indices which are centered on the heat balance of the human body. In line with this process, a human is regarded as a passive recipient of ambient environmental stimuli with only physiological thermal responses.

However, plenty of empirical evidence regarding the deviation and flaw of predictions made by thermal indices alone were, to some extent, related to human adaptation in the contexts of certain climate and culture.

Previous conceptual frameworks of outdoor comfort assessment using the heat balance model simplify the mechanism of comfort assessment into a straightforward process flow from meteorological influences and physiological responses to thermal sensation. The primary assumption of steady-state and uniform thermal settings for this conventional framework model is violated in the complex outdoor conditions. In order to stress the human in the center of the process as an active role interacting with environmental stimuli, the framework underlying the adaptive comfort model has been proposed based on three dimensions: behavioral adjustment, physiological acclimatization, and psychological adaptation (de Dear and Brager, 1998; de Dear, 2011). Figure 3.1 presents the widely applied conceptual framework of field studies for thermal index modification through subjective assessments. The objective prediction of thermal indices based on the measured meteorological data and standardized clothing insulation and metabolic rate is calibrated by surveyed subjective thermal sensation for localizing thermal sensation scales. The modification of thermal indices with local scales and neutral ranges is based on the indirect consideration of the human personal characteristics, climatic and socio-demographic backgrounds, previous thermal experiences, thermal expectations, and behavioral factors.

However, comfort assessment is the result of a complex process strongly influenced by norms and expectations, which may vary depending on seasons and regions (Chappells and Shove, 2005; Nicol and Roaf, 2017). Moreover, people’s expectations of comfort change over the years, thus the process of specifying comfort is subject to localized, context-dependent considerations (Chappells and Shove, 2005). By this nature, the rational indices based on the heat balance model are constantly challenged due to the lack of consideration of contextual factors and people’s socio-demographic, behavioral and psychological factors. Furthermore, regarded as a cognitive process, outdoor comfort assessment is also influenced by physical, physiological, psychological, and other processes (Knez and Thorsson, 2006). In this sense, the influence of meteorological variables in urban environments only partly accounts for subjective comfort assessment (Nikolopoulou and Steemers, 2003). The remaining parts may be explained by the contextual factors and individual’s psychological adaptation (Nikolopoulou et al., 2001; Knez and Thorsson, 2006; Eliasson et al., 2007; Lin, 2009; Nikolopoulou, 2011).

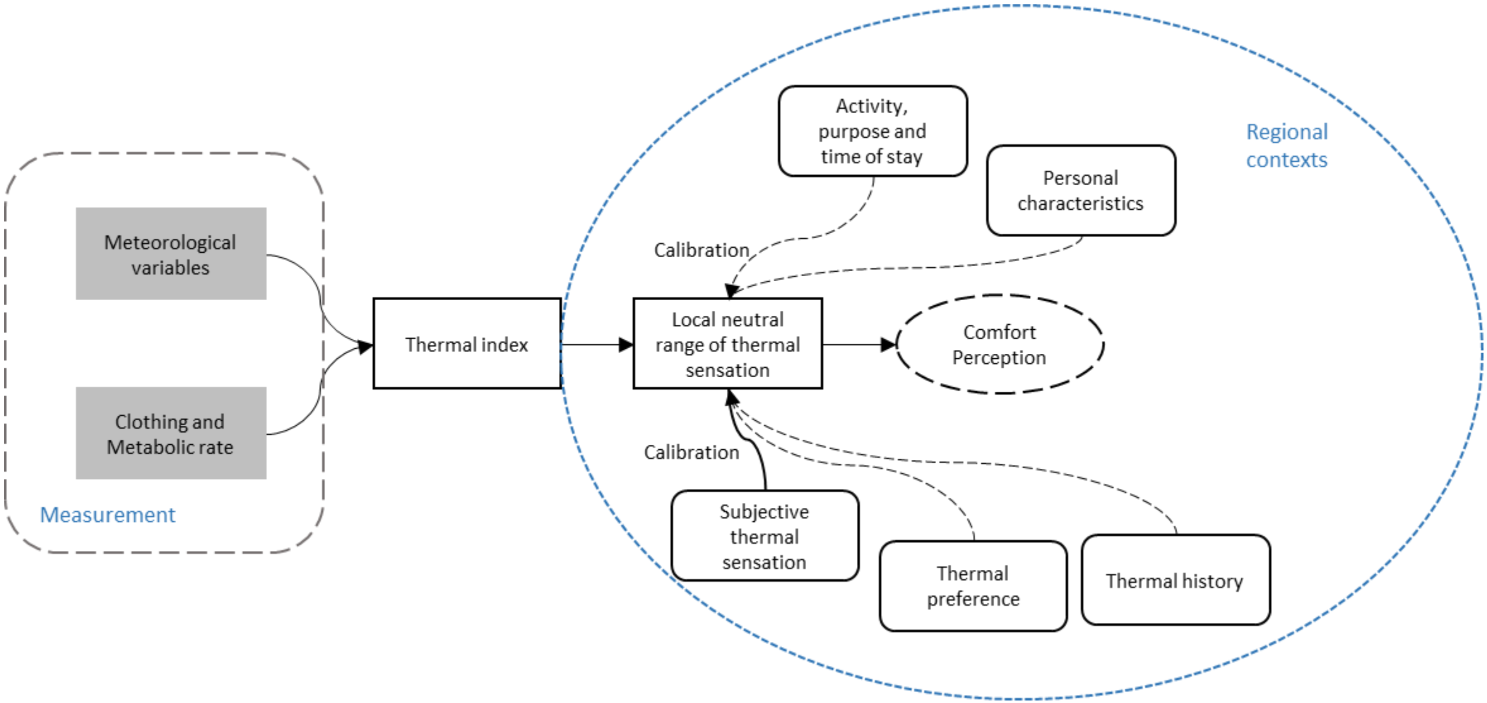


Figure 3.1 Conceptual framework of existing outdoor comfort studies

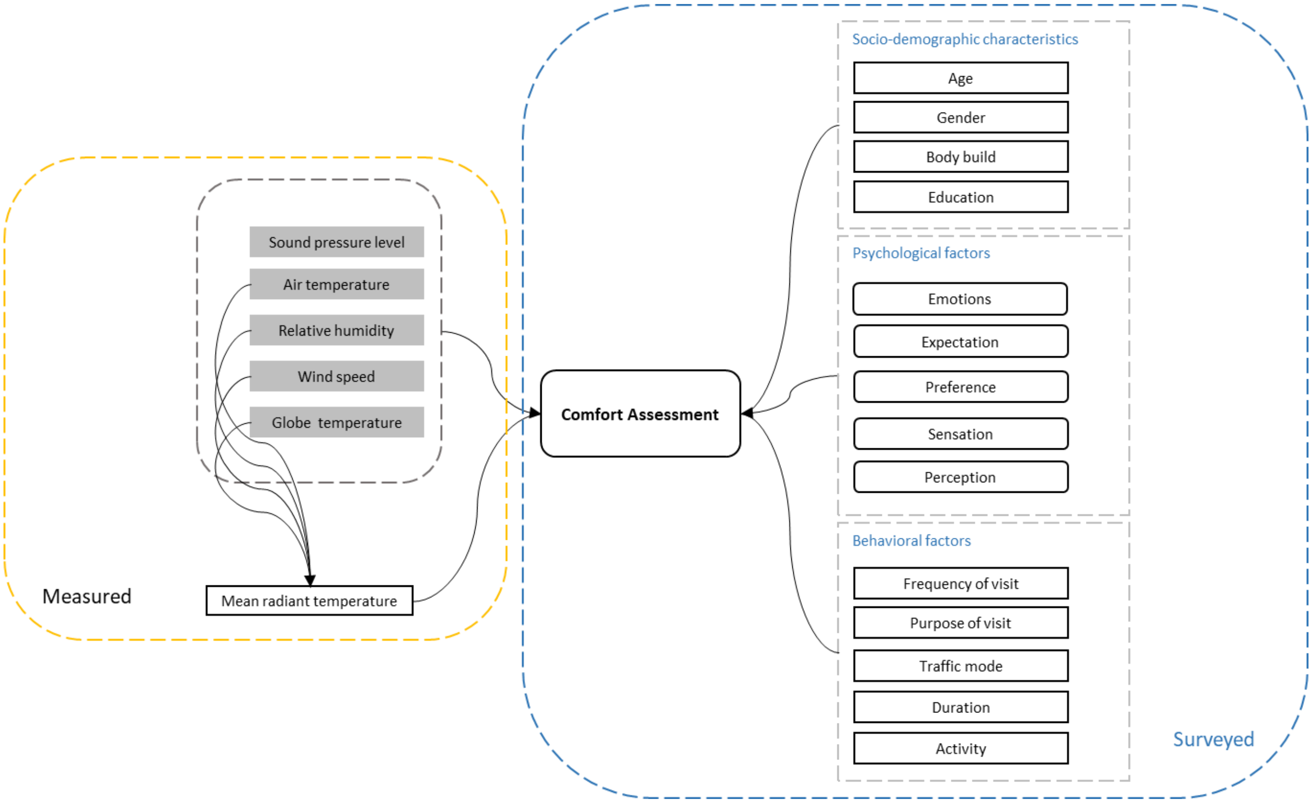


Figure 3.2 Conceptual framework with expanded set of influential factors

From the theoretical perspective, the structure of the conceptual framework underlying outdoor comfort assessment involves three main components dealing with the interactions between urban environment drivers, human factors, and behavioral aspects (Shooshtarian, 2019). The environmental drivers include urban spatial features, microclimatic conditions, and socio-cultural context. Human factors refer to human body build, physiological conditions, expectation, preference, and past thermal experience, while behavioral aspects involve the type of outdoor activities, and adaptive reactions to the outdoor environment. The comprehensive conceptual framework we developed in this thesis is rooted in the three components of drivers, given that outdoor comfort assessment is a complex and wide-ranging concept.

Figure 3.2 presents the proposed conceptual framework with an expanded set of place-related and person-related factors. Besides the factors related to the physical and physiological mechanism in the heat balance models, many non-thermal factors are incorporated in the expanded conceptual framework of outdoor comfort assessment. The physiological and psychological characteristics of respondents vary individually which implies errors may be introduced when purely applying the standardized thermal indices in outdoor complex situations (Nikolopoulou et al., 2001; Coccolo et al., 2016). In our conceptual framework, besides the measured microclimate, people make their subjective comfort assessments in urban public spaces mainly based on their experiences, preferences, and expectations. Therefore, the mechanism and structure of comfort assessment process will be fully speculated involving individual’s psychological and behavioral factors. The socio-demographic characteristics of outdoor space users are also required in the newly proposed conceptual framework for evaluating their outdoor comfort.

3.5 Conclusions

Thermal comfort is conceptually described as a state of mind approximating one’s satisfaction with the environment, which is difficult to capture through only physical factors (Hensen, 1990; van Hoof et al., 2010; ASHRAE, 2017). Given such complexity, assessing comfort in outdoor environments is not a simple matter. Despite the considerable amount of literature on outdoor comfort, the concept of comfort is still ambiguous and lacks consensus in both theoretical models and methodology. This chapter has clarified the concept of outdoor comfort and its theoretical background and brought insights to the relationship between comfort and its influential factors.

As soon as we admit the realm of behavioral and psychological factors to be part of the crucial determinants of outdoor comfort assessment, we are courting complexity. Advancements have been made in the past decades, however, in acknowledging comfort as a condition of the mind expressing holistic satisfaction with the entire environment, which should be assessed by subjective evaluation, based on climatic and cultural contexts. As presented in this chapter, an expanded research framework incorporating psychological, behavioral, and meteorological factors and environmental context is more theoretically sound and warrants a comprehensive assessment of outdoor comfort.

4.

Data Collection and Descriptive Statistics

4.1 Introduction

The main objective of this doctoral research is to investigate comfort assessment in urban public spaces with an expanded set of influential determinants, involving both microclimatic and environmental stimuli and human factors, in a certain climatic and cultural context. To this end, the data collection was carried out, which consists of four sequential parts: Questionnaire design in light of the comprehensive conceptual framework, selection of study locations based on an experimental design, detailed plan for fieldwork, and administration of simultaneous in-situ measurement and survey.

Previous empirical investigations which were directly carried out in certain locations without experimental design may likely be based on correlated spatial attributes and thus result in biased modeling results of comfort assessment. In this study, we therefore selected the study locations based on an experimental design for attributes combinations of public spaces in terms of urban landscape, vegetation, facilities, and services.

4.2 Study area

The data collection was conducted in the city center of Eindhoven, The Netherlands. Eindhoven is the fifth largest city of the Netherlands with about 230,000 population, with abundant high-tech industry. The region ranks high in terms of the number of patents per capita across the world. This city is located in the southeast of the country (see Figure 4.1).

The study area is located in a mild climate zone, namely Cfb according to the Köppen-Geiger classification with a typical maritime temperate climate, where summer is generally cool and winter is milder than in other climates at similar latitudes (Kottek et al., 2006; van den Hurk et al., 2006). Thus, the UHI effect in Dutch cities has long been hypothesized to be relatively insignificant (Heusinkveld et al., 2014). Nevertheless, hot summer days with air temperature rising above 30˚C have occurred in the Netherlands, and such days are expected to occur more frequently, exacerbated by climate change (Huynen et al., 2001).

The Netherlands is a highly urbanized and densely populated country. Urban densification and climate change will affect the livability, especially the human comfort, of Dutch cities. Consequently, the UHI effect in Dutch cities becomes increasingly more significant for certain vulnerable groups of the urban population, including the elderly, young children, and people with some diseases. Moreover, the climate involves many windy and chilly days. The monthly minimum, maximum, and mean air temperatures, and monthly precipitation of Eindhoven in 2015 are shown in Figure 4.2.

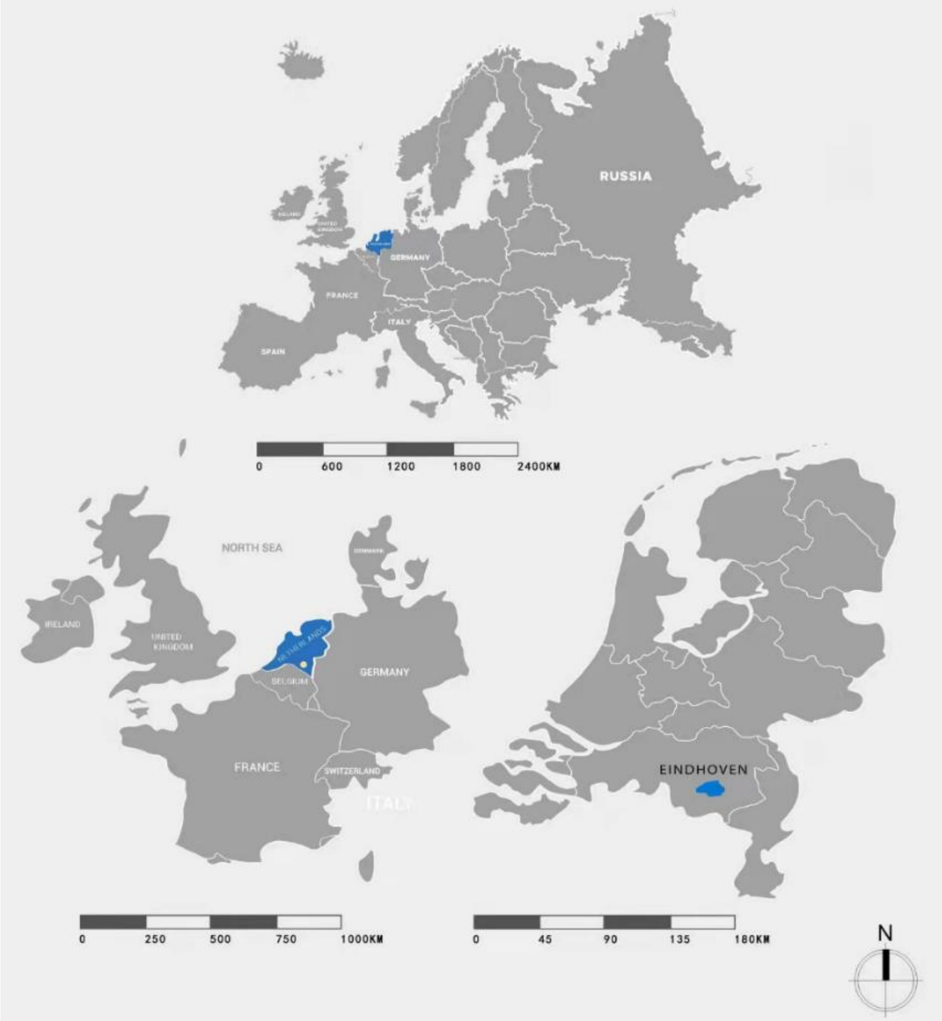


Figure 4.1 Location of Eindhoven in The Netherlands

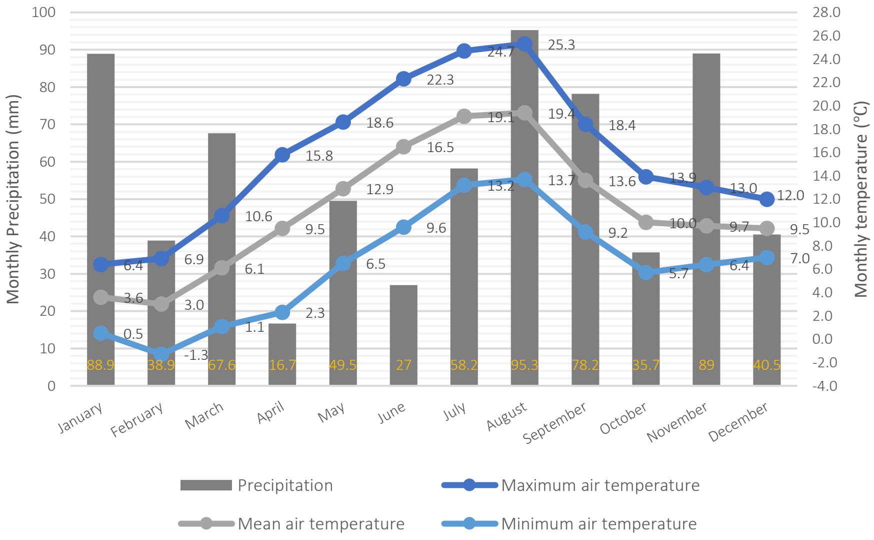


Figure 4.2 Monthly air temperature and precipitation of Eindhoven in 2015

4.3 Data collection

4.3.1 Study location selection

To avoid bias regarding the influence of attributes and settings of urban public spaces on individuals' outdoor comfort assessments, the related environmental and functional attributes should be independent with each other across the study locations. This precondition is typically violated in previous studies on outdoor thermal comfort which rely on a random selection of locations. To avoid such bias, this study applies the principles underlying orthogonal fractional factorial designs to select the locations of the field investigations.

Considering five attributes, each with two levels, including water landscape or fountain (W), facility for resting (R), green lawn or land-cover (G), kiosk or catering service (K) and trees and shelter proofing sun and wind (S), the full orthogonal experiment design involves 32 (=2^5) possible profile combinations. As shown in Table 4.1, an orthogonal fraction of the full factorial design was selected, consisting of eight independent profile combinations corresponding with eight different study locations (see Table 4.2) for the field investigations. These specific locations (S1 – S8) are marked on the map of

Eindhoven city center, as shown in Figure 4.3 with pictures of scene related to different locations.

Table 4.1 The profile combinations of the orthogonal fractional factorial design

Study area	G	S	K	F	W
S1	+1	+1	+1	+1	+1
S2	+1	-1	-1	-1	+1
S3	-1	+1	-1	+1	+1
S4	-1	-1	+1	-1	+1
S5	-1	-1	-1	+1	-1
S6	-1	+1	+1	-1	-1
S7	+1	-1	+1	+1	-1
S8	+1	+1	-1	-1	-1

Table 4.2 The location of the studied areas

Study area	Description
S1	Green space nearby a restaurant “Zwarte Doos”
S2	Green space nearby landscape water body in “Simon Stevenplein”
S3	“18 Septemberplein” in Eindhoven city center
S4	Paved square nearby landscape water body in “Simon Stevenplein”
S5	Small, paved passageway in “Kennedyplein”
S6	Aisle and rest zone of central station and bus station in “Neckerspoel”
S7	Small green space between “Vertigo” building and “Matrix” building
S8	Green space south of the Auditorium

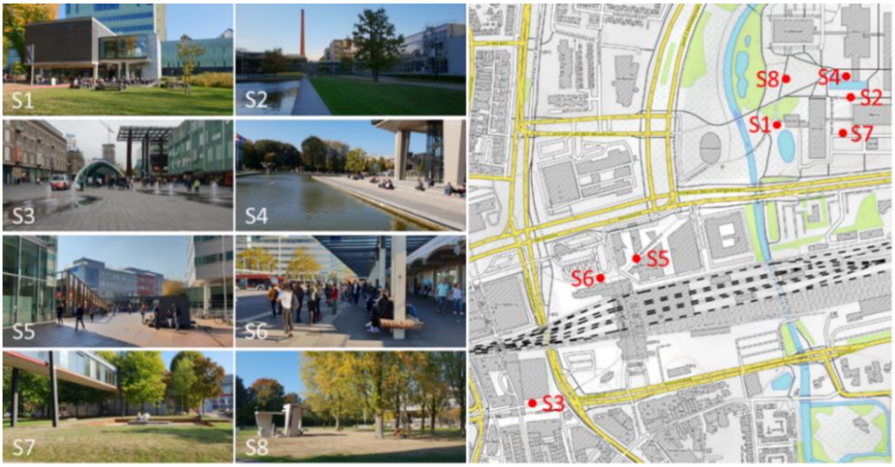


Figure 4.3 The sights and locations of the studied areas (map source: www. mapbox.com)

4.3.3 Measurement device

The device used for meteorological measurements was installed and tested in the Building Physics Laboratory of the Department of Built Environment in Eindhoven University of Technology with the help of technicians two weeks before the in-situ field work. All meteorological sensors and the acoustic meter were connected with a data-logger and charged by a portable power bank. The detailed specifications on sensors for meteorological variables, such as air temperature (T_a), globe temperature (T_g), relative humidity (RH) and wind velocity (v) are elucidated in Table 4.3.

Table 4.3 The specification of sensors for movable microclimate monitor

Variable	Sensor model	Resolution	Accuracy
T_a	NTC	0.01K	±0.05K
T_g	NTC (in a black ball)	0.01K	±0.05K
RH	HUMITTER 50U	0.1%	±3%, 10-90%
v	CLIMA	0.1m/s	±0.3m/s rms, $v \leq$ 5m/s ±3% rms, $v >$ 5m/s ±5% rms, $v >$ 50m/s

4.3.4 Field work

The data collection was carried out in the selected public spaces in Eindhoven from the end of March to the beginning of April, during eight inconsecutive days without precipitation namely 16, 19, 20, 23, 26 and 27 March and 2 and 3 April, in 2015. The daily weather characteristics, including wind velocity (mean: v_m maximum: v_{max} and minimum: v_{min}), temperature (mean: T_m, maximum: T_{max} and minimum: T_{min}) and relative humidity (mean: RH_m, maximum: RH_{max}, and minimum: RH_{min}) in these days are listed in Table 4.4. A movable monitoring device was used for measuring all physical variables, so the field study altered in different public spaces by time of day. The monitoring device had to be tested and set up again when the surveyed location was altered.

Table 4.4 The daily weather characteristics of Eindhoven during the field work

Date	v_m (m/s)	v_{max} (m/s)	v_{min} (m/s)	T_m (℃)	T_{max} (℃)	T_{min} (℃)	RH_m (%)	RH_{max} (%)	RH_{min} (%)
16-3-2015	2.3	4.0	0.0	5.8	12.9	-0.8	78	98	50
19-3-2015	1.8	3.0	0.0	5.7	8.1	1.9	91	99	81
20-3-2015	1.6	3.0	0.0	3.1	4.9	-0.2	96	99	87
23-3-2015	1.8	4.0	1.0	4.3	11.9	-3.8	78	98	53
26-3-2015	4.4	8.0	2.0	4.7	7.2	0.4	90	99	63
27-3-2015	4.6	8.0	1.0	6.0	11.3	-1.3	76	97	57
09-4-2015	5.5	8.0	2.0	5.8	9.4	0.6	73	93	48
10-4-2015	2.1	4.0	1.0	6.3	10.4	-0.3	67	93	41

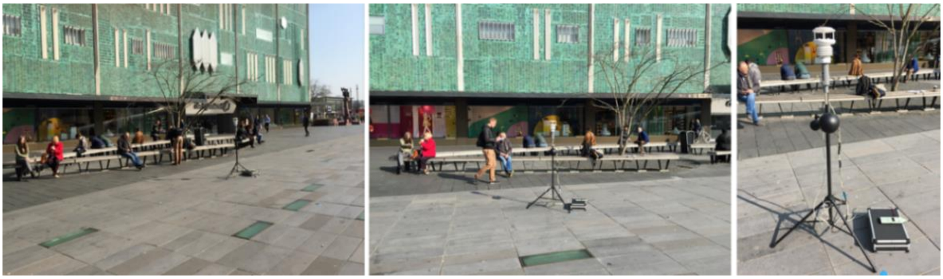


Figure 4.4 The scenes of survey and measurement

The portable device with sensors and a data-logger was set up to monitor the microclimate conditions and background sound pressure levels automatically. Microclimatic variables, including T_a, T_g, RH and v, and sound pressure level (l) were measured and recorded automatically by movable devices with sensors and corresponding data-logger. The sensors of T_a, T_g and RH were mounted on the tripod at the fixed standard height of 1.1m according to ISO7726 (ISO 7726, 1998), and the anemometer for v was installed at the height of 1.7m. The measuring device was set up in the study location and launched 15 min ahead of measurement as a stabilizing period in order to obtain reliable results. In addition, an acoustic meter was used for recording the background sound pressure level.

The surveys and measurements were conducted between 10:00 a.m. and 5:30 p.m. with the assistance of 54 Master students from the Department of Built Environment in Eindhoven University of Technology. Respondents were randomly invited to participate in the survey within approximately 2 meters distance around the measurement device. The duration of each survey was between 7 and 16 minutes. A scene of the survey is shown in Figure 4.4. Some respondents were interviewed while sitting on a bench with a monitoring device set nearby. The survey started with a concise explanation of the research purpose. The exact start and end time of each survey were recorded by research assistants, who monitored the duration of the survey for synchronizing the measured variables for the analysis. In general, respondents spent ten to twenty minutes to complete the questionnaire. The example of questionnaire form (English version) is attached in Appendix.

More than 1000 questionnaire forms were collected. However, some were discarded during the screening process since they were unfinished. Ultimately, the entire dataset consisting of 701 effective and intact questionnaires were available for analysis and modeling.

4.4 Descriptive statistics

4.4.1 Physical conditions of the public spaces

The mean radiant temperature (T_{mrt}) was calculated for evaluating the solar short-wave radiation and the long-wave radiation from the surface ground and surrounding objects. The equation is expressed as below based on ISO7726 (ISO 7726, 1998):

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10 \times 10^8 \times v^{0.6}\left(T_g - T_a\right)}{\xi D^{0.4}} \right]^{0.25} - 273 \qquad (4.1)$$

where D is the diameter (=150mm in this study) of black ball sensor for T_g and ξ is the emissivity coefficient (=0.95 in this study).

As shown in Table 4.5, meteorological variables and sound pressure level varied during field investigations within a certain range in the study areas. The air temperature was relatively low with a minimum value of 4.2˚C and mean value of 11˚C. The wind speed was up to 3.9 m/s. The fluctuation of mean radiate temperature was significant during fieldwork due to the variation of sunshine exposure and wind conditions in different locations of urban public spaces.

4.4.2 Socio-demographic and behavioral statistics

The distributions of physiological and socio-demographic characteristics are shown in Table 4.6. Males account for 61.1% of all respondents. The majority of respondents have the Dutch nationality. Around 86.6% of the respondents are under 40 years old. Moreover, the education levels of respondents are mainly in the range from “Secondary vocational school” to “Master”. As for the body build of respondents, the Body Mass Index (BMI) is widely used as a general indicator of whether a person has healthy body weight relative to their height. The new BMI is a simple calculation using a person’s height and weight, which is expressed as:

$$BMI = \frac{1.3 \times W}{H^{2.5}} \qquad (4.2)$$

where W is weight of an individual person measured in kilogram, and H is height of an individual person in unit of meter. The World Health Organization regards a BMI of less than 18.5 as underweight, while a BMI equals to or greater than 25 is considered overweight. With a BMI over 30, a person is considered obese (World Health Organization, 1995; Prospective Studies Collaboration, 2009). The BMI of healthy weight is found in range from 18.5 up to 25. Statistics show most respondents’ BMI fall in the 18.5 to 25 range (75.6%).

Table 4.5 The meteorological variables of microclimatic conditions and sound pressure level

Variables	Minimum	Maximum	Mean	Median	SD
T_a (℃)	4.2	24.7	11.0	9.7	4.6
RH (%)	24.9	91.2	56.3	55.5	17.6
v (m/s)	0.2	3.9	1.5	1.1	0.9
T_{mrt} (℃)	4.6	51.7	17.9	15.1	10.3
l (dB)	51.0	72.9	64.9	65.7	4.3

Table 4.6 The socio-demographic and physiological characteristics of respondents

Variable	Category	Percentage
Gender	Female	38.9%
	Male	61.1%
Age	< 20	27.0%
	20-40	59.6%
	40-60	7.8%
	≥ 60	5.6%
BMI	< 18.5	6.6%
	18.5-25	75.6%
	25-30	15.1%
	≥ 30	2.7%
Nationality	Dutch	77.2%
	Non-Dutch	22.8%
Education	High school or less	9.6%
	Secondary vocational school	18.3%
	College diploma	13.7%
	Bachelor	30.7%
	Master	24.8%
	PhD	2.9%

Table 4.7 The proportions of respondents regarding behavioral factors

Variable	Category	Percentage
Motion before survey	Sitting	26.8%
	Standing	15.8%
	Walking	57.4%
Transportation mode	By foot	37.7%
	By bike	22.2%
	By bus, train, and car	40.1%
Frequency	First time	2.3%
	Seldom	13.7%
	Occasionally	18.0%
	Sometimes	26.1%
	Often	39.9%
Duration (entire outdoor activities)	< 15 mins	30.5%
	15 - 30 mins	30.5%
	30 - 60 mins	17.2%
	60 - 120 mins	10.7%
	≥ 120 mins	11.1%
Duration (current area)	< 15 mins	43.2%
	15 - 30 mins	30.8%
	30 - 60 mins	12.9%
	≥ 60 mins	13.1%
Purpose	Public transport transfer	21.0%
	Social activity	6.6%
	Shopping	16.8%
	Rest	15.3%
	Leisure	10.7%
	Passing by	27.8%
	Other	1.8%

The proportions of respondents about their behavioral factors are shown in Table 4.7. It is generally assumed that the more frequently one is in the place the more familiar one is with the microclimate conditions and spatial settings. Since all surveys were conducted in public spaces of the city center (e.g., shopping area, transportation hub), a large proportion of respondents' visiting frequency is once a week or higher (more frequent than "scarcely"). Regarding outdoor duration, we inquired both the total duration of outdoor activities and the time spent in the area where the surveys were conducted. Over 78.1% of the respondents spent less than 1 hour in the outdoor environment, most of which only spent less than half an hour. As for the time spent in the studied areas, most respondents stayed less than half an hour. 43.2% of the respondents stayed for only 15 minutes.

The proportions of respondents' sensations of wind, humidity, sunlight, background sound pressure level and air quality, and their thermal sensation in the studied public spaces during the surveys are depicted in Figure 4.5. According to the diagram, 55.7% of the respondents' thermal sensations are on the cold side. 12.8% of the respondents felt very cold during the survey. Regarding humidity, 57.8% of the respondents felt dry. The number of respondents who thought the ambience was noisy exceeds the number of respondents who thought the surroundings were quiet. As for wind, more than half of the respondents sensed it was windy to some extent. Approximately 55% of the respondents felt the sunlight is not strong enough, more than half of them felt the sunlight was weak or even very weak. In addition, the majority of the respondents experienced fresh air quality.

As illustrated in Figure 4.6, respondents who preferred no change in the wind and sunlight conditions during their survey account for 30% of the respondents. The percentage respondents preferring higher wind speed equals the percentage of respondents preferring less wind speed. Respondents who want more sunlight are more than those who want to reduce sunlight. Furthermore, the proportions of respondents' assessment regarding comfort, and their acceptability and need satisfaction of outdoor activities are depicted in Figure 4.7. Most respondents thought the conditions were suitable for outdoor activities. Moreover, the majority of the respondents were satisfied with their outdoor activities. Although respondents vary in the sensation of environmental conditions and preferred wind and sunlight strength, most of their comfort assessment is falling on the comfortable side.

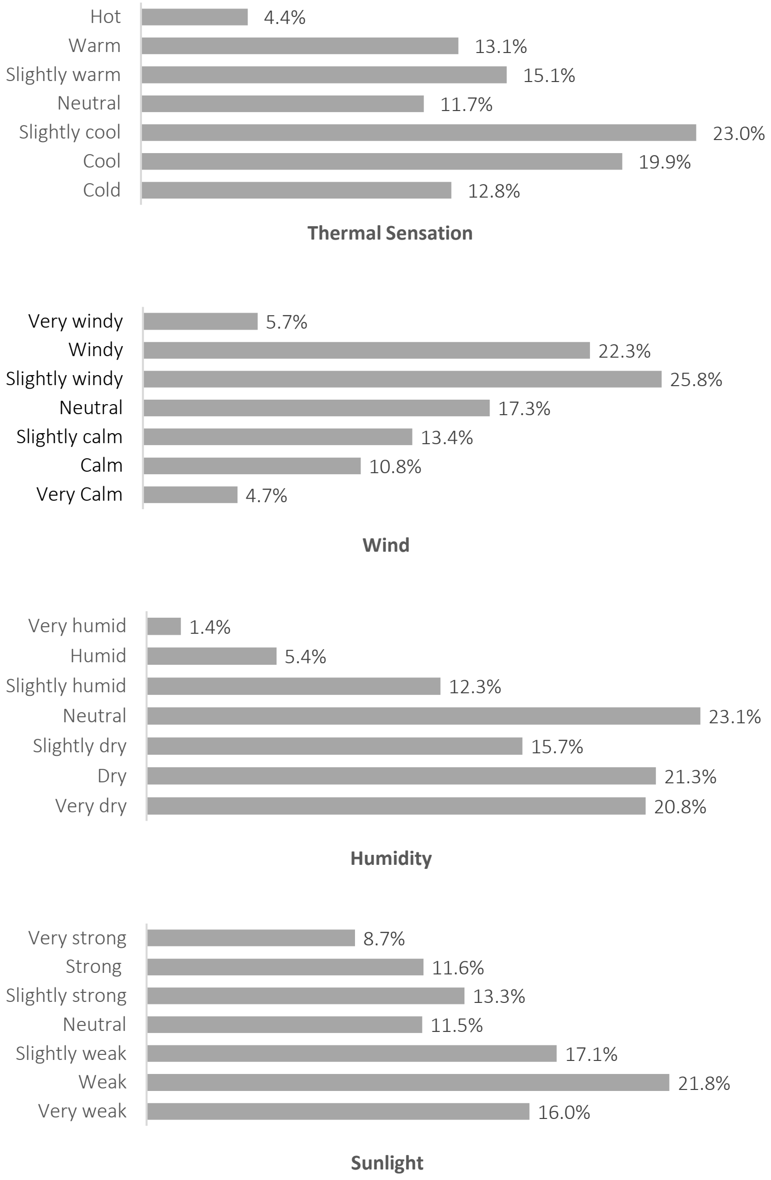
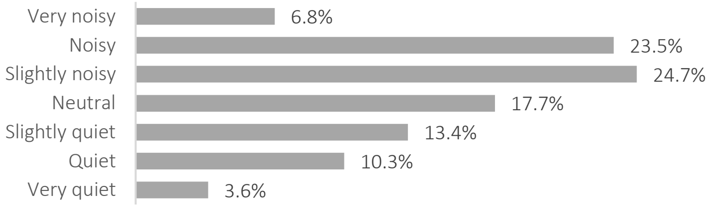
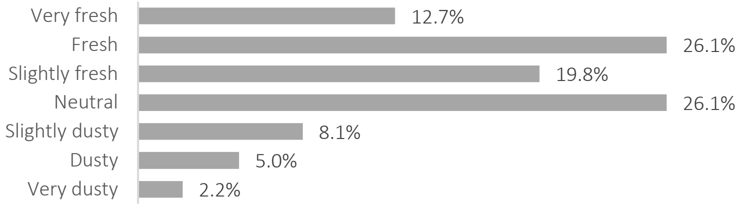


Figure 4.5 Proportion of respondents’ sensations of microclimatic and environmental conditions

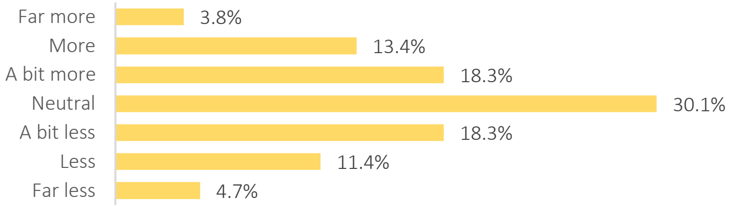


Sound pressure level

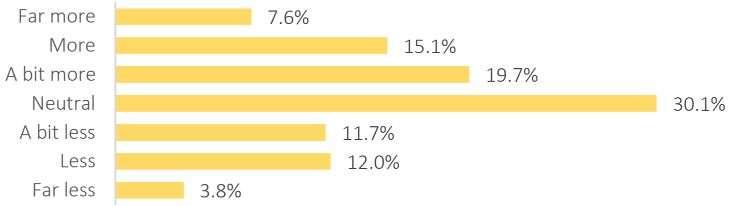


Air quality

Figure 4.6 Continued

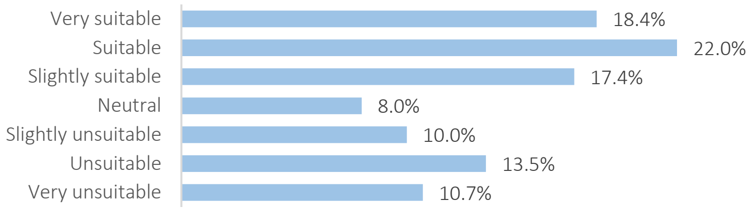


Wind

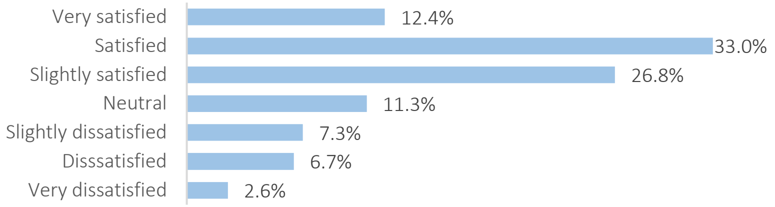


Sunlight

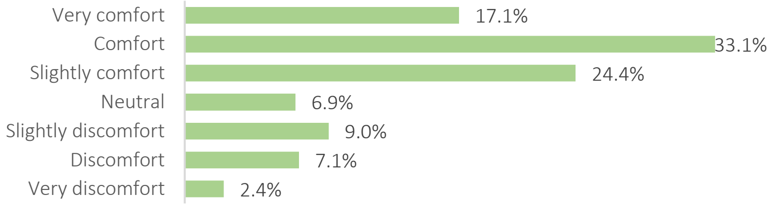
Figure 4.7 Proportion of respondents' preference of wind and sunlight



Acceptability of outdoor activites



Need satisfaction of outdoor activities



Comfort assessment

Figure 4. 8 Proportions of respondents' overall comfort assessments, and acceptability and need satisfaction of outdoor activity

4.5 Conclusions

This chapter provided information on the background of the case study city Eindhoven and the orthogonal design for the selection of study locations. Furthermore, the survey and measurement administration and the questionnaire design undertaken for survey have been introduced. The portable device for measuring meteorological variables and background sound pressure level was presented with the specifications and accuracy range of sensors.

The results of the descriptive statistics from the concurrent two types of data collection provide an overview of the microclimatic conditions and sound pressure level at the study locations, which is conductive to better understand the contextual conditions of respondents' comfort assessments. Moreover, respondents' profiles were discussed in terms of socio-demographic characteristics, body builds, and behavior related factors. The distributions of respondents' thermal sensations, perceptions and preferences of microclimatic and environmental stimuli, acceptability and need satisfaction of outdoor activities and their comfort assessments were presented. These data constitute the basis of the analyses reported in the next chapters.

5.

Linear and Nonlinear Relationships [1]

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[1] This chapter is based on Peng, Y., Feng, T., and Timmermans, H. (2019). Expanded comfort assessment in outdoor urban public spaces using Box-Cox transformation. Landscape and Urban Planning, 190, 103594.

5.1 Introduction

The heat balance theoretical model simplifies the mechanism of comfort assessment into a straightforward process flow from meteorological influences to physiological responses (Brager and de Dear, 1998). The importance of other environmental stimuli (e.g., sound, air quality and sunlight) as well as psychological and behavioral factors in the assessment of outdoor comfort has generally been downplayed (Chappells and Shove, 2005; Vischer, 2008; Rossi et al., 2015). Findings of previous field studies indicate that individuals’ mitigation or aggravation of discomfort depends on their personal background and local meteorological conditions, leading to an context-based adaptive modeling approach (Humphreys and Nicol, 1998). In line with this point of view, an implicit natural tendency of people to adapt to changing outdoor conditions has been addressed. Both psychological adaptation and behavioral adjustment improved the tolerance of individuals to a significant wide range of thermal conditions. Much progress has been made in terms of theory and practice with the introduction of the context-based adaptive approaches for different microclimates and environments, which indirectly integrates human thermal preference and emphasized the human behavioral reactions to avoid discomfort (de Dear and Brager, 1998; Potchter et al., 2018). Therefore, it is crucial to fully understand the mechanisms underlying outdoor comfort assessments considering both microclimatic and environmental conditions and human factors in accordance with conceptual framework with expanded set of explanatory variables.

In the heat-balance model, an individual is assumed as a passive recipient of environmental stimuli. From this point of view, the effects of given thermal conditions are mediated only by the physics of heat and mass exchanges between the body and the surrounding environment as well as physiological thermoregulation of human body. Thus, thermal comfort is supposed to emerge from the achievement of heat balance between human body and ambient thermal environment. The underlying postulates tends to hold in indoor settings. However, they are challenged when faced with outdoor situations. Due to the dynamic and non-uniform microclimatic and environmental conditions in urban public spaces, the heat flow to and from the human body may not be balanced. Heat-balance theory lacks a coherent explanation to account for people's responses to outdoor conditions since it ignores the effects of psychological and behavioral factors (Stathopoulos et al., 2004; Lin and Matzarakis, 2008). Evidenced by the results of numerous field studies, although the effects of microclimatic stresses can in part be predicted by physiological indices, still substantial difference remains between actual and predicted comfort assessment one when applying the heat balance-based thermal index to naturally ventilated buildings. There are even less reasons to assume this will not be the case in outdoor environments. Thus, the heat balance theory and related indices have been criticized for the lack of universal applicability and its strict reliance on “ideal” conditions along with ignoring contextual attributes and human psychological and behavioral processes that influence comfort and the process of measuring outdoor comfort.

In addition, the equivalence of thermal comfort and neutral thermal sensation was challenged since the concept of “Alliesthesia” was addressed to differentiate thermal pleasure from thermal neutrality (Michel, 1971; Spagnolo and de Dear, 2003a; Liu et al., 2020). The existing methods which treat a neutral or acceptable thermal condition as a substitute of a comfortable condition has also been criticized since evidence was found that the temperature that people preferred was different from their neutral temperature (Cheung and Jim, 2017). Thus, more broadly, the attainment of physiological thermal comfort cannot be simply assumed to be equal to psychologically comfortable (Indraganti and Rao, 2010).

5.2 Conceptual framework

As mentioned in previous chapters, we argue that a conceptual framework with an expanded set of influential factors is required to facilitate comprehensively understanding and better predicting the assessment of comfort in complex urban public spaces. In more detail, all the potential causal effects of psychological and behavioral factors are expected to be incorporated and considered in the modeling process. According to the literature, numerical analysis of the integrated impact of diverse non-thermal behavior factors is still rare. No studies to date have systematically examined the influence of individuals' socio-demographic characteristics, emotional status, expectations, preferences and outdoor behaviors (Langevin et al., 2013). Furthermore, linear effects of multiple variables have been challenged since changes of some variables may lead to variance in comfort assessment. Therefore, based on the proposed theoretical framework, the linear and nonlinear modeling approaches of comfort assessment taking into account a broader range of explanatory factors are presented in the following sections of this chapter. Given the diversity of outdoor environments and the variability of individuals’ psychological and socio-demographic characteristics, the opportunities and constraints of physical, social, and behavioral contexts may affect comfort.

On the other hand, microclimate in public spaces is characterized by a number of physical attributes (e.g., air temperature, relative humidity, wind speed, mean radiant temperature) which, in effect, are perceived by occupants individually with their own bias. In addition, we suppose that, before getting to a specific public space, an individual already formed prospective microclimatic and environmental conditions based on his/her own knowledge, experience, and information. This expected scenario was accordingly set as a cognitive reference within a local institutional acclimatization and experience (Lenzholzer, 2010; Lenzholzer and Koh, 2010; Lenzholzer and van der Wulp, 2010). Apparently, the physical spatial settings of public spaces offer both potential opportunities and constraints for individuals' adaptation. If people feel really discomfort in a certain outdoor open space, they will leave immediately. Following this line of reasoning, people’s visiting purposes, transportation modes and duration of outdoor exposure may affect their comfort assessment. Moreover, with intention and forethought, people set goals and anticipate likely outcomes of prospective outdoor conditions and their actions. However, these were rarely investigated in existing studies.

Compared with the traditional heat balance model, the hypothetical relationships between comfort assessment and influential factors in the multiple linear model and nonlinear model are expanded to consider human comfort from a wider perspective by incorporating physiological bodily sensation with a holistic perception in terms of person-related and place-related factors. The relative importance of diverse influences on comfort assessment was systematically examined. The simple cause-effect process in the conventional heat balance model was substituted by taking mediating effects of human psychological and behavioral influences into account. When implementing outdoor activities, people normally have a special need and preference within a particular outdoor setting. Their comfort assessments are the outcome of the interaction between individual expectations and preferences and the opportunities and constraints induced by specific microclimatic and temporal-spatial settings within a particular socio-cultural context.

In summary, comfort assessment in real-world outdoor urban environments represents a comprehensive judgment process in which individuals consider and realize their needs and preferences within a given urban temporal-spatial setting. The assessments related to comfort assessment of occupants in public spaces are based on their own experience and is related to specific purposes and corresponding outdoor behavior. In addition, their adaptation takes place with the specific outdoor activities in public spaces. Thus, we assume the underlying process of comfort assessment is determined by various hypothetical impacts (see Figure 5.1). Some person-related variables, like socio-demographics, emotional status, visiting purpose, transportation mode and experienced thermal condition characterize individual's own expectation and preference. These variables are dynamic, and the values may continue updating

when interacting with their surroundings. The adaptation which makes better comfort assessment is also involved from the interaction with environments. In this regard, comfort assessment is not treated as a static and independent process, but rather as the temporary outcome of a series of experience and consequent adaptation resulted from psychological and behavioral aspects.

5.3 Multiple linear regression

Based on the comprehensive conceptual framework with an expanded set of influential factors, we take both microclimatic and environmental variables and human factors into account in the multiple linear regression. The explanatory variables were expanded compared with the previous models of thermal sensation or neutral temperature of adaptive models. With the multiple linear regression, a quantitative analysis has been conducted to reveal the effects of various aspects of outdoor environments and respondents themselves. Hence,

$$y_i = \beta_0 + \sum_{k=1}^{n} \beta_k x_{ik} + \varepsilon \tag{5.1}$$

where y_k is the value of overall comfort through the face-to-face interview for person i, β_0 is the constant, β_k is a parameter of the kth factor, x_{ik} denotes the kth variable for person i which includes the physical features of a public space and respondents' information of socio-demographic, psychological and behavioral aspects.

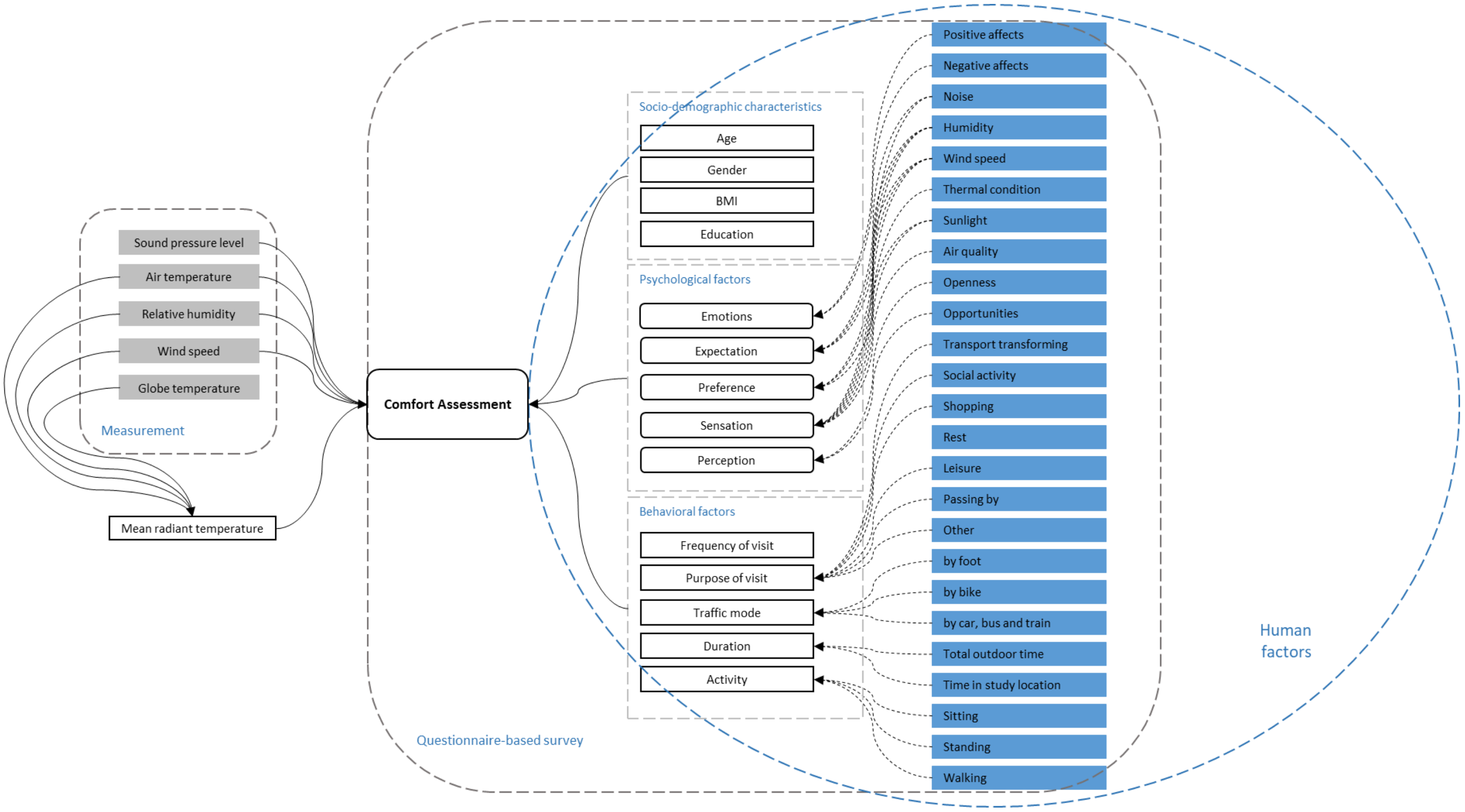

Figure 5.1 Diagram of influence of expanded human factors on comfort assessment

5.4 Nonlinear model with Box-Cox transformation

To explain and elaborate the effects of explanatory variables on the individuals' responses of comfort assessment, the multiple linear regression was the first choice of modeling method. However, this approach is limited in its linearity of the relationship between outdoor comfort and explanatory variables. To better understand the potential nonlinear relationship between comfort assessment and predictors, the Box-Cox transformation (Box and Tidwell, 1962) is employed on explanatory factors. As the estimation follows a stepwise procedure, only the variables with a reasonable t-value of coefficient β and λ could be transformed and remained. Ultimately, the nonlinear regression model with the transformation was developed and estimated using the maximum likelihood algorithm. The formulas of the regression model with Box-Cox transformation are presented below:

$$y_k = \beta_0 + \sum_{k=1}^{n} \beta_k x'_{ik} + \varepsilon' \tag{5.2}$$

$$x'_{ik} = \begin{cases} \dfrac{x_{ik}^{\lambda} - 1}{\lambda}, & \lambda \neq 0 \\ ln\, x_{ik}, & \lambda = 0 \end{cases} \tag{5.3}$$

where the dependent variable y_k is comfort assessment for person i, β_0 is the constant term, β_k is a coefficient of the k th explanatory factor, x'_{ik} is the k th Box-Cox transformed independent variable for person i, ε' is an error term and λ is the coefficient of the Box-Cox transformation.

5.5 Results and discussion

5.5.1 Linear relationships

The estimates of the multiple linear regression are illustrated in Table 5.1. As important variables of outdoor thermal conditions, wind speed and mean radiant temperature have a significant influence on comfort assessment in urban public spaces. During the fieldwork in the shoulder season of the Netherlands, the average air temperature measured is 16 °C, which is far from the state of an uncomfortable hot temperature. The negative coefficient of wind velocity indicates that the faster the wind speed, the less comfort people feel in outdoor environments. In contrast, the mean radiant temperature has a positive impact on comfort. This is understandable because the mean radiant temperature affects the thermal loading, indicating that a higher heat loading may lead to more comfort in the context of local climate. However, the effect of mean radiant temperature on comfort assessment is not very significant. In case of the air temperature and relative humidity, no significant effects were found. With respect to the acoustic environment, no linear relation was found between sound pressure level and the overall comfort assessment.

Table 5.1 Estimation results of the multiple linear regression model

Variable	β	*p*-value
(Constant)	2.768**	0.04
Air temperature	0.012	0.78
Relative humidity	0.001	0.90
Wind speed	-0.175*	0.07
Mean radiant temperature	0.011*	0.09
Sound pressure level	-0.005	0.50
Age	-0.005	0.18
Gender	0.301***	0.01
BMI	0.012	0.44
Education	-0.136***	0.00
Positive affects	0.042***	0.00
Negative affects	-0.039***	0.00
Visiting frequency	0.117***	0.01
Siting	0.059	0.69
Standing	-0.034	0.85
Expected thermal sensation	0.075**	0.04
Expected humidity	0.093***	0.01
Expected wind velocity	-0.100***	0.01
Expected sound pressure level	0.072**	0.04
Perceived openness	0.186***	0.00
Perceived opportunities	0.032	0.34
Total outdoor duration	-0.102***	0.01

* $0.05 < p < 0.1$; ** $0.01 < p \leq 0.05$; *** $p \leq 0.01$

Table 5.2 Continued

Variable	*β*	*p*-value
Perceived humidity	-0.099***	0.01
Perceived wind speed	-0.125***	0.00
Perceived sunlight	0.152***	0.00
Perceived sound pressure level	-0.082**	0.03
Perceived air quality	0.079**	0.03
Preferred thermal sensation	-0.044	0.26
Preferred humidity	0.010	0.82
Preferred wind velocity	0.093***	0.01
Preferred sunlight	0.074**	0.05
By foot	-0.303**	0.02
By bike	-0.089	0.53
Transit	-0.068	0.86
Resting	0.040	0.92
Social	-0.100	0.81
Shopping	0.246	0.53
Leisure	-0.062	0.88
Passing by	-0.042	0.92

* $0.05 < p < 0.1$; ** $0.01 < p \leq 0.05$; *** $p \leq 0.01$

As for the respondents' socio-demographic characteristics, age, gender, BMI, and education level were utilized in the multiple linear regression. According to the result, no significant impact of age and BMI were found. The gender of the respondent significantly affects their overall comfort assessment, which indicates that males express a higher degree of comfort than females. Likewise, the difference in thermal sensation between males and females under similar boundary conditions has been explained in previous studies (Indraganti and Rao, 2010; Karjalainen, 2012). In addition, the negative relationship between education level and overall comfort was identified. People with higher education levels are inclined to express a lower degree of overall comfort in outdoor conditions.

Unlike the previous modeling approach of outdoor comfort assessment, in this study, people's emotions and other psychological variables pertaining to the exposures in environments of study locations have been quantitatively introduced and measured in line with the comprehensive conceptual framework with the expanded set of effects. Results show that both positive affect and negative affect of respondents significantly and consistently impact comfort. In other words, a more positive emotion leads to a higher level of comfort assessment, while a negative emotion results in a lower comfort assessment. From the perspective of human psychological adaptation, a positive emotion may promote potential adaptation by enhancing people's tolerance and enlarging the range of conditions perceived comfortable.

More importantly, evidence shows that if people expected warmer thermal sensation, higher humidity, and louder background sound pressure level before arrival, they were more likely to feel comfortable. Additionally, if people expected higher outdoor wind speed, they tend to have a lower comfort assessment. This may be because strong wind is always irritating. However, results show the preferred wind speed has a positive relationship with comfort assessment, which indicates that those who prefer higher wind speed felt more comfortable. In the meantime, respondents' preference of sunlight is positively related to their comfort evaluation. No significant effects on comfort assessment were found with respect to respondents' preference of thermal sensation and humidity.

With respect to behavioral aspects, we considered variables such as visiting frequency, transportation modes (categorized as by foot, by bike considering by public transport and private car as the reference), purpose of being in the surveyed outdoor space (categorized as transit, resting, social or cultural activity, shopping, leisure, passing by considering other as the reference), and total duration of outdoor activity. As shown, many behavioral variables are statistically significant. The positive estimate of visiting frequency indicates that the more frequent a respondent visits the studied area the higher the perceived comfort. This is understandable considering the fact that comfort assessment could depend on how well people know the place. In addition, respondents who either stay longer in the outdoor environment or come by foot tend to have a lower comfort assessment. It means that longer duration of the stay or walking a lot has a negative effect on comfort assessments.

Furthermore, the effects of the perceived spatial attributes are revealed. The representative variables are subjective evaluation of opportunities provided by urban facilities and perceived openness of the public space. It is found the perceived openness has a significant influence on comfort whereas a positive correlation exists between acceptable openness and comfort assessment. If the building blocks enclose a public space to an unacceptable extent, it may cause a negative effect on users' comfort. Overall, the explanatory variables show an acceptable goodness-of-fit (adjusted R^2 = 0.335). More importantly, results of the expanded linear model show that most psychological behavior variables have a significant effect on assessment of outdoor comfort. This confirms our original assumption and the expanded conceptual framework.

5.5.2 Nonlinear effects

The estimation results of nonlinear modeling using the Box-Cox transformation are presented in Table 5.2. It shows that the significance of most explanatory variables is improved in the nonlinear model relative to the multiple linear regression model. A remarkable boosting of the t-value related to β took place for wind velocity and sound pressure level related to the physical attributes of public spaces, as well as age and body mass index which are related to the respondents. A λ which is not equal to 1 means that the related explanatory variable take on a specific transformation. For example, the transformation of wind speed approximates the logarithm (λ =0), while for mean radiant temperature it is close to a power function (λ =-2.08). In addition, both age and body mass index have significant negative effects on comfort, which indicates that the elderly and people with a higher body mass index feel less comfortable. However, in the linear regression model, body mass index had little impact on comfort evaluation. Nevertheless, the conclusion regarding the negative effects of body mass index is in line with the results found in previous studies that also found the increase of body mass index can reduce the value of thermal sensation to some extent (Tuomaala et al., 2013).

The nonlinear model with the Box-Cox transformation yields a slightly better goodness-of-fit (adjusted R^2=0.361) than the multiple linear regression model. This means the actual outdoor comfort assessment, as a result of respondents' mental activities and judgements, may be better linked to the variables of the environment and human factors, in a nonlinear way.

Table 5.3 Estimation results of nonlinear regression with Box-Cox transformation

Variable	β	p-value	λ	*p*-value
(Constant)	62.389***	0.00	1	N/A
Air temperature	0.028	0.30	1	N/A
Relative humidity	0.003	0.37	1	N/A
Wind speed	-0.311***	0.01	0.00*	0.06
Mean radiant temperature	0.011*	0.06	1	N/A
Sound pressure level	-0.327***	0.00	0.02***	0.00
Age	-41.468***	0.00	-1.49***	0.00
Gender	0.306***	0.01	1	N/A
BMI	-45.174***	0.00	-2.35***	0.00
Education	-0.347***	0.00	-0.27***	0.00
Positive affects	15.201***	0.00	-0.76***	0.00
Negative affects	-49.265***	0.00	-1.59***	0.00
Visiting frequency	0.119**	0.02	1	N/A
Siting	0.044	0.38	1	N/A
Standing	0.077	0.36	1	N/A
Expected thermal sensation	0.090*	0.07	0.69	0.24
Expected humidity	0.088	0.01	1	N/A
Expected wind velocity	-0.030**	0.00	1.85***	0.00
Expected sound pressure level	0.061**	0.08	1	N/A
Perceived openness	0.920***	0.00	-0.14***	0.00
Perceived opportunities	0.06	0.21	0.50	0.29
Total outdoor duration	-0.083***	0.05	1	N/A
Perceived humidity	-0.210***	0.00	0.38**	0.02
Perceived wind speed	-0.126***	0.00	1	N/A
Perceived sunlight	0.590***	0.00	-0.29***	0.00
Perceived sound pressure level	-0.260**	0.02	0.14***	0.00
Perceived air quality	0.240**	0.02	0.21***	0.01
Preferred thermal sensation	-0.032	0.28	1	N/A
Preferred humidity	0.002	0.40	1	N/A

* $0.05 < p < 0.1$; ** $0.01 < p \leq 0.05$; *** $p \leq 0.01$

Table 5.4 Continued

Variable	β	p-value	λ	*p*-value
Preferred wind velocity	0.889***	0.00	-0.91***	0.00
Preferred sunlight	0.070*	0.07	1	N/A
By foot	-0.318**	0.02	1	N/A
By bike	-0.144	0.24	1	N/A
Transit	-0.272	0.31	1	N/A
Resting	-0.044	0.40	1	N/A
Social	-0.173	0.37	1	N/A
Shopping	0.185	0.36	1	N/A
Leisure	-0.142	0.38	1	N/A
Passing by	-0.165	0.37	1	N/A

* $0.05 < p < 0.1$; ** $0.01 < p \leq 0.05$; *** $p \leq 0.01$

5.5.3 Elasticity analysis

To further explore the variables' contribution in predicting outdoor comfort assessment in urban public spaces, an elasticity analysis was conducted. The results are shown in Table 5.3. We found that some human factors have a relatively larger elasticity, such as emotional status, perception of openness of public space, sensation of wind velocity and sunlight exposure. This means the change of values of these variables will have a larger effect on comfort assessment than other variables.

5.6 Conclusions

The comprehensive conceptual framework of comfort assessment in urban public spaces with an expanded set of influential factors was estimated using a multiple linear regression model and a nonlinear model with the Box-Cox transformation. The models incorporate both physical environment attributes and human psychological and behavioral factors. The methodology proposed in this chapter can be applied in various climate zones and diverse cultural contexts.

The model results provide convincing evidence that the mechanism of comfort assessment is beyond a single energy exchange dimension. The linear relationship between comfort and an expanded set of factors was verified, and later the nonlinear relationship was demonstrated using a Box-Cox transformation. To the best of our knowledge, this is the first study to develop such a numerical comprehensive model with an extended set of explanatory variables in outdoor comfort research. The findings provide more insights in the actual assessment of outdoor comfort. The social-economic characteristics significantly affect comfort assessment, so does emotional status. The psychological and behavioral factors were also found to play an important role in comfort assessment.

Table 5.5 Elasticity of significant explanatory variables

Explanatory variables	Linear	Non-linear
Wind velocity	-0.05	-0.06
Mean radiant temperature	0.06	N/A
Sound pressure level	N/A	-0.07
Age	N/A	-0.06
BMI	N/A	-0.01
Positive affects	0.24	0.23
Negative affects	-0.12	-0.13
Visiting frequency	0.09	N/A
Expected thermal sensation	0.09	0.04
Expected wind velocity	-0.03	-0.09
Expected humidity	0.06	N/A
Expected sound pressure level	0.07	N/A
Total outdoor duration	-0.05	N/A
Preferred wind velocity	0.07	N/A
Preferred sunlight	0.06	N/A
Perceived openness	0.20	0.14
Perceived wind velocity	-0.11	N/A
Perceived humidity	-0.06	-0.06
Perceived sunlight	0.11	0.08
Perceived sound pressure level	-0.07	-0.06
Perceived air quality	0.08	0.07

6.

Direct and Indirect Relationships [2]

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[2] This chapter is based on Peng, Y., Feng, T., and Timmermans, H. (2019). A path analysis of outdoor comfort in urban public spaces. Building and Environment, 148, 459–467.

6.1 Introduction

The diverse and complex context of urban public spaces and their spatial settings with the corresponding microclimate faced by individuals are driving an increasing need for a full understanding of outdoor comfort. Still, people have different perceptions and preferences when they are exposed to different environments, despite having identical thermal balances indicated by heat balance theory. In this regard, comfort is an outcome of the interaction between an individual's preferences and perceived opportunities and constraints induced by specific outdoor microclimate and temporal-spatial urban settings within a particular institutional and local context.

A qualitative method linking thermal and spatial information and people’s perceptions has been developed (Lenzholzer et al., 2018). The divergence between thermal index and actual response in field studies show that an individual’s thermal expectation and preference induced by contextual factors are specific to different urban settings and corresponding microclimates. The heat-balance indices may not be universally applicable across contexts (Lin et al., 2011). The importance of physical, physiological and psychological influential aspects have been addressed by several empirical in-situ investigations based on either heat balance theory or adaptive approaches (Brager and de Dear, 1998; Knez et al., 2009; Lin et al., 2011). However, the direct causal relationships between comfort and influences have been modelled without considering psychologically mediated effects. Still, the mechanism of the influence on comfort was simplified as one single step from the triggering factors to direct assessment. Few studies investigate the indirect effects that are different from the cause-effect process (Knez et al., 2009; Chan et al., 2017). Systematically investigating the perceptual mechanism of comfort assessment therefore becomes necessary and critical (Lenzholzer, 2012).

This chapter therefore aims to outline an expanded and integrated conceptual framework that illustrates comfort assessment in non-uniform and unsteady outdoor environments by considering the nature and strength of both direct and indirect influences. The simplified causal relationships are modelled through path analysis discovering the intermediary function of related psychological factors. The path analysis entails the comfort assessment by both physical microclimate conditions and human factors in a structured process (e.g., emotional status, perceived meteorological situations and urban spatial settings). We contend that outdoor comfort cannot be viewed as only a manifestation of neutral status in heat balance, but rather the outcome of a perceptual process associated with respondents' expectations and preference formed by their outdoor behaviour, thermal experience, socio-demographic characteristics, and emotional status, which are influenced by experiences implementing behavioural adjustments and psychological adaptations. Thus, we utilise the acceptability and need satisfaction of outdoor activities as two mediators. The microclimate and other environmental stimuli perceived by individuals are related to the degree of their acceptability and the satisfaction of outdoor activities. As such, the new approach is consistent with the basic premise underlying the development of path analysis to replace the traditional methodology by explicitly taking into account both direct and indirect effects.

6.2 Conceptual framework

Comfort assessment is conceptualized as a process in which individuals attempt to adapt themselves and satisfy the particular need in outdoor environments, given a microclimate and perceived temporal and spatial constraints with their own experience. A conceptual structure of the direct and indirect effects on comfort is presented in Figure 6.1. Based on the hypothesis, the paths have been set up to include the connections between the endogenous variables and the influences from the exogenous variables. Through existing investigations, we predefine the relationships between comfort assessment and the acceptability and need satisfaction of outdoor activities. In addition, the endogenous variables are impacted by the manifold exogenous variables in terms of place-related attributes (e.g., microclimate condition, environmental stimuli) and human-related factors (e.g., social demographics, preference, and perception of environment). The hypothesized connections are illustrated in Table 6.1. Having identified the relationships, a maximum likelihood estimation method was used to estimate the parameters.

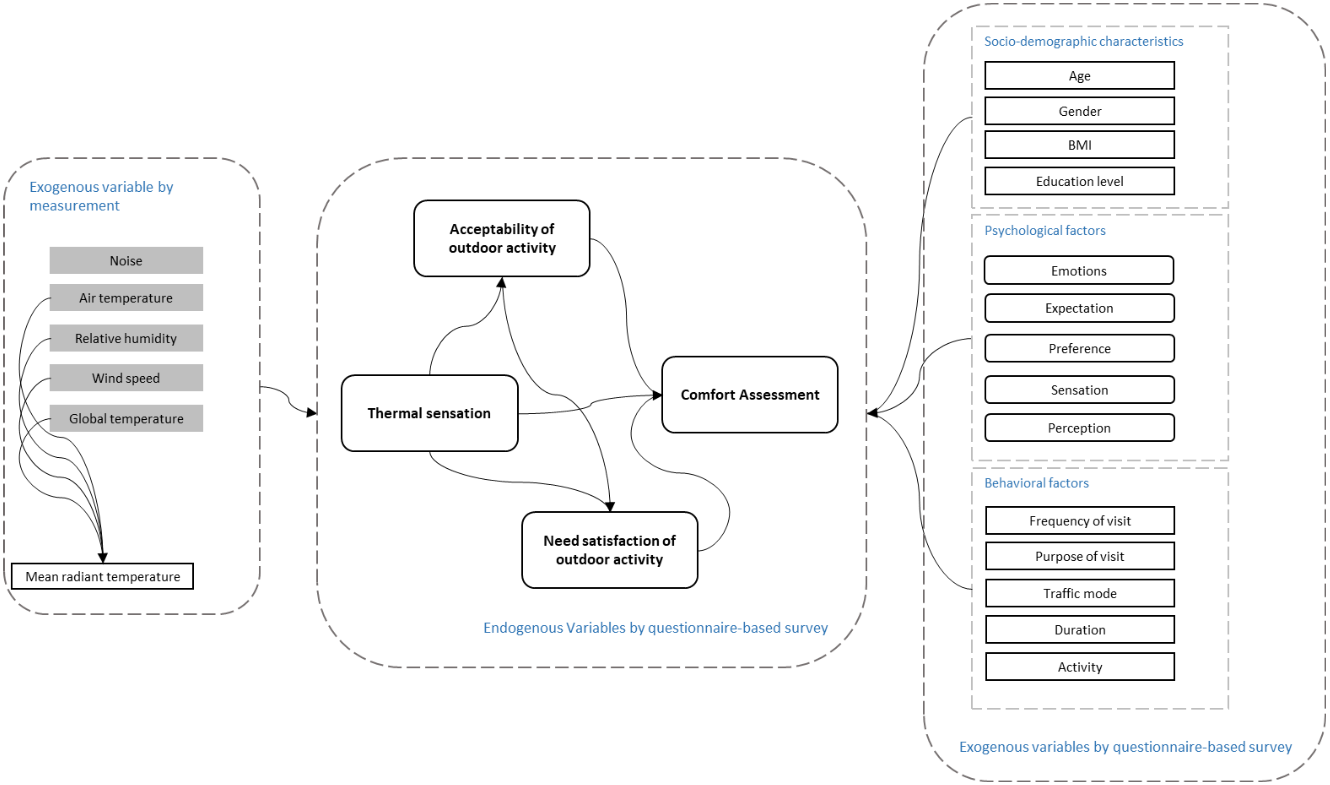

Figure 6.1 Diagram of conceptual framework with direct and indirect relationships

Table 6.1 Hypothetical relationships

Endogenous variables	Exogenous variables
Thermal sensation	socio-demographic characteristics
	behavior factors
	perception of wind, humidity, and sunlight
	physical microclimate
Acceptability of outdoor activity	expectation of thermal and wind condition
	perception of wind, humidity, and sunlight
	perceived adaptive opportunity
	physical microclimate
	Thermal sensation
Need satisfaction of outdoor activity	socio-demographic characteristics
	emotional status
	environment propensity
	behaviour factors
	preference of wind and sunlight
	perception of sound pressure level and air
	adaptive preparation
	Thermal sensation
	Acceptability of outdoor activity
Comfort	Thermal sensation
	Acceptability of outdoor activity
	Need satisfaction of outdoor activity
	socio-demographic characteristics
	emotional status
	expectation of thermal and wind condition
	perception of sound pressure level and air
	perception of spatial attribute
	preference of wind and sunlight
	behaviour factors

6.3 Path analysis

Path analysis is an extension of multiple regression analysis, which is regarded as a special case of structural equation modeling (SEM) (Streiner, 2005). As SEM deals with both measured and latent variables, path analysis deals with observed variables only. In this study, path analysis is utilized to estimate the magnitude and significance of hypothetical relationships between comfort and sets of variables related to physical microclimate and individuals' socio-demographic characteristics, emotional status, expectations and perceptions of microclimate and environment condition, along with relevant behavioral factors.

The dependent variable in the path analysis is individuals' outdoor overall comfort assessment, which is different from the thermal sensation. Further, we believe that, to conduct outdoor activities, individuals need to be involved in active interactions with the urban environments. If the experience of a location does not satisfy the expectation, the individual will continue to adapt themselves. However, if the adaptation is repetitively constrained, the assessment may be negative. Individuals may still be pleased with the experience although the unpleasant experiences accumulated could reinforce that individual's perception.

The path analysis aims to overcome the potential shortcoming in conventional models, e.g., linear regressions by transforming the causal influences into direct and indirect effects. These possible relationships and their strength are cornerstones of the comfort assessment mechanism and must be revealed by path analysis. For example, we postulate that microclimate affects comfort assessment through thermal sensation and the acceptability of outdoor activities. The time individuals spend in outdoor environments may have potential impacts on comfort. We assume that there are relationships between the overall outdoor comfort and individuals' thermal sensation, thermal acceptability and need satisfaction of outdoor activities. In addition, the integrated exogenous influences, such as microclimate condition, individuals' socio-demographic characteristics, behavior factors, emotional status and subjective perception of urban settings and corresponding microclimate and environment attributes are also investigated.

6.4 Results

As demonstrated in Table 6.2, the path model is testified as a good-fitting model based on the values of the Comparative Fit Index (CFI) and Tucker Lewis Index (TLI), which are greater than the empirical cut-off criterion (Bentler and Bonett, 1980). Further, the Standardized Root Mean Square Residual (SRMSR) is far less than 0.08. The value of Root Mean Square Error of Approximation (RMSEA), which measures the discrepancy per degree of freedom, is smaller than the empirical threshold, 0.05. In summary, the structure of the direct and indirect relationships is proved as significant.

Results of the intercepts of endogenous variables are shown in Table 6.3. The coefficients of all direct and indirect connections are presented in Table 6.4 with the level of significance. Based on the estimation results, a majority of the exogenous variables have indirect impacts on comfort assessment through mediators. Still, there are some variables that have both significant direct and indirect effects.

The microclimatic variables, such as air temperature, wind velocity and relative humidity, show significant indirect influence on comfort. However, the mean radiant temperature has no noteworthy effect. In particular, air temperature significantly impacts an individual's outdoor thermal sensation. The direct relationship between air temperature and the acceptability of outdoor activity was also investigated, whereas no evident effect was found. In contrast, relative humidity slightly influences acceptability of outdoor activity in a negative way, but it does not act on thermal sensation. Regarding the influence of wind, it is reasonable that wind velocity negatively impacts respondents' thermal sensations and their acceptability of outdoor activity because the data collections were carried out in the early spring with relatively low average air temperature. In addition, in the context of Dutch historical meteorology, wind turbulence has been always criticized as an annoying phenomenon, especially in the cold and cool seasons. To speak of mean radiant temperature, as a physical meteorological influence, although it is the most decisive determinant in some traditional thermal indices, in this model, only a negligible effect was revealed with a low significant level according to the estimate for both thermal sensation and the acceptability of outdoor activity.

Regarding socio-demographic characteristics, the influences of age, sex and education level have been demonstrated through the path model. As shown in Table 6.4, a significant negative direct connection was found between age and thermal sensation. In the context of the cold season in Eindhoven, senior interviewees responded to the thermal sensation tending to the colder side, as they may have a narrower range of neutral thermal sensation than younger respondents and may be more sensitive to any deviation from an optimal environment and express more discomfort through thermal sensation. Nevertheless, we only interviewed individuals between 13 and 85. The influence of age on juveniles and children needs further investigations.

The education level of respondents is confirmed to have only a direct negative impact on comfort assessment, while sex has both direct and indirect connections with comfort assessment. The indirect effect is imparted by the mediator of the need satisfaction of outdoor activity. Respondents with a higher education level had a lower comfort level. In addition, the male was inclined to have a more comfortable feeling than the female in an outdoor environment and felt more satisfaction in outdoor activity. A growing number of studies have found significant differences in thermal comfort between sexes and many field studies showed that females express more discomfort than males, especially in cool conditions (Karjalainen, 2012), which is similar to the result of the current path analysis. The emotional status of respondents was investigated in the survey by the standard method and represented as positively or negatively affecting comfort. Both emotional aspects were connected with need satisfaction and comfort assessment. Positive effects may increase the satisfaction and comfort, while negative effects may reduce com- fort. The preference to urban settings or natural environments was taken into account as a determinant. Respondents who prefer an urban setting are more satisfied compared with those who are keen on a natural scene.

Table 6.2 Indices for Goodness of fit of the path analysis

CFI	TLI	SRMSR	RMSEA
0.935	0.889	0.014	0.043

Table 6.3 Estimation of the intercepts

Variable	Intercept	Standard Error	*p*-Value
Thermal sensation	2.339	0.816	0.004
Acceptability of outdoor activity	5.892	0.963	0.000
Need satisfaction	1.218	0.578	0.035
Comfort	1.254	0.442	0.005

Table 6.4 Estimation results of the path model

Variable	Estimate	Standard Error	p-Value
Thermal Sensation on			
air temperature	0.159***	0.039	0.000
wind speed	-0.267***	0.083	0.001
relative humidity	0.004	0.007	0.588
mean radiant temperature	0.005	0.006	0.378
Age	-0.006*	0.004	0.097
sitting	0.263**	0.114	0.021
standing	0.352**	0.145	0.016
by foot	-0.308***	0.113	0.007
by bike	-0.054	0.128	0.676
perceived wind speed	-0.131***	0.032	0.000
perceived humidity	-0.058*	0.031	0.059
perceived sunlight	0.249***	0.030	0.000
total outdoor duration	-0.197***	0.037	0.000
Acceptability of outdoor activity on			
air temperature	-0.052	0.045	0.249
wind speed	-0.263***	0.095	0.006
relative humidity	-0.050***	0.008	0.000
mean radiant temperature	0.004	0.007	0.576
prospective thermal sensation	0.168***	0.040	0.000
prospective wind speed	0.060*	0.037	0.106
perceived opportunity	0.076**	0.035	0.032
perceived wind speed	-0.065*	0.039	0.095
perceived humidity	-0.064*	0.036	0.075
perceived sunlight	0.146***	0.037	0.000
Thermal sensation	0.265***	0.045	0.000
Need Satisfaction of outdoor activity on			
gender	0.205***	0.102	0.044
environmental preference	-0.046*	0.026	0.080
positive affects	0.026***	0.007	0.000
negative affects	-0.033***	0.010	0.001
by foot	-0.496***	0.122	0.000
by bike	-0.132	0.134	0.326

* 0.05< p < 0.1; ** 0.01< p ≤ 0.05; *** p ≤ 0.01

Table 6.4 Continued

Variable	Estimate	Standard Error	*p*-Value
Need Satisfaction of outdoor activity on			
waiting for bus or train	0.462	0.374	0.216
resting	1.000***	0.385	0.009
social activity	0.234	0.410	0.569
shopping	0.901**	0.377	0.017
leisure	0.789**	0.390	0.043
passing by	0.910**	0.380	0.017
perceived spatial openness	0.145***	0.036	0.000
adaptive adjustment	0.491***	0.146	0.001
total outdoor duration	-0.128**	0.051	0.012
duration in current place	0.197***	0.064	0.002
perceived air quality	0.096***	0.035	0.006
perceived sound pressure level	-0.066**	0.032	0.041
preference of wind speed	0.083***	0.034	0.014
Thermal sensation	0.211***	0.035	0.000
Acceptability of outdoor activity	0.117***	0.031	0.000
Comfort on			
gender	0.263***	0.091	0.004
education level	-0.144***	0.034	0.000
visiting frequency	0.079**	0.038	0.037
positive affects	0.029***	0.006	0.000
negative affects	-0.032***	0.009	0.000
prospective thermal sensation	-0.074**	0.032	0.020
prospective wind speed	-0.101***	0.028	0.000
perceived air quality	0.088***	0.031	0.004
perceived sound pressure level	-0.059**	0.029	0.040
preference of wind speed	0.071**	0.030	0.020
preference of sunlight	0.048*	0.029	0.097
perceived spatial openness	0.127***	0.031	0.000
Thermal sensation	0.303***	0.034	0.000
Acceptability of outdoor activity	0.130***	0.028	0.000
Need satisfaction	0.246***	0.032	0.000

* $0.05 < p < 0.1$; ** $0.01 < p \leq 0.05$; *** $p \leq 0.01$

In case of behavior-related factors, results show that respondents with a motion state of sitting and standing before the interview were inclined to experience a warmer sensation, compared with those who were walking. With regard to the transportation mode, in particular, walking negatively influenced thermal sensation and the need satisfaction of outdoor activities compared with biking and taking private vehicles or public transportation. Biking, as a popular transportation mode for daily life, has no observable difference compared with taking a private automobile or public transportation. Further, the indirect impacts of walking on comfort assessment are through thermal sensation and need satisfaction. In addition, in terms of time spent in the outdoor environment, the duration of the whole series of outdoor activities influences both thermal sensation and the need satisfaction. People who spent more outdoor time rated lower thermal sensation and need satisfaction; however, the respondents who stayed longer in the studied public space facilitated their rating of need satisfaction of outdoor activity. The purpose of people's outdoor activity for resting, shopping, leisure and passing positively affects their comfort through need satisfaction. The frequency of visiting was proved to have a positive connection with comfort assessment. People who visited the place more often are in favor of a more comfortable assessment. According to the results of previous investigations, the long-term memory and cognitive schemata of particular spatial settings and microclimatic variables play a role in individual's comfort assessment (Lenzholzer 2012; Lenzholzer and Koh 2010; Lenzholzer and de Vries 2019).

We also considered the individuals' perceived microclimate condition, sound pressure level, and air quality, which play an important role in modeling comfort assessment. When respondents perceived higher wind speed and humidity, they reduced their evaluation on comfort. In contrast, higher perceived sunlight positively influences the respondent's com- fort. In addition, these influences affect comfort assessment through four paths, namely: (1) thermal sensation; (2) acceptability of outdoor activity; (3) thermal sensation and need satisfaction of outdoor activity; and (4) acceptability and need satisfaction of outdoor activity. The individuals' perception of sound pressure level negatively impacts the comfort assessment directly and through need satisfaction indirectly. However, the perceived air quality positively influences comfort in both direct and indirect ways. Respondents are more satisfied with better air quality for outdoor activities. In addition, the perceived openness of the public space, as an indicator of spatial setting, positively influences comfort. Through need satisfaction the indirect impact of perceived openness is passed on comfort as well.

Considering that comfort assessment may rely on individuals' experience, expectation and preference, our results show that the expected thermal and wind condition have evident connections with the acceptability of outdoor activity and comfort assessment. If respondents expect a warmer outdoor thermal condition, they respond with higher acceptability but a less comfortable feeling. The influence of expected wind speed negatively influences acceptability and comfort assessment. In terms of the impacts of respondents' expectation of thermal and wind condition, individuals who thought the outdoor thermal condition to be warm may have a high acceptability of outdoor activity. However, when they go out and experience an outdoor thermal condition that is colder than their expectation or out of their neutral range, they might respond with a lower comfort assessment.

In the case of wind expectation, the situation is different from the expectation on thermal condition. Individuals with high wind speed expectation find outdoor activities disagreeable and also degrade their comfort feeling. The effects of the preference of wind speed and sunlight on need satisfaction of outdoor activity and comfort assessment are positive and significant. Since the data collection was conducted in a cool shoulder season, the preference of sunlight naturally drives up the comfort assessment in outdoor environments. In addition, people who prefer higher wind speed in general perceive more comfort.

Furthermore, due to the importance of people's adaptation has been addressed in existing outdoor comfort studies, we asked people, based on the actual spatial settings and facilities, whether they did self-adaptation before outdoor activities and what their perceived opportunities of adaptation are in the studied areas. Results signify that the need satisfaction of outdoor activity increases if people adapted before going out. Similarly, if respondents perceive more adaptive opportunities, they will endorse outdoor activities.

6.5 Conclusions

Research on outdoor comfort in urban public spaces is of high importance to increase the site attractiveness, people's outdoor activities, and the quality of life in general. Comfort feeling in urban public spaces not only depends on an achievement of neutral thermal sensation, but also on the combined influences of the perceived contextual information, service level of infrastructure, and even people's psychological factors. A proper method to evaluate the actual comfort of individuals is necessary for various stakeholders in urban management, design, and planning, in order to improve the existing infrastructure and outdoor environments.

Therefore, to enhance the understanding of comfort assessment in urban public spaces, this chapter presents a more comprehensive framework for outdoor comfort by incorporating physical microclimate, social demographic information and individuals' subjective perceptions, expectations, and preferences. A path analysis method is used to examine the direct and indirect effects of various factors on the subjective comfort in urban public spaces using the data collected in a field survey. Although our modeling is conducted in the context of a Dutch city that is characterized by a temperate ocean climate, the methodology proposed is generic and applicable in other contexts, e.g., different public spaces, diverse climate zones.

The results show that people's thermal sensation increases in accordance with air temperature but decreases with increasing wind speed. The prospective microclimate of outdoor environments in terms of thermal sensation and wind speed influences the acceptability of outdoor activity in a positive way. However, their direct effects on comfort are negative. Individuals who expected a warmer thermal condition and windy outdoor environment had a higher acceptability of being out; in contrast, they have a lower comfort assessment. When the real condition did not approximate previous expectations, respondents were more likely to lower their assessments of comfort. Moreover, preference of wind positively influences the need satisfaction of outdoor activity and comfort assessment, which indicates that respondents with a preference for windier outdoor conditions were apt to feel more comfortable. The preference for sunlight also shows a direct positive effect on comfort.

When respondents prepared for adaptation to outdoor environments or received more information on the adaptive opportunities approved by the public space spatial settings, they may perceive more comfort. On the other hand, a better acquaintance with a certain space and the positive impression of spatial openness improves an individual's comfort assessment. Hence, behavioral adaptation, and good understanding of the microclimate and urban settings could influence the acceptance level and satisfaction of outdoor activities, as well as comfort assessment.

Further, we found that comfort assessment got worse with increasing activity duration in the outdoor environment because the thermal sensation and satisfaction with outdoor activity kept going down. However, the time spent in public spaces positively influenced satisfaction, thereby improving the assessment of comfort. This may be attributed to the differences in visiting purpose. For instance, people who are immersed in the destination and carry out their own activities may have a higher satisfaction. However, the total duration in the outdoor environment normally comprises not only the activity time of in the given public space but also the time for travel and for waiting.

As comfort feeling is fundamentally different from neutral thermal sensation, we speculate that the higher comfort assessments of respondents depend on high motivation and the acceptance of being outdoors, and the satisfaction with outdoor activities. We contend that the direct simplified process from physical condition to comfort assessment has to be substituted with an extended framework with more complex structure of relationships between comfort assessment and the determinants from different aspects. Regarding comfort assessment per se, the majority of participants responded with a comfort feeling based on their own condition. If we include the respondents who responded neutrally, neither comfort nor discomfort, approximately 81.5% of the respondents perceived no discomfort in urban public spaces. Thus, to further understand the outdoor comfort issue, more comprehensive data collection and more sophisticated modeling approaches are required. Moreover, the impact of transportation and urban spatial setting on thermal and comfort related experiences might be considered in future studies.

7.

Heterogeneity in Comfort Assessment [3]

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[3] This chapter is based on Peng, Y., Feng, T., and Timmermans, H. (2021). Heterogeneity in outdoor comfort assessment in urban public spaces. Science of the Total Environment, 790, 147941.

7.1 Introduction

Many empirical studies conducted to calibrate rational thermal indices based on the local contexts and individual preferences recognized the variability in comfort assessments in similar environmental conditions (Lam et al., 2018; Shooshtarian, 2019). The characteristics of the human body vary individually, which implies that the standardized human physiological model may introduce errors in real-world situations (Coccolo et al., 2016). On the other hand, outdoor complex environments are characterized by diverse microclimates and environmental stimuli with large temporal and spatial variation (Nikolopoulou et al., 2001; Höppe, 2002; Spagnolo and de Dear, 2003b).

The discrepancies between the predictions of rational indices and the subjective assessments have been revealed in many empirical investigations, questioning the general applicability of rational indices in outdoor environments and emphasizing individuals' conscious and unconscious adaptations (Nikolopoulou et al., 2001; Nikolopoulou and Steemers, 2003; Thorsson et al., 2004; Knez and Thorsson, 2006; Nikolopoulou and Lykoudis, 2006; Pantavou et al., 2013). The pure application of rational indices in outdoor comfort assessment leads to a narrow focus on a small number of variables which have a physical basis, and to a lack of attention to individuals' psychological factors and inter-individual differences (Nikolopoulou et al., 2001; Nikolopoulou and Steemers, 2003; Knez and Thorsson, 2006; Knez et al., 2009; Andrade et al., 2011; Lin et al., 2013). In addition, unlike thermal sensation, outdoor comfort involves individuals' perceptions of various non-thermal environmental stimuli (Rossi et al., 2015), which are inevitably affected by non-physical factors, such as individuals' socio-demographic characteristics, emotions, preferences, expectations, and adaptations (Knez et al., 2009; Lenzholzer and Koh, 2010; Klemm et al., 2015).

In this context, it is critical to appreciate that thermal comfort is defined as a state of mind, which expresses satisfaction with the thermal environment (ASHRAE, 2017). Beyond what is described in physiological models, perceived comfort refers to an outcome of an interactive process between an individual and his/her environment, which may vary from one person to another. Moreover, evidence from field studies prove individuals' subjective outdoor comfort assessments are much more elastic than have been predicted through thermal indices (Nikolopoulou and Steemers, 2003). de Dear and Brager (1998) introduced adaptive theory to outdoor comfort modeling, which is built on the premise that individuals play an active role to restore comfort by adapting to the ambient thermal conditions instead of being simply passive recipients of thermal stimuli according to the heat-balance model (Brager and de Dear, 1998; de Dear and Brager, 1998). In reality, people may have different preferences about the ideal thermal environment, which violates the underlying assumption of the heat-balance model that thermal neutrality is equal to thermal comfort (Nikolopoulou and Lykoudis, 2006). The uncertainty in uncovering the specifics of thermal interactions are credited to the individuals' acclimatization, behavioral and psychological adaptation and "Alliesthesia" (Auliciems, 1981; Nikolopoulou and Lykoudis, 2006; Eliasson et al., 2007; Parkinson and de Dear, 2015). The comprehensive conceptual models of outdoor comfort incorporate human dimensions which indicates people's satisfaction under a given thermal condition depends on a broad range of individuals' behavioral and psychological factors in respect of adaptations and expectations that are typically context-based (Nikolopoulou and Steemers, 2003; Knez et al., 2009; Shooshtarian, 2015; Shooshtarian and Ridley, 2016; Lenzholzer and de Vries, 2019; Li et al., 2020; Peng et al., 2021).

Many on-site investigations revealed the inconsistency of outdoor comfort assessments and allude to the major causes referring to individuals' differences in preferences, expectations and adaptations (Nikolopoulou and Lykoudis, 2006; Hwang and Lin, 2007; Thorsson et al., 2007; Knez et al., 2009; Lin, 2009). The factors that influence individuals' expectations and the process of adaptations in real contexts are highly complex, and the perception of outdoor microclimatic and environmental conditions differs across individuals in the sense that the same factor may exert variant effects on subjective comfort assessment (Nikolopoulou and Steemers, 2003; Stathopoulos et al., 2004; Oliveira and Andrade, 2007; Lin, 2009). For instance, higher temperature may lead to discomfort for some people, but not for those who like a warmer environment, while someone who is less concerned about temperature may feel discomfort when exposed to strong solar radiation or weak wind speed. When intending to go out, individuals expect variability in their exposure to outdoor environments, variations of sun and shade, and wind speed (Zacharias et al., 2001; Givoni et al., 2003; Gehl, 2011). The potential effect of heterogeneity on individuals' comfort assessments has not been widely examined in outdoor comfort modeling, and empirical evidence is needed.

Given the complexity of the microclimates, environmental stimulus and individuals' behaviors in outdoor comfort studies, heterogeneity is likely to exist in samples that are used to develop, test, and refine models. However, both existing rational indices (e.g. PMV, PET and UTCI) and empirical models, i.e. ASV models and Ordered models, (Nikolopoulou and Steemers, 2003; Lai et al., 2018) assume the coefficients (parameter vectors) of influential explanatory factors are the same for all individuals, which result in a lack of insights into the extent of heterogeneity in outdoor comfort assessment. The standard method of investigating subjective comfort assessment in outdoor environments is to carry out simultaneously interviews and meteorological measurements (Kánto et al., 2012; Johansson et al., 2014). Based on the standard method, studies have analyzed the effects of urban form, vegetation and personal characteristics on comfort assessment in outdoor urban environments (Sharmin et al., 2015; Krüger and Drach, 2017; Krüger et al., 2017; Johansson et al., 2018; Peng et al., 2021). Besides the standardization, it is of crucial importance to plan experiments well in the sense that valuable information is obtained using only a limited number of samples in given environments. In previous cross-sectional field studies, however, subjects were not randomly assigned according to attributes of urban public spaces. Moreover, individuals experience a wide range of thermal conditions when moving through time and space in different urban micro-environments. It is difficult to reconstruct all parts of experiences of people in on-site surveys due to time constraints, let alone to thoroughly obtain the detailed information on people's past expectations and preferences for the current environment as well as their process of behavioral and psychological adaptations.

Observed heterogeneity occurs between groups are expected a priori that incorporates moderators or contextual factors (Becker et al., 2013). From this point of view, much effort has been spent on attempts to account for the inconsistent comfort assessments under similar thermal conditions by stratifying individuals into homogeneous groups based on observed person-related variables such as socio-demographic characteristics (age, gender, education level, job condition, financial situation, lifestyle and cultural background), psychological factors (environmental attitude and thermal preference), behavioral factors (purpose of visit, past activity, duration of outdoor stay, length of local residence, usage of air-conditioner) (Knez and Thorsson, 2006, 2008; Thorsson et al., 2007; Aljawabra and Nikolopoulou, 2010; Krüger and Rossi, 2011; Karjalainen, 2012; Tung et al., 2014; Shooshtarian, 2015; Krüger et al., 2015; Shooshtarian and Ridley, 2016; Elnabawi et al., 2016; Amindeldar et al., 2017; Lai et al., 2017; Lam et al., 2018).

On the one hand, stratification with respect to heterogeneous comfort assessments cannot be accurately determined a priori by related observed variables. No consistency exists in the findings about the effect of age (Knez and Thorsson, 2006; Krüger and Rossi, 2011; Pantavou et al., 2013; Shooshtarian and Ridley, 2016). Similarly, conclusions of various previous studies on gender difference in assessing outdoor comfort are contradictory. Some studies found insignificant or no effects of gender (Knez and Thorsson, 2006; Krüger and Rossi, 2011; Pantavou et al., 2013; Shooshtarian and Ridley, 2016), others have indicated the influence of gender varies in different contexts (Oliveira and Andrade, 2007; Tung et al., 2014). Specially, the females have superior thermal physiological tolerance than the males, however, women might fear heat and sun exposure and behaviorally adjust themselves using umbrellas and searching for shade. Even if the assumption holds, the heterogeneity may be misclassified if stratification is performed based on the wrong variables. For instance, it may be assumed that the heterogeneity was caused by cultural background, but it may be influenced by differences in the past thermal experiences of respondents. On the other hand, it is impossible to explore complex high-order interactions among confounding variables. For example, females probably feel more discomfort under strong solar radiation than males in some Asian regions (Tung et al., 2014). Even two females from the same region may still have different comfort assessments under the same conditions due to the difference in their experiences. The true distribution of heterogeneity is never known a priori; therefore, it is hard to find homogeneous segments of individuals in modeling stratification. The unobserved heterogeneity in individuals’ outdoor comfort assessments is not necessarily captured by the variables that are preconceived and specified by existing theory and the conceptual model as it can exist beyond the previously identified variables.

In addition, the assessment of outdoor comfort may involve a path structure framework considering the complicated direct and indirect relationships between endogenous and exogenous variables. For example, individuals’ positive emotion impacts directly their comfort assessments, while the time individuals spend in the studied area may significantly influence their comfort assessment through the intermediate effect of need satisfaction of outdoor activity. A path model for outdoor comfort assessment was developed, in which explanatory variables such as individual demographic, psychological and contextual variables were incorporated in the path’s causal relationships. However, based on adaptive theory and previous findings, heterogeneity may exist in the relationships (direct and indirect) between endogenous variables and exogenous variables, and the relationships among endogenous variables, which implies idiosyncratic groups of outdoor comfort assessment. This means that the effects of endogenous variables on comfort assessment under the assumed causal structure may vary according to different groups of people. However, to the best of our knowledge, studies on heterogeneity represented by latent segmentations in the estimated cause-effect relationships are still missing in the literature. The knowledge of heterogeneity in comfort assessment remains fragmentary. To verify the hypothetical heterogeneity in human comfort assessment in urban public spaces, this dissertation introduces a latent class analysis based on path model.

This chapter aims at broadening our knowledge how the different comfort assessments correspond to unobserved classes of the population in similar environments. Individuals' inconsistent outdoor comfort assessments are assumed to depend on unobserved classes, rather than simply being a function of measured variables. Therefore, we assume heterogeneity prevails in individuals' comfort assessments in outdoor environments and estimate path structures for different underlying groups of the population. Latent class analysis is used as an alternative to stratification. A model is developed which allows the simultaneous estimation of latent classes and path structures of miscellaneous influential factors to identify underlying groups with a homogeneous comfort assessment and heterogeneous patterns of comfort assessment between groups. The latent classes are identified to improve the predictivity of the path model, and the membership will be linked with observable individual characteristics.

7.2 Latent class path model

The present conceptual framework aims at developing a model to uncover individuals' heterogenous comfort assessment given the complex direct and indirect effects of an expanded set of place-related and person-related variables and modify the misrepresentations caused by the data aggregation and confounders in the previous path model. Figure 7.1, which depicts a diagram of the conceptual framework incorporating heterogeneity in comfort assessment, shows the hypothetical conditional effects across latent classes and the corresponding influence of membership covariates. The latent class path model (LCPM) has been advanced for synthetically considering the effects of covariates on the class membership, and the effects varied between classes in a path structure (Jiang et al., 2020). As two essential parts of the proposed model, the path analysis is used for identifying the structure accounting for the nature and strength of relationships among a set of measured variables, while the latent class analysis is synchronized with path analysis to unravel class probabilities of individuals (Muthén and Muthén, 2000). In general, the estimation of LCPM will be conducted for better interpreting the data by searching typical pattern approximately shared by latent classes. Theoretically, a latent class characterized by a pattern of conditional probability indicates the chance of certain comfort assessment the respondent evaluated. Accordingly, each individual has a specific probability of belonging to a certain class.

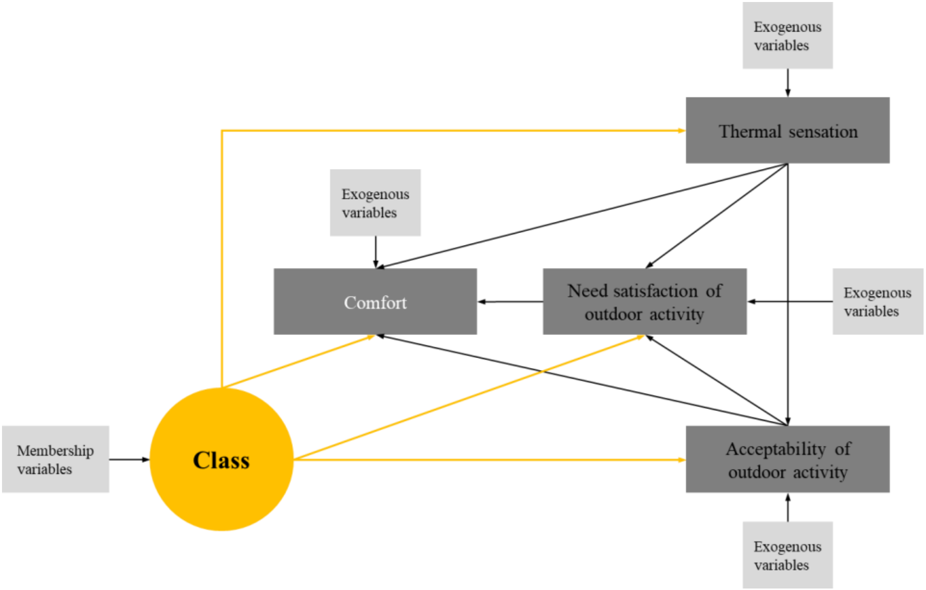

Figure 7.1 The conceptual framework of latent class in comfort assessment in urban public spaces

The probability of class membership is allowed to vary as a function of covariates. Suppose latent classes in a heterogeneous population are denoted by c_i and the vector of covariates (measured items) for class membership is represented by $\boldsymbol{Z}_i$, for individual i. To examine the covariate dependent probability for individual i in a given class $c_i = k \ (k = 1, 2, \cdots, K)$ denoted by π_{ik}, a multinominal logistic regression is expressed as:

$$\pi_{ik} = P(c_i = k|\boldsymbol{Z}_i) = \frac{\exp(\lambda_{0k} + \boldsymbol{Z}_i\boldsymbol{\lambda}_k)}{\sum_{k=1}^{K} \exp(\lambda_{0k} + \boldsymbol{Z}_i\boldsymbol{\lambda}_k)} \tag{7.1}$$

where the intercept is denoted by λ_{0k}, and the vector of weight parameter is denoted by $\boldsymbol{\lambda}_k$. The last class K is set as reference, specifically $\lambda_K = 0$. Accordingly, $\boldsymbol{Z}_i\boldsymbol{\lambda}_k$ measures the log-odds of belonging to class k instead of class K given the vector of $\boldsymbol{Z}_i$.

The studied population is a mixture of individuals from different latent classes so that the scores on a set of indicators are assumed to come from the same probability distributions. Suppose the vector of continuous indicators, also known as the endogenous variables (except comfort assessment) in path structure, denoted by $\boldsymbol{\Omega}_{im}$ indexed by $m\ (m = 1, 2, \cdots, M-1)$. The ω_{im} is the m th endogenous variable associated with the vector of influential factors, denoted by $\boldsymbol{X}_{im}$. The probability density function of the measured scores of ω_{im} is described as:

$$\theta_{im} = \sum_{k=1}^{K} [\pi_{ik} f(\omega_{im} | c_i = k, \boldsymbol{X}_{im})] = \sum_{k=1}^{K} (\pi_{ik} \theta_{imk}) \tag{7.2}$$

where π_{ik} is the probability density function of being a member of latent class k for individual i, and the class-specific normal density in the path structure denoted by θ_{imk}. The value of π_{ik} sums to 1 across K classes, and θ_{imk} is a class-specific conditional probability depending on the mean value and covariance of indicators estimated for each latent class.

Suppose the outcome assessment is denoted by y_i, with the ordinal response $y_i = j\ (j = 1, 2, \cdots, J)$ for individual $i\ (i = 1, 2, \cdots, I)$, and y_i^* as the related continuous latent reference which is associated with the vector of independent variables $\boldsymbol{X}_{iM}$, as presented in the regression model

$$y_i^* = \boldsymbol{X}_{iM} \boldsymbol{\beta} + \varepsilon \tag{7.3}$$

where ε is the normally distributed error term conditioned on $\boldsymbol{X}_{iM}$, and $\boldsymbol{\beta}$ is the vector of weight parameters. The ordinal comfort assessment y_i is resulted from

$$y_i = \begin{cases} 1, & if\ \ y_i^* \le \mu_1 \\ 2, & if\ \mu_{j-1} \le y_i^* \le \mu_j \\ & \vdots \\ J, & if y_i^* \ge \mu_{J-1} \end{cases} \tag{7.4}$$

where μ_j is the threshold point of y_i^*. The proportional odds of link function is the logit transformation. The cumulative ordinal logit model is expressed as:

$$logit \left[\frac{P(y_i \le j)}{P(y_i > j)} \right] = \mu_j - \boldsymbol{X}_{iM} \boldsymbol{\beta} \tag{7.5}$$

where the log of the probability that y_i has a value greater than the lower values given $\boldsymbol{X}_{iM}$ is modeled. The regression coefficient vector $\boldsymbol{\beta}$ is constant across the logits, whereas the intercepts μ_j are not.

Regarding comfort assessment y_i which is the Mth endogenous variable but ordinal, the vector of all the related influential factors, denoted by $\boldsymbol{X}_{iM}$, consists of both exogenous and endogenous variables. Based on ordered logit model (Equation 3), the joint probability function of the comfort assessment given $\boldsymbol{X}_{iM}$ conditional on latent class c_i is expressed as:

$$P_{ijk} = P(y_i|c_i = k, \boldsymbol{X}_{iM})$$

$$= \begin{cases} \dfrac{\exp(\mu_{1k} - \boldsymbol{X}_{iM}\boldsymbol{\beta}')}{1 + \exp(\mu_{1k} - \boldsymbol{X}_{iM}\boldsymbol{\beta}')}, & j = 1 \\ \dfrac{\exp\left(\mu_{jk} - \boldsymbol{X}_{iM}\boldsymbol{\beta}'\right)}{1 + \exp\left(\mu_{jk} - \boldsymbol{X}_{iM}\boldsymbol{\beta}'\right)} - \dfrac{\exp\left(\mu_{jk} - \boldsymbol{X}_{iM}\boldsymbol{\beta}'\right)}{1 + \exp\left(\mu_{jk} - \boldsymbol{X}_{iM}\boldsymbol{\beta}'\right)}, & j = 2, \cdots, J - 1 \\ 1 - \dfrac{\exp\left(\mu_{Jk} - \boldsymbol{X}_{iM}\boldsymbol{\beta}'\right)}{1 + \exp\left(\mu_{Jk} - \boldsymbol{X}_{iM}\boldsymbol{\beta}'\right)}, & j = J \end{cases} \tag{7.6}$$

where the μ_{jk} is the threshold linked with latent class. Assuming conditional independence, the probability of ordinal outcome, denoted by P_{ij}, is expressed as:

$$P_{ij} = \sum_{k=1}^{K} [\pi_{ik} P(y_i|c_i = k, \boldsymbol{X}_{iM})] = \sum_{k=1}^{K} \left(\pi_{ik} P_{ijk}\right) \tag{7.7}$$

where the joint probability P_{ijk} of comfort assessment $y_i = j$ conditional on class k, which is indicated by the arrow from the circle of latent class to the rectangle of comfort assessment in the diagram of conceptual framework (see Figure 7.1). The conditional probability of endogenous variables given the latent class is obtained by a product:

$$P(y_i, \boldsymbol{\Omega}_{im}|c_i, \boldsymbol{X}_{im}, \boldsymbol{Z_i}) = P_{ijk} \prod_{m=1}^{M-1} \theta_{imk} \tag{7.8}$$

Further, the manifest endogenous variables probability is expressed as:

$$P(y_i, \boldsymbol{\Omega}_{im} | \boldsymbol{X}_{im}) = \sum_{k=1}^{K} \left(P_{ijk} \prod_{m=1}^{M-1} \theta_{imk} \right) \pi_{ik} \tag{7.9}$$

By Bayes' Theorem, given $\hat{\pi}_{ik}$, $\hat{P}_{ijk}$ and $\hat{\theta}_{imk}$, respectively, the posterior probability that each individual belongs to each class, conditional on the observed variables becomes

$$\begin{aligned} P(c_i | y_i, \boldsymbol{\Omega}_{im}, \boldsymbol{X}_{im}, \boldsymbol{Z}_i) &= \frac{P(y_i,\ \boldsymbol{\Omega}_{im} | c_i, \boldsymbol{X}_{im}, \boldsymbol{Z}_i) P(c_i | \boldsymbol{Z}_i)}{P(y_i, \boldsymbol{\Omega}_{im} | \boldsymbol{X}_{im})} \\ &= \frac{\hat{\pi}_{ik} \hat{P}_{ijk} \prod_{m=1}^{M-1} \hat{\theta}_{imk}}{\sum_{k=1}^{K} \left(\hat{P}_{ijk} \prod_{m=1}^{M-1} \hat{\theta}_{imk} \right) \hat{\pi}_{ik}} \end{aligned} \tag{7.10}$$

As an iterative method for estimating the LCPM of comfort assessment conditional on latent class membership, the Expectation-Maximization (EM) algorithm has been typically employed where the unknown parameters can be estimated as weighted sums of latent proportions (Takai and Kano, 2009). Based on log-likelihood, denoted by $\ln L$, the membership probability and the conditional effects on the strength of relationships in the path structure are modeled simultaneously. The $\ln L$ can be written as:

$$\begin{aligned} \ln L &= \ln \left[\prod_{i=1}^{I} P(c_i = k | \boldsymbol{Z}_i) P(y_i, \boldsymbol{\Omega}_{im} | c_i, \boldsymbol{X}_{im}, \boldsymbol{Z}_i) \right] \\ &= \sum_{i=1}^{I} \ln \left[\prod_{k=1}^{K} \pi_{ik} \left(\prod_{j=1}^{J} P_{ijk} \right) \left(\prod_{m=1}^{M-1} \theta_{imk} \right) \right] \end{aligned} \tag{7.11}$$

The membership of individuals belonging to a latent class is assumed as missing information. When estimating the parameters of LCPM, the EM algorithm maximizes $\ln L$ by alternating two steps until convergence, expectation, and maximization, which is treated as an estimation problem in the presence of missing data. Hence, the EM algorithm is based on the complete log-likelihood, which is denoted by $\ln L^*$ and written as:

$$\ln L^* = \gamma_{ik} \ln \left[\prod_{i=1}^{I} P(c_i = k | \boldsymbol{Z}_i) P(y_i, \boldsymbol{\Omega}_{im} | c_i, \boldsymbol{X}_{im}, \boldsymbol{Z}_i) \right]$$

$$= \sum_{i=1}^{I}\sum_{k=1}^{K}\gamma_{ik}\ln\left[\pi_{ik}\left(\prod_{j=1}^{J}P_{ijk}\right)\left(\prod_{m=1}^{M-1}\theta_{imk}\right)\right]$$

$$= \sum_{i=1}^{I}\sum_{k=1}^{K}\gamma_{ik}\ln(\pi_{ik}) + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{m=1}^{M-1}\gamma_{ik}\ln\left(P_{ijk}\theta_{imk}\right) \tag{7.12}$$

where $\gamma_{ik} = 1$, if individual i belongs to latent class k, and $\gamma_{ik} = 0$, otherwise.

The corresponding conditional expect value of lnL^* given the current parameter value Φ^{t-1} (t is the iteration number) and the observed data, which is obtained as:

$$E(\Phi|\Phi^{t-1}) = E(ln\, L^* \,|y_i, \boldsymbol{\Omega}_{im}, \boldsymbol{X}_{im}, \boldsymbol{Z}_i, \Phi^{t-1})$$

$$= \sum_{i=1}^{I}\sum_{k=1}^{K}\hat{\gamma}_{ik}\, ln\left[\pi_{ik}\left(\prod_{j=1}^{J}P_{ijk}\right)\left(\prod_{m=1}^{M-1}\theta_{imk}\right)\right] \tag{7.13}$$

The posterior expect value of γ_{ik} based on Bayes' Theorem is computed as:

$$\hat{\gamma}_{ik} = E\left(\gamma_{ik}\middle|y_i, \boldsymbol{\Omega_{im}}, \boldsymbol{X_{im}}, \boldsymbol{Z}_i, \hat{\Phi}^{t-1}\right)$$

$$= P\left(\gamma_{ik} = 1\middle|y_i, \boldsymbol{\Omega_{im}}, \boldsymbol{X_{im}}, \boldsymbol{Z}_i, \hat{\Phi}^{t-1}\right)$$

$$= \frac{P(c_i = k|\boldsymbol{Z}_i)P(y_i, \boldsymbol{\Omega}_{im}|c_i, \boldsymbol{X}_{im}, \boldsymbol{Z}_i)}{\sum_{i=1}^{I}P(c_i = k|\boldsymbol{Z}_i)P(y_i, \boldsymbol{\Omega}_{im}|c_i, \boldsymbol{X}_{im}, \boldsymbol{Z}_i)} \tag{7.14}$$

The E-step computes $\hat{\gamma}_{ik}$ for individual i in latent class k. The M-step maximizes $E(\Phi|\Phi^{t-1})$ with respect to each γ_{ik} substituted by $\hat{\gamma}_{ik}$ as the new prior probability, obtaining Φ^t.

7.3 LCPM estimation

In order to detect the correct number of latent classes, models were estimated with incremental numbers of classes (from 2 to 4). Multiple statistical indices were computed, to detect the best fit model. To support the decision on class number, a combination of criteria was used (see Table 7.1), including information-based methods, likelihood ratio statistical tests, and entropy. The criteria include Akaike Information Criterion (AIC) (Akaike, 1974, 1987), Bayesian Information Criterion (BIC) (Schwarz, 1978), sample-size adjusted BIC (SABIC) (Sclove, 1987), Entropy (Celeux and Soromenho, 1996), Lo-Mendell-Rubin Likelihood Ratio Test (LMR) (Vuong, 1989; Lo et al., 2001) and Bootstrap Likelihood Ratio Test (BLRT) (McLachlan and Peel, 2000; Nylund et al., 2007).

AIC is not consistent and sometimes overestimates the number of classes. By contrast, BIC and SABIC has been reported to perform well and consistently (Jedidi et al., 1997; Yang, 2006). A lower value indicates the best fitting model (Yang, 2006; Nylund et al., 2007; Sharma and Tiwari, 2007; Berlin et al., 2014). Entropy is a standardized index of model-based classification accuracy. The value of normalized entropy is between 0 and 1. A value approaching 1 indicates a clear separation of latent classes. Therefore, a higher value of normalized entropy represents a better fit. In addition, when an entropy value is greater than 0.80, the number of latent classes is identified as the most optimal modeling solution for goodness of fit (Celeux and Soromenho, 1996). The LMR and BLRT provide a value that can be used to compare the increase in model fit between neighboring class models and determine if there is a statistically significant improvement in fit for the inclusion of one more class. Based on the values of these criteria, we selected the model with two latent classes (denoted by *C1* and *C2*) as the most appropriate in this study.

The membership of each latent class was estimated and shown in Table 7.2. The coefficient vectors related to the weight of covariates, including gender, age, education level, preceding adaptation, transport mode, and visiting frequency and purpose, for two classes are denoted by $\boldsymbol{\lambda}_{C1}$ and $\boldsymbol{\lambda}_{C2}$. As for gender of respondents, the significant effect was found that the males have a higher probability than females to be categorized as the members of *C2*. The potential to be allocated to *C2* is increasing when respondents are ageing. The BMI, which represents the physical condition of respondent, is not working and fall flat in membership prediction. While respondents with a postgraduate degree more likely belong to *C1* compared to those with undergraduate degree and high school education or lower. Respondents who are accustomed to visit the study areas are more likely to be members in *C1*. Moreover, the transport mode and purpose of visit significantly affect the latent class membership. It is a high probability of being in *C1* if respondents walked to the study areas with the purpose of shopping.

Table 7.1 The estimate indices for comparison of different number of latent classes

Class Amount	AIC	BIC	SABIC	Entropy	LMR	BLRT
2	9047.070	9497.768	9183.423	0.909	0.0016	0.000
3	8995.171	9705.362	9210.030	0.723	0.7787	1.000
4	8942.284	9911.968	9235.649	0.703	0.9093	1.000

Table 7.2 The covariates of membership in different latent classes

Covariate	Acronym	λ_{C1}	λ_{C2}	*p*-Value
Gender (Male=1)	Gd**	-0.346	0.346	0.019
Age	Age**	0.021	-0.021	0.028
Body mass index	BMI	-0.058	0.058	0.137
Education: undergraduate	ED1	-0.131	0.131	0.475
Education: postgraduate	ED2**	0.552	-0.552	0.017
Preceding adaptation	AD***	-0.558	0.558	0.001
Visit frequency: occasionally	FR1	-0.210	0.210	0.479
Visit frequency: sometimes	FR2***	0.649	-0.649	0.002
Visit frequency: often	FR3	-0.127	0.127	0.549
Transport mode: by foot	M1***	0.717	-0.717	0.000
Transport mode: by bike	M2	0.066	-0.066	0.753
Purpose: transport transferring	P1	0.248	-0.248	0.442
Purpose: social activity	P2***	-0.959	0.959	0.004
Purpose: shopping	P3***	0.822	-0.822	0.009
Purpose: rest	P4	-0.135	0.135	0.669
Purpose: leisure	P5*	-0.810	0.810	0.072
Purpose: passing by	P6**	-0.578	0.578	0.030

* $0.05 < p < 0.1$; ** $0.01 < p \leq 0.05$; *** $p \leq 0.01$

Table 7. 3 The estimation results of LCPM.

		Class 1		Class 2	
Variables	Acronym	$\boldsymbol{\beta}_{C1}$	*p*-value	$\boldsymbol{\beta}_{C2}$	*p*-value
Thermal Sensation on					
Air temperature	*Ta*	0.098*	0.072	0.173***	0.000
Wind velocity	*v*	-0.344***	0.003	-0.237***	0.000
Sensation of wind	*Sv*	-0.037	0.646	-0.166***	0.000
Sensation of sunlight	*Ss*	0.275***	0.002	0.245***	0.000
Total outdoor time	*Dt*	-0.165*	0.056	-0.173***	0.000
Acceptability of outdoor activities on					
Relative Humidity	*RH*	-0.055***	0.000	-0.038***	0.000
Wind velocity	*v*	-0.285	0.144	-0.115	0.114
Expectation of thermal condition	*Et*	0.041	0.680	0.183***	0.000
Sensation of wind	*Sv*	-0.047	0.626	-0.076	0.114
Sensation of sunlight	*Ss*	0.351***	0.005	0.087**	0.036
Sensation of air quality	*Sa*	-0.134	0.182	0.092**	0.046
Sensation of sound pressure level	*Sl*	0.063	0.503	0.100**	0.036
Perceived adaptive facilities	*PA*	0.091	0.268	0.073*	0.082
Thermal sensation		0.271**	0.044	0.273***	0.000
Need satisfaction of outdoor activities on					
Positive affects	*Pos*	-0.009	0.453	0.016***	0.010
Negative affects	*Neg*	-0.009	0.643	-0.024***	0.004
Total outdoor time	*Dt*	-0.256***	0.005	-0.083*	0.076
Time in current place	*Dc*	0.348**	0.018	0.211***	0.000
Sensation of air quality	*Sa*	0.094	0.164	0.056*	0.079
Sensation of sound pressure level	*Sl*	0.066	0.285	-0.098***	0.000
Perceived openness	*PO*	-0.011	0.875	0.134***	0.001
Thermal sensation		0.079	0.359	0.051*	0.081
Acceptability of outdoor activities		0.088	0.223	0.094***	0.001
Comfort on					
Positive affects	*Pos*	0.103***	0.004	0.051***	0.000
Negative affects	*Neg*	-0.019	0.626	-0.086***	0.000
Expectation of thermal condition	*Et*	-0.239**	0.030	-0.106*	0.086
Expectation of wind velocity	*Ev*	-0.420***	0.005	-0.086	0.157
Thermal sensation		0.815***	0.000	0.477***	0.000
Acceptability of outdoor activities		0.092	0.440	0.143**	0.035
Need satisfaction of outdoor activities		0.381	0.295	0.720***	0.000

* $0.05 < p < 0.1$; ** $0.01 < p \leq 0.05$; *** $p \leq 0.01$

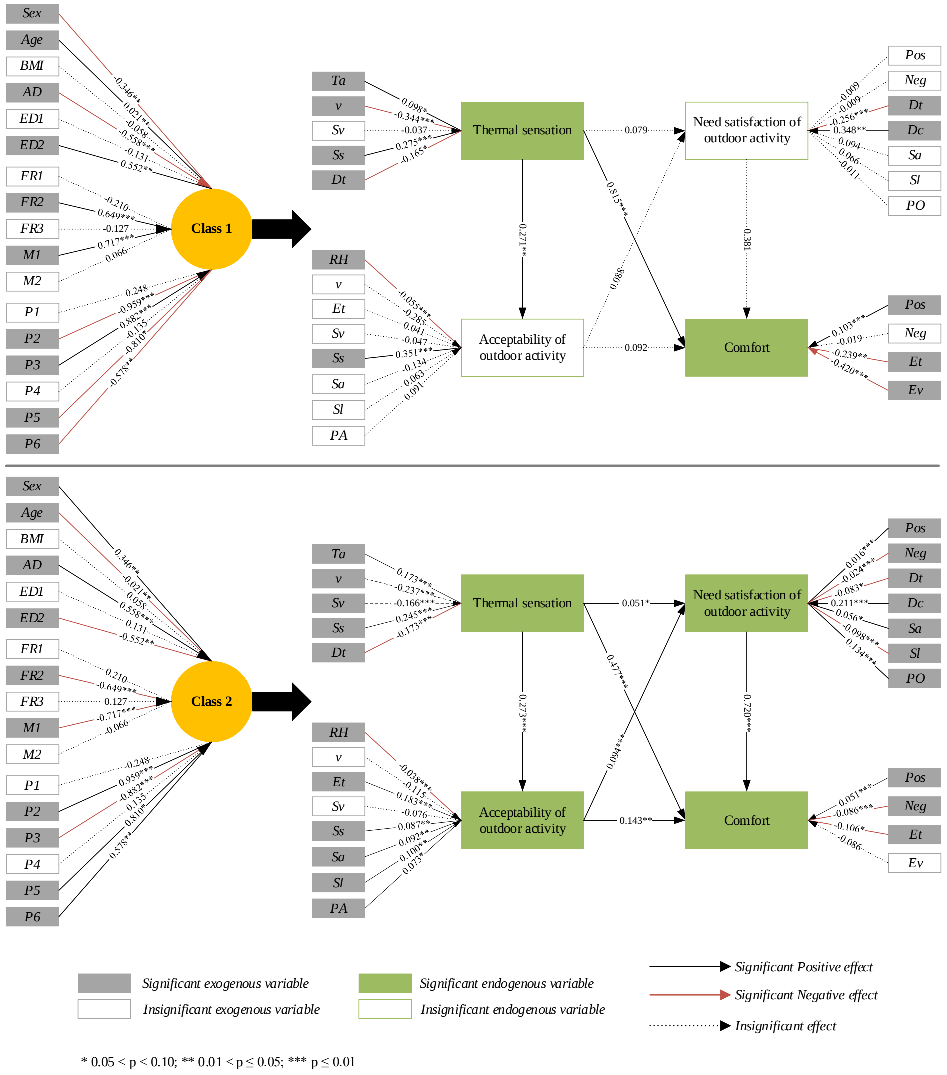

Figure 7.2 Diagram of the estimation result of LCPM

Drawing on samples from cross-sectional surveys in different urban public spaces, the findings of estimation regarding the path coefficients and the corresponding statistical significance among two different latent classes are shown in Table 7.3. Consistent with the existing literature (Tsitoura et al., 2016, 2017), the measured microclimatic variables, including air temperature and wind velocity, and the total outdoor exposure duration of respondents significantly influence their thermal sensation in both identified latent classes. However, the magnitude of coefficients and significance regarding these direct exogenous effects are different in two latent classes. The air temperature positively influences on respondents' thermal sensation, whereas wind velocity and respondents' total outdoor exposure duration affect respondents' thermal sensation reversely. Meanwhile, the differential path structures of two latent classes regarding the nature and strength of relationships among comfort assessment and the arguments, including endogenous and exogenous variables, are depicted in the diagrams (see Figure 7.2). The obvious variations in path structures across latent classes strengthen the argument of heterogeneity in the patterns of comfort assessment. Looking deeper into the relationships among endogenous variables and comfort assessment, there is only one connection between thermal sensation and comfort assessment in the path structure with respect to *C1*. In contrast, three direct connections in the path structure regarding *C2* approve the hypothetical relationships respectively between the individual's comfort assessment and thermal sensation, acceptability of outdoor activity and need satisfaction. In addition, more significant connections between endogenous variables can be observed in *C2* than in *C1*. The results underscore the influence of psychological impacts of outdoor activity in *C2*.

The effects of exogenous variables on thermal sensation regarding the measured air temperature and wind velocity as well as the respondent's sensations of wind speed and sunlight strength and total duration of exposure in outdoor environments are significant in *C2*. The measured air temperature and respondent's sensation of sunlight are in proportion to comfort assessment. However, the contrary is proved that influences of measured wind velocity, and respondent's sensation of wind velocity and total duration of exposure in outdoor environments negatively impact comfort assessment. The significant exogenous influences on thermal sensation in *C1* are only wind velocity and respondent's sensation of sunlight.

The direct relationships between exogeneous variables and comfort assessment also differ across latent classes. Positive emotional affects account for comfort assessment regardless of classes membership. However, the individual's negative emotional affects only take effects on comfort assessment in *C2*. Comfort assessment varies inversely with the expectations of outdoor thermal condition in both classes, while the expectation of wind velocity negatively influences comfort assessment in *C1*.

Aside from the variance in direct impact across latent classes, the estimates of LCPM also provide evidence to substantiate the difference in indirect effects between latent classes. Moreover, the relationships between exogenous variables and corresponding endogenous variables differ largely across latent classes. As for thermal sensation, compared with the structure regarding *C1*, one more inverse influence from sensation of wind is significant in the path structure of *C2*.

Wide differences between the two latent classes are found in terms of exogenous effects on need satisfaction and acceptability of outdoor activity. According to the estimated results related to *C1*, acceptability of outdoor activity is negatively affected by measured humidity and individual's sensation of sunlight. Moreover, need satisfaction of outdoor activity is affected by time spent in the study area and the time spent for all outdoor activities. In case of *C2*, more indirect effects are revealed, which relate to people's perceptions of environment and momentary emotional affects.

7.4 Conclusions

With respect to the rational thermal indices based on the heat-balance model, the predicted result of thermal comfort is treated as an average estimated outcome of individuals' comfort assessment in a certain thermal condition, no matter what people evaluate and their past behaviors and experiences. However, the literatures pertaining to empirical outdoor comfort studies have indicated that the modeling of comfort assessment should represent the complex nature of the involved person-related determinants and acknowledge the heterogeneity in the sampled population. Therefore, we remove the implicit assumption of "average person" through extending the theoretical framework by introducing heterogeneous outdoor comfort assessment across different latent classes. It is conceptually appealing that latent class integrated with path analysis exerts the thinking about heterogeneity in comfort model and reveals the role of human being more holistically. A finite mixture approach to the path model was developed in which latent class estimation improves the understanding of systematic heterogeneity in assessment of outdoor comfort.

The results of the model estimations indicate:

(1) the paths among exogenous and endogenous variables, and corresponding coefficients in structure model vary across two latent classes, which is representing the different nature and strength of the relationships between influential factors and outdoor comfort assessment.

(2) Latent class 1 assesses the comfort mainly based on thermal sensation and expectations of thermal and wind conditions. Latent class 2 comprehensively considered the non-thermal influences and psychological acceptability and need satisfaction of outdoor activity.

(3) Such a difference may be attributed to the individual's socio-demographic characteristics and behavioral factors, as treated in membership specification. For example, the comfort assessment of younger males in class 2 who made preparations before going outside are influenced by their acceptability and need satisfaction regarding social or leisure outdoor activities. However, such an effect was not found for people in class 1.

In conclusion, the heterogeneity in the process of outdoor comfort assessment modeling is persuasive as it stands. The conceptual framework and LCPM present the theoretical improvement on outdoor comfort assessment modeling. Methodologically, the consideration of heterogeneity in modeling contributes to the outdoor comfort literature by allowing researchers to detect unobservable moderating classes which account for heterogeneity among the studied population. To examine the pervasiveness of heterogeneity and strengthen the effects of individuals' difference in comfort modeling, more empirical investigations are expected to provide supportive evidence in different regions and contexts. The findings of this study relied on the cross-sectional data where no changes in the latent classes and path structure can be explored. More comprehensive studies in future are expected to contribute and support the decision-making process from a longitudinal perspective for better planning and management of outdoor comfort spaces.

8.

Conclusions

8.1 Summary

Comfort in urban public space is a goal to be sought through the concerted efforts of residents, planners, policy makers and other different stakeholders concerned. Comfortable public spaces improve urban residents' quality of life by accommodating encounters with fellow citizens, offering recreational opportunities and considerable social and commercial value. This dissertation builds a disruptive conceptual framework for providing a better understanding of the expanded set of factors influencing outdoor comfort assessment in urban public spaces. The findings of this empirical investigation present a discourse of whether and to what extent human behavioral and psychological factors are associated with their comfort assessment in a certain geographical context. In light of context-based adaptive approach, the findings of this study confirm the active role of individual people's varying perceptions and expectations on different microclimatic and environmental variables. Further, some progress has been made in exploring the comprehensive conceptual framework with an expanded set of influential factors on comfort assessment in urban public spaces. The nonlinear effects of influential factors have been addressed, as well as the direct and indirect effects of influential factors on comfort assessment were investigated. Moreover, the heterogeneity in comfort assessment among individuals has been examined.

To understand the response of people to the outdoor built environments with respect to thermal conditions, sound pressure level and air quality, field investigations were carried out in a real-world outdoor setting in the city center of Eindhoven, including a questionnaire-based survey and simultaneous measurement of meteorological conditions. In total, 701 respondents completed the survey. Their outdoor comfort assessments were analyzed using multiple linear regression, nonlinear regression with Box-Cox transformations, path analysis, and a latent class path model.

This study provides a full perspective of a human-centered paradigm to rethink the philosophy of comfort with reference to human preferences, expectations, perceptions, acceptability, and satisfaction, among other psychological and behavioral factors. The main findings verified the necessity of an expanded set of factors and indicated that the relationship between comfort and thermal neutrality is not straightforward. Nonlinear effects of microclimatic variables and environmental stimuli on human perceptions and comfort assessment were validated. Meanwhile, the mediate effects through psychological factors link outdoor comfort and the exogenous influences of external microclimatic and environmental conditions and direct sensations of individuals. The results also raise awareness of the need to reconsider variations among different individuals in outdoor comfort assessments.

Although a growing body of literature is arguing the theoretical limitation of existing approaches of outdoor comfort assessment, the varying individuals' expectation and adaptation in certain geographical and socio-cultural contexts have been seldomly studied from a human-centered perspective. Motivated by this knowledge gap in outdoor comfort studies, this doctoral research fills the gap through an integrative method, which investigates subjective comfort assessment in urban public spaces with an explicit focus on the role of humans with respect to socio-demographic characteristics, behavioral factors, and psychological factors, and the corresponding microclimatic and environmental stimuli. This study contributes to the literature on modeling human outdoor comfort in urban public spaces, especially providing insights into human factors. It also stresses the importance of extending the current standards of thermal comfort to provide more valid comfort assessing approaches in outdoor environments.

The other contribution of this study to the theory of comfort assessment in outdoor environment is introducing the comprehensive conceptual framework with an expanded set of determinants. In formulating the conceptual framework, overall comfort assessment is assumed as a function of the place-human interaction, in which the importance of human perceptions and adaptations emerges. The discourse was presented with regard to the expanded set of influential factors, including microclimatic variables and human socio-demographic, behavioral and psychological factors. This framework provides the opportunity to explore the influence of contextual factors on individuals' assessments.

Chapter 5 explored the effects of the measured objective microclimatic variables and surveyed personal socio-demographic characteristics, behavioral factors and subjective psychological factors using both linear and nonlinear models. The estimation results provide convincing evidence that behavioral and psychological dimensions have significant effects on human comfort assessment in urban public spaces, beyond the single heat exchange dimension.

Chapter 6, further, addressed the mediate effects of psychological factors through path analysis. The results highlighted the intermediate effect of endogenous psychological variables. Besides thermal sensation, individual's comfort assessment heavily relies on acceptability and need satisfaction of conducting outdoor activities. Unlike the direct influences in linear and nonlinear models, some exogenous variables indirectly impact comfort assessment via the intermediate endogenous variables. The simplified process from physical condition to comfort assessment has been substituted with an extended framework with verified direct and indirect influences based on the interaction of human and environment.

Chapter 7 focused on heterogeneity in comfort assessment among different individuals, providing insight on the unobserved classification in respondents depending on personal characteristics and behavioral factors related to long-term and short-term experiences. Latent class analysis was applied and integrated into the path structure. Two unobservable moderating groups were verified, stressing the underlying individual differences pertaining to human thermal history and experience.

8.2 Implications for urban planning

Research on outdoor comfort in urban public spaces is of high importance to increase the site attractiveness, promote people's outdoor activities, and improve the living quality in general. Thereby, outdoor comfort should be an important consideration in the process of urban planning, design, policymaking, management, and related practices. The raising awareness of human-environment interaction drives more attention on responsive urban design and planning in climate and cultural contexts. It is important to acknowledge the characteristics of the target populations, understanding how they interact with urban microclimates and environments, and to compromise their preferences in favor of spending time outdoors. This research aims to introduce the comfort assessment methods and contribute to the scientific understanding of comprehensive determinants in real-world urban settings.

This study, thereby, provides a disruptive conceptual framework with an expanded set of influential factors for outdoor comfort assessment modeling, meanwhile, presents an integrated approach to ravel the underlying diversity of population in comfort assessment. The findings shed light on to what extent people’s preferences, expectations and adaptations influence their comfort in a complex outdoor urban environment. The expanded conceptual framework also brought insights of context-based adaptation into comfort modeling, which beyond the way of only incorporating the effect of thermal conditions. The socio-demographic characteristics and behavioral factors are proved to affect people’s expectations and preferences, therefore, the practices of developing or redeveloping urban public spaces should take the influence of diverse users and the main driver of their backgrounds into account. In addition, the results of this study regarding locations with different features will help implementing the measures of improvement in various urban settings.

When it comes to the municipal management on urban public spaces, the methodology and findings of this study imply that better solutions may be obtained if the nature and strength of the relationship between comfort and its determinants are fully informed. Higher quality of public spaces incorporating the provision of facilities and opportunities for adaptation will also encouraging more outdoor attendance. For design and planning in practice, planners should not only consider the microclimate environment but also the characteristics of public spaces and behavioral factors, such as transport modes, frequency of visit, durations, and purposes.

8.3 Limitations and future research

Due to limited human resources and budget, a relatively small sample size was obtained in one city in this study. It implies that the generalizability of the results is rather limited, although the methodology, which has some innovative components, is generic. In particular, the selection of locations using orthogonal design and the use of the latent class path model solved the problem of bias estimates in most previous applications of regression models of outdoor comfort assessment and offer a different perspective on heterogeneity from latent classes of comfort assessment equations to heterogeneity in causal structures leading to outdoor comfort assessments. Longitudinal surveys and measurements in different spaces with similar thermal conditions could provide more useful information regarding the interactions between people and their immediate environments.

In addition, time limitations in the survey to some extent hindered acquiring in-depth descriptions concerning respondents' thermal history, and their full course of past activity experiences, which could have provided adaptation insights into the dynamics of outdoor comfort in different urban public spaces.

The findings of this study widen our understanding of comfort assessment in urban public spaces from the perspective of a human-centered paradigm. Based on this study in the Netherlands, it is important to draw a more general conclusion through investigations in different climatic and cultural contexts. Furthermore, rather than relying on data collected in one season, future studies are highly recommended to be carried out in different seasonal contexts.

Finally, further research concerning the people’s expectations of diverse predictors on comfort assessment and the corresponding ameliorations of outdoor settings is worth to examine. Such investigation may explore people’s need-based preferences that encourage them to spend more time on outdoor activities, which may contribute to developing incentives and policies to improve urban livability and vitality and residents’ well-being.

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Appendix

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Questionnaire

Intro: We are carrying out research about thermal comfort in this public space and how it is related to your behavior and the microclimatic, environmental, and spatial attributes of this space. Do you mind if I invite you to take part in the survey of a few questions? It will take you about 10 minutes. Thank you!

No.		Location		Date		Begin		End	

PART 1

Age	Gender
Race	Hometown
Height	Education
Weight	Health condition
Time in outdoor	Time in this place

Motion state	☐Sitting	☐Standing	☐Walking
Stay	☐Sun	☐Shade	☐Wind shield

PART 2

The following scale consists of a number of words that describe different feelings and emotions. Read each item and then list the number from the scale next to each word. Indicate to what extent you feel this way right now, that is, at the present moment OR indicate the extent you have felt this way over the past week.

1 = Not at all	2 = A little	3 = Moderately	4 = Quite a bit	5 = Extremely

Interested	Distressed	Excited	Upset	Strong
Guilty	Scared	Hostile	Enthusiastic	Proud
Irritable	Alert	Ashamed	Inspired	Nervous
Determined	Attentive	Jittery	Active	Afraid

EINDHOVEN UNIVERSITY OF TECHNOLOGY

Questionnaire

PART 3

*0 means neutral feeling or condition, similarly hereinafter

1. What were your expectations for this place before your current outdoor sojourn?

Cold	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Hot
Calm	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Windy
Dry	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Humid
Quiet	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Noisy
Dusty	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Fresh

2. Which type of building were you in before your current outdoor sojourn?

☐ Air-conditioned	☐ Free running

3. What is your general preference to the type of environment?

Urban facilities	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Natural landscape

4. How you think this place are good for outdoor activity?

Unacceptable	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Acceptable

5. How do you think the openness of this place?

Unsuitable	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Suitable

6. How familiar are you with this place?

Unfamiliar	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Familiar

7. How often do you come to the current outdoor space? (f: frequency of visit, w: week, m: month)

☐ First time	☐ Seldom	☐ Occasionally	☐ Sometimes	☐ Often
0	f < 1/m	f ≤ 1/w	1/w < f ≤ 3/w	3/w < f

8. What is your purpose for coming or sojourning in this outdoor place now?

☐ Transfer	☐ Social activity	☐ Shopping	☐ Rest	☐ Leisure
☐ Passing-by	Other:			

9. How do you think other people's activities influence on your position choice and comfort?

Not at all	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Extremely

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Questionnaire

PART 3

*0 means neutral feeling or condition, similarly hereinafter

10. How do you think you can make yourself comfort by the opportunities provided in this place?

Not at all	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Extremely

11. How do you want to change your original planned time schedule?

Reducing	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Extending

12. What are your preferences regarding the conditions of this place?

Colder	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Warmer
Calmer	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Windier
Drier	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Wetter
Cloudier	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Sunnier

13. What kind of measures have you taken for more comfortable feeling?

☐ Add clothing	☐ Reduce clothing	☐ Wear hat	☐ Wear scarf	☐ Wear gloves
☐ Use umbrella	☐ Wear sunglasses	☐ Have food	☐ Drink warm	☐ Drink cold
☐ Change posture	☐ Change position	☐ Change schedule	Other:	

14. How do you think this place fulfill your needs for outdoor activity?

Not at all	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Extremely

15. How do you perceive the microclimate and environment of this place?

Cold	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Hot
Calm	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Windy
Dry	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Humid
Cloudy	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Sunny
Quiet	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Noisy
Dusty	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Fresh

16. How do you assess the overall comfort of this place at present?

Uncomfortable	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Comfortable

Author Index

Subject Index

Curriculum Vitae

You Peng was born on 24 January 1984 in Zhuzhou, Hunan province, China. After receiving a master’s degree in Architecture at Hunan University in Changsha, Hunan province, China, in 2010, he became an architect working in a firm of architectural design and urban planning. In 2011 he started a PhD project in Urban Planning and Transportation research group of the Department of Built Environment at Eindhoven University of Technology, of which the results are presented in this dissertation. His research interests mainly focus on design and decision support for a range of domains from the climate responsive architectural design and urban planning, smart and sustainable cities, to the evaluation of the environmental quality in different urban contexts.

List of Publications

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Comfort in Urban Public Spaces

This dissertation builds a disruptive conceptual framework for providing a better understanding of the expanded set of factors influencing outdoor comfort assessment in urban public spaces. A full perspective of a human-centered paradigm is provided to rethink the philosophy of comfort with reference to human preferences, expectations, perceptions, acceptability, and satisfaction, among other psychological and behavioral factors.

To understand the response of people to the outdoor built environments with respect to thermal conditions, noise level and air quality, field investigations were carried out in a real-world outdoor setting in the city center of Eindhoven, including a questionnaire-based survey and simultaneous measurement of meteorological conditions. In total, 701 respondents completed the survey. Their outdoor comfort assessments were analyzed using multiple linear regression, nonlinear regression with Box-Cox transformations, path analysis, and a latent class path model.

The main findings verified the necessity of an expanded set of factors and indicated that the relationship between comfort and thermal neutrality is not straightforward. Nonlinear effects of microclimatic variables and environmental stimuli on human perceptions and comfort assessment were validated. Meanwhile, the mediate effects through psychological factors link outdoor comfort and the exogenous influences of external microclimatic and environmental conditions and direct sensations of individuals. The results also raise awareness of the need to reconsider variations among different individuals in outdoor comfort assessments.

DEPARTMENT OF THE BUILT ENVIRONMENT

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