PEDESTRIAN ACTIVITY, OUTDOOR THERMAL COMFORT AND URBAN STREET DESIGN: CASE STUDIES FOR THE SEOUL-LO 7017 IN SEOUL AND THE HIGH LINE IN NEW YORK CITY

A Dissertation

by

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Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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August 2021

Major Subject: Urban and Regional Sciences

ABSTRACT

Designing thermally comfortable urban public spaces has become an important issue in urban design and planning. Due to rapid urbanization and climate change, the frequency and intensity of extreme heat events have sharply increased. This trend has led to multiple problems related to health and wellbeing of urban residents through multiple pathways. One of the key pathways is by negatively affecting pedestrian activities which are important forms of healthy outdoor physical and social activities. Specifically, the excess heat load causes significant pedestrian discomfort, which decreases the use of public spaces by altering the patterns of outdoor activities. To shape a safe and pleasant walking environment in the age of climate change, it is increasingly essential to understand the relationships between outdoor thermal comfort, pedestrian activities, and urban street design.

Using the two urban walkway - ‘The High Line’ In New York City, U.S. and ‘Seoul-lo 7017’ in Seoul, South Korea - this dissertation research explored the relationship between thermal comfort and pedestrian activities (Topic 1) and its association with characteristics of urban street design (Topic 2). These walkways serve as ideal locations to explore this topic given primary function of leisure walking which responds more sensitively to the design and microclimatic characteristics of the streets than utilitarian walking. This research focuses on quantifying the impact of thermal comfort on pedestrian activity and the usage of street spaces, and on evaluating the association between thermal comfort and urban street design features. Given that the process of thermal adaptation shapes the heat-pedestrian activity relationship, this study further identified the heat thresholds of walking activity describing the range of tolerance of heat stress that respond to the different features of microclimate street design (Topic 3).

The overall results of the three studies included in this dissertation research indicated that meteorological conditions and outdoor thermal comfort significantly impacted pedestrian activity. The first study showed that different meteorological (season, weather and microclimate) scales and components affected pedestrian activities differently. The second study indicated that the combination of urban design factors at the street- and block-scale levels influenced pedestrian thermal comfort. The last study suggested that a heat threshold of sitting and walking was influenced by sky view factors (SVFs) regulating solar access and shading effects.

Findings from this study showed that proper modification of microclimatic street design features can improve pedestrian thermal comfort and increase the acceptable range of thermal conditions for walking and sitting activities. This study provides new empirical evidence to guide the design of highly heat-resistant street spaces that support pedestrian activities in the age of global warming.

DEDICATION

This dissertation is dedicated to my parents, Hyunsook Kim and Sungmo Kim, my brother Youhyun Kim, and my wife Seonju Jang who have supported me with love and care during my lifetime.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Robert Brown, and my committee members, Dr. Chanam Lee, Dr. Wei Li, and Dr. Xuemei Zhu, for their guidance and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

Finally, thanks a lot to my mother, father and my wife for their patience and endless love.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Professor Dr. Robert Brown [advisor], Dr. Chanam Lee, and Dr. Wei Li of the Department of Landscape Architecture and Urban Planning and Professor Dr. Xuemei Zhu of the Department of Architecture.

All work conducted for the dissertation was completed by the student independently.

Funding Sources

Graduate study was supported by a fellowship from Texas A&M University and there are no outside funding contributions to acknowledge related to the research and compilation of this document.

NOMENCLATURE

AIC & BIC	Akaike's & Bayesian Information Criteria
ASOS	Automated Synoptic Observing Stations
AWS	Automatic Weather Stations
BMA	Bayesian Model Averaging
BVFs	Building View Factors
C	Convective heat loss
COMFA	Comfort Formula
E	Evaporative heat loss
EB	Energy Budget
FE	Fixed Effect
HLM	Hierarchical Linear Mixed Modeling
HW ratio	Height to Width ratio
ICC	Intraclass Correlation Coefficient
K	Conductive heat loss
Kabs	Absorbed solar radiation of a person
KMA	Korean Meteorological Administration
Labs	Absorbed terrestrial radiation of a person
LCZ	Local Climate Zones
LM	Lagrange Multiplier
LOOCV	Leave One Out Cross Validation

M	Metabolic heat production within the body
OLS	Ordinary Least Square
PA	Panel Analysis
Preci	Precipitation
PST	Physiological Subjective Temperature
R	Radiative exchanges
RE	Random Effect
Rh	Relative humidity
Sol	Solar radiation
SVFs	Sky View Factors
Ta	Air temperature
TCCR	Tree Canopy Cover Ratio
TE	Effective Temperature
Tg	Globe temperature
Tmrt	Mean radiant temperature
TVFs	Tree View Factors
UHI	Unban Heat Islands
UTCI	Universal Thermal Climate Index
VIF	Variance Inflation Factor
WBGT	Wet Bulb Globe Temperature
Ws	Wind speed

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1. INTRODUCTION

1.1. Background and Objectives

Due to global warming and rapid urbanization, the frequency and intensity of extreme heat events and Urban Heat Islands (UHI) have sharply increased in most US cities over the past few decades (Hardin et al. 2018; Lowe 2016; Climate central, 2019). This ongoing trend has caused significant thermal discomfort that alters the patterns of outdoor physical and social activities in urban public spaces (Coates et al, 2014; Fang et al, 2015; Johansson, 2006; E. Sharifi, 2017). For pedestrians, excessive heat stress is reported as a critical barrier to their walking, and therfore deteriorates walkability, livability, and urban vitality (Sharifi et al, 2018; Tumini, Garcia, & Rada, 2016). In this regard, as a part of sustainable development, designing thermally comfortable street spaces has become a major concern in urban design research and pratice.

The impact of meteorological and thermal conditions on outdoor pedestrian activity has been investigated in diverse fields of study. In transportation, the impact of adverse weather conditions on walking has been examined within the context of individual travel behavior, such as daily choice for outdoor activity, destination, and transportation mode (Böcker et al., 2013). Biometeorological studies, on the other hand, have focused more on evaluating outdoor thermal comfort and physiological responses of people walking under various heat conditions (Chen & Ng, 2012; Hasegawa et al., 2017). In environmental design, survey and observation studies often examined the behavioral use of public spaces and spatial distribution of visitors in relation to microclimate conditions (Nikolopoulou & Lykoudis, 2007; Klemma et al., 2017). These studies have demonstrated that the meteorological conditions and thermal comfort are significant determinants of pedestrian activity across regions and socio-cultural contexts.

The heat-pedestrian activity relationship can be decribed by the theory of thermal adaptation (Figure 1.1) (Gail S. Brager et al, 1998). This thoery provides a conceptual framework of how people respond and adapt to the given thermal stimuli to meet their requirement by adjusting their inner and outer conditions (Nikolopoulou, M., et al, 2001; Chen, L.& Ng, E. 2012). Particularly, the behavioral adjustment - spontaneous reactions of physical adaptation - is considered as a key factor impacting their decision to walk or not and where they choose to sit. Furthermore, this adaptation process determines the acceptable range of thermal conditions for pedestrians. While this range is strongly associated with the microcliamtic features of street design (De Freitas et al. 2007; Li et al. 2012; Li et al. 2013), their empirical relationship has rarely been examined.

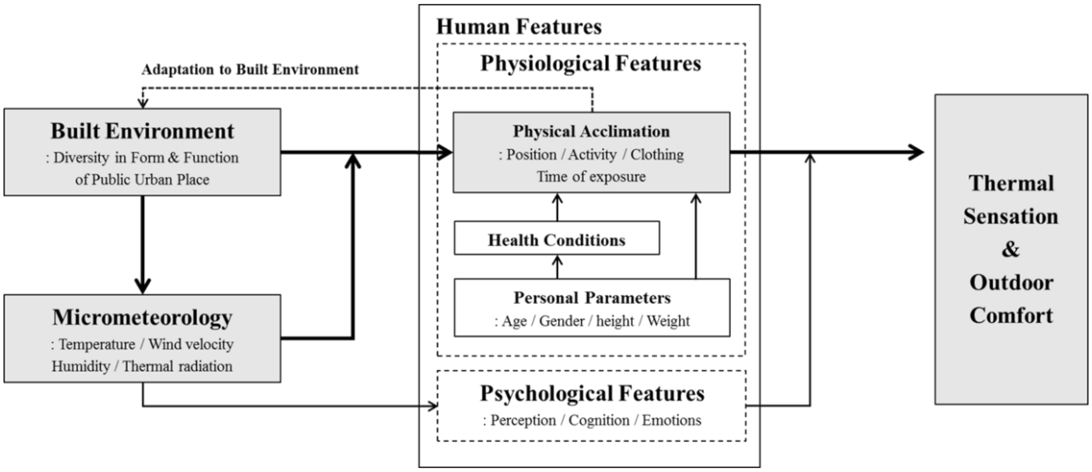


Figure 1.1 Conceptual Framework: Behavioral Thermal Adaptation

To fill this important knowledge gap, the following three reseach questions will be addressed in the three individual studies (Topic A, B and C) included in this disseration research (Figure 1.2):

In a humid sub-tropical climate, how does daytime thermal comfort affect pedestrian activity in terms of behavioral thermal adaptation? And, how is this a heat-pedestrian activity relationship related to the microclimatic features of urban street design?

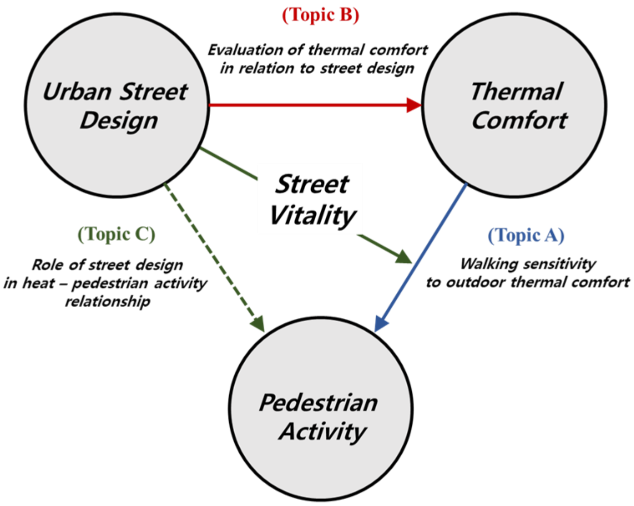
A) What factors and scales of the methodological condition and urban street design determine pedestrian thermal comfort?

B) How can pedestrian thermal comfort be evaluated in relation to microclimatic features of urban street design?

C) What impact does urban street design have on the relationship between thermal comfort and pedestrian activity?

To address these questions, this study explored the relationship between thermal comfort and pedestrian activities (Topic A), and between thermal comfort and urban street design (Topic B). The association between thermal comfort and urban street design was evaluated spatially and temporally. The microclimate and thermal comfort impacts on pedestrian activity and usage of urban street spaces were investigated. Given that the process of thermal adaptation shapes the heat-pedestrian activity relationship, this study further identified the specific heat thresholds of walking activity, that respond to the different features of microclimatic street design (Topic 3)

Two urban pedestrian streets - The High Line in New York City, U.S. and Seoul-lo 7017 in Seoul, South Korea - served as the study sites. These sites have the common features of elevated and linear green walkway located in the city center. As part of a city renewal project, they are designed for promoting walking activity in the city center by creating a pedestrian-friendly environment and providing amenities to support diverse leisure activities. These walkways provide a wide range of microclimate conditions coupled with urban design features such as solar geometry, greenery and building materials. Additionally, given their major functions as pedestrian streets to promote leisure walking which is more sensitive to the microclimatic conditions of the walkway than utilitarian walking (Liu 2016; Sharifi and Boland 2018), these two urban walkways are ideal places to explore the dynamic relationships between walking activities, thermal comfort, and urban street design.



Key Focuses

(Topic A)
Application of Outdoor Thermal Comfort Index

- The impact of meteorological conditions at different scales and factors on leisure walking count while examining the explanatory power of thermal comfort indexes.

(Topic B)
Evaluation of Urban Street's Thermal Conditions

- The combined effects of street- and block- scale urban design factors on pedestrian thermal comfort using a multilevel spatial approach.

(Topic C)
Identification of Optimal Range of Thermal Conditions for Pedestrian Activity

- The influence of microclimatic street design features (Solar geometry of SVFs) on a heat-pedestrian activity relationship including walking and sitting activity.

Figure 1.2 Dynamics Relationships among Outdoor Thermal Comfort, Pedestrian Activity, and Urban Street Design

1.2. Research Significance

Theoretically, this study examined the concept of behavioral thermal adaptation using direct observation of pedestrian activities. This concept establishes a framework on how people adapt to the given thermal stimuli by adjusting their behavior. Accordingly, an emphasis was placed on identifying the tolerance range of thermal conditions and exploring the impact of microclimatic design features on the thermal sensitivity of pedestrian activity. This research also offers policy implications to promote pedestrian activity by providing outdoor activity guidelines and regulations to lower heat-related risks.

Methodologically, this study expanded the application of the outdoor thermal comfort indexes to include the evaluation of walking environments. Current evaluation tools for walkability have a limitation in capturing thermal discomfort related to microclimatic features of urban street design. Due to their ability to identify heat vulnerable street spots based on the estimation of thermal loadings caused by street environmental factors, thermal comfort indexes can serve as effective assessment tools to measure the quality of urban streets in terms of their bio-meteorological aspect.

Practically, this study investigated the effects of microclimatic urban street design on pedestrian thermal comfort. The combined effects of multi-scale urban design elements on thermal comfort were examined by exploring different types of street geometry, greenery, and building materials. The study findings could provide street design guidelines that allow the creation of thermally comfortable streets. Accordingly, this study can contribute to creating optimal street environments for improved pedestrian thermal comfort and increased pedestrian activities.

In summary, pedestrian thermal comfort can be improved by properly modifying the design of urban streets. Thermally comfortable street design promotes walking activities with enhanced safety and street vitality in the age of climate change. The findings of this study offer urban designers and landscape architects with the scientific evidence and design guidelines to develop climate-sensitive urban street designs.

1.3. Dissertation Structure

This dissertation has five chapters. Chapter 1 provides a brief background of the research, states research objectives and questions, and highlights the significance of this research topic. Chapters 2, 3 and 4 present the three independent studies, corresponding to the three research questions (Topic A, B and C) of this dissertation. Each of these chapters is completed with an abstract, introduction, literature review, research methods, results, discussion and conclusion.

Chapter 2 (Topic A) examined the heat - leisure walking relationship by analyzing the effects of season, weather, and microclimate as well as outdoor thermal comfort on walking (i.e., the number of pedestrians). In also identified the thresholds of heat stress that pedestrian would tolerate while walking on urban streets. We analyzed the secondary data of hourly pedestrians counts at Seoul-lo 7017, a pedestrian street in Seoul, between 9:00 am to 6:00 pm each day for the full year of 2018. A time-series regression was applied to predict the pedestrian count using publicly available meteorological data as independent variables. Five outdoor thermal comfort indexes were used to calculate the pedestrians' thermal comfort, and their predictive power was evaluated using a machine learning technique.

Chapter 3 (Topic B) investigated the effects of microclimatic urban design features on daytime pedestrian thermal comfort by using a multilevel approach. Specifically, it estimated how different scales of street-scale and block-scale design factors affected the physiological thermal comfort of pedestrians in an urban walkway. The High Line in New York City was selected as the study site for this topic, and data were captured through on-site field measurements conducted in July 2019. To do so, it first evaluated pedestrian thermal comfort by mapping the spatial distributions of thermally uncomfortable hot street spots. Second, the correlation between individual urban design factors and thermal comfort was explored. Finally, the effects of street- and block-scale design factors on thermal comfort were estimated by using hierarchical linear mixed model.

Chapter 4 (Topic C) explored the effects of microclimatic street design features on the heat-pedestrian activity. This chapter focuses on revealing the different scales of meteorological conditions that impact walking and sitting activity. It estimates the microclimate effects on these activities while considering the features of street design; and further identifies the heat thresholds of walking and sitting according to different solar geometrical features measured by sky view factors (SVFs). Panel data analysis was applied to estimate microclimatic street design impacts and identify the associated heat threshold levels. The High Line's five major recreational activity spots were chosen as the study site, and the data were collected from on-site microclimate measurements and unobtrusive observation using video recordings.

Chapter 5 summarized the key findings of chapters 2, 3 and 4, and provided implications for researchers and professionals (e.g., urban designers, urban planners, and landscape architects).

2. EFFECT OF METEOROLOGICAL CONDITIONS AND OUTDOOR THERMAL COMFORT ON LEISURE WALKING

2.1. Introduction

Walking is beneficial to a person's health and wellbeing. A growing body of literature indicates that outdoor walking can help promote physiological and psychological health. It contributes to lowering the risk of heart disease and stroke, high blood pressure, colon and breast cancer, type II diabetes, and reduced depression and anxiety while improving muscular fitness and controlled weight loss (Carron et al. 2003; Health United States 2005). In addition, by getting more people to walk, communities could become safer, and more supportive of social cohesion and interactions, and local economies (Office of the Surgeon General 2015). Despite many known advantages, surveys show that US residents spend only 3% of their time exercising (Centers for Disease Control and Prevention 2010).

The meteorological conditions play a significant role in affecting outdoor physical activities such as walking. Adverse climate or weather is considered a major barrier to walking among all people of all ages and across different regions and countries (Brodersen et al. 2005; Copperman et al. 2007). Rain, snow, strong winds, cloudiness, and excessive heat have strong negative relationships with trip demand, travel distance, and usage of public spaces for exercise and recreation (Cools et al. 2010; Böcker et al. 2013). Heat stress is especially important in warm climates as it poses significant risks to pedestrians such as heat exhaustion, heat cramps, and heat stroke. Moreover, it causes lower street vitality by decreasing outdoor activities of pedestrians in the street (Sharifi et al. 2016; Sharifi and Boland 2018). As the number of scorching days is sharply increasing in most US cities due to climate change (Climate Central 2019), it is increasingly important to identify and remove the meteorological obstacles to ensure safe and comfort of pedestrians.

Over the past few decades, efforts have been made to link walking activities with meteorological conditions. The meteorological factors most frequently explored include precipitation, temperature, cloudiness, windspeed, and humidity. Precipitation is the most powerful cause for decreased walking regardless of its frequency and intensity (Aultman-Hall et al. 2009; Attaset et al. 2010). Air temperature also has a considerable effect on walking (Montigny et al. 2012; Vanky et al. 2017; Suminski et al. 2008). During the hot summer seasons, high temperatures cause reduced walking frequency, especially when combined with strong sunlight (Attaset et al. 2010; Shaaban and Muley 2016). While heavy clouds tend to reduce pedestrian counts in urban streets, sunshine increases the frequency and duration of walking trips in North American cities (Vanky et al. 2017; Attaset et al. 2010; Montigny et al. 2012). These studies have demonstrated that the meteorological conditions are significant predictors of walking activity across diverse regions and cultures.

However, previous studies have not systematically addressed meteorology scales in time and space in terms of the microscale, mesoscale, and synoptic scale (Margery 1993). As these different scales all have an integral impact on walking activity, the degree of weather effects depends not only on the severity but also on the seasonal variations and on-site microclimate circumstances (Chan and Ryan 2009; Tucker and Gilliland 2007). Therefore, it is essential that weather effects are examined by considering multiple scales of meteorological conditions.

Heat stress plays a vital role in determining the acceptable range of walking conditions (De Freitas 2003; Li and Lin 2012; Lin et al. 2013; Sharifi and Boland 2018). The association of heat status with walking activity is reported to be nonlinear, exhibiting a breaking point. When the temperature reaches this point, it triggers alterations in walking activity. The theory of thermal behavioral adaptation terms this the “heat threshold”, which describes the range of heat stress tolerance (Brager and Dear 1998; De Freitas et al. 2007; Li and Lin 2012). If heat stress reaches or passes the heat threshold (upper limit value of this range), pedestrians begin to avoid exposure to the given thermal stimuli by searching for shady areas, stopping outdoor activities, or remaining indoors. The threshold varies depending on the types of physical activity (De Freitas et al. 2007; Li 2008; Li and Lin 2012), and the acceptable heat thresholds for leisure or utilitarian walking remain largely unknown.

This study explored the effect of meteorological conditions and outdoor thermal comfort on the number of people who engage in leisure walking in an urban pedestrian street. Specifically, the effects of different meteorological condition scale including the season, the weather, and the microclimate on leisure walking counts were investigated using time-series analysis while considering the temporal cycle and events of social activities. Special attention was given to identifying the walking heat threshold that determined the range of heat stress tolerance. To measure heat stress, the physiological thermal comfort level of a pedestrian was estimated using five outdoor thermal comfort indexes that are validated and popularly used in the field (Staiger et al. 2011; Coccolo et al. 2016). By comparing each index's capacity to predict walking counts using a machine learning technique, their applicability to behavioral studies was examined.

Leisure walking was chosen for this study due to its high sensitivity to meteorological conditions. Walking for social, leisure, and recreational purposes has been shown to have a stronger association with seasonal and weather variations than utilitarian and routine walking since it is highly flexible, optional, and voluntary (Liu 2016; Sharifi and Boland 2018). A one kilometer long elevated urban walkway called "Seoul-lo 7017" in Seoul, South Korea, was chosen as the case study site because of its major function to support leisure walking and the diverse microclimatic design features. This study collected year-long hourly walking count data using multiple surveillance cameras on the walkway. The publicly available meteorological data used in this study were obtained from the Automatic Weather Stations (AWS) and Automated Synoptic Observing Stations (ASOS) in Seoul Metropolitan Area, provided by the Korean Meteorological Administration (KMA).

2.2. Literature Review

The meteorological conditions have different scales of climate, weather, and microclimate. Weather refers to the atmosphere status at any given time and place and is described in terms of air temperature, humidity, wind speed, pressure, and radiation. Climate is the regionally prevailing weather conditions over large areas for long periods of time. The microclimate is the locally prevailing weather conditions that hold over a very small area and can be altered by features in the urban landscape such as building geometry, tree canopies, and surface materials. While the different scales of meteorological conditions are clearly defined, they interact with each other spatially and temporally. Therefore, it is crucial to examine the weather effect on walking across different scales, considering the seasonal trends and the microclimatic conditions of the given street locations.

The impact of meteorological conditions on walking has been frequently investigated in the three fields: transportation, biometeorology, and environmental design. In transportation, the impact of adverse weather conditions on walking activity was often examined in terms of individual travel behavior such as daily decisions for outdoor activity, travel destinations, and transportation mode choices (Koetse & Rietveld, 2009; Böcker et al., 2013). Biometeorological studies have focused more on assessing thermal comfort and physiological responses to heat conditions (Chen & Ng, 2012; Hasegawa et al., 2017). In environmental design, the major concerns have been the behavioral choice and thermal preference of pedestrians related to spatial characteristics of the public space (Nikolopoul & Lykoudis, 2007; Klemma et al., 2017).

2.2.1. Meteorological Determinants

2.2.1.1. Individual Effects

Previous studies on climate effects on walking activity have two main focuses: individual effects and combined effects. While the individual effects have long been studied, relatively little attention has been paid to the combined integrative effects. Given that thermal comfort is determined by mixed effects of diverse microclimate components, it is necessary to identify not only what components of weather and microclimate have interaction effects, but also how these interactions are related to seasonal changes.

Regarding the individual effect, precipitation has been shown to be a major weather determinant of the walking volume with a strong negative relationship. Generally, it has a strong negative relationship with walking activity. For example, it is reported that rainfall reduces the average hourly volume of pedestrians by approximately 13% in Montpelier, Vermont (Altman-Hall, 2009) and 35% to 56% in Alameda County, California (Attaset et al., 2010). A similar result has been reported in Honshu island in Japan, where daily step counts of elderly Japanese were negatively correlated to the rainfall (Togo et al., 2005). Interestingly, the type of precipitation was not critical. There was no difference in pedestrian flow between rain, snow and drizzle in a study in a study by Montigny (2012). Miranda’s study (2013) found a two-hour time-lag effect of rainfall on walking volume (2013).

Air temperature is one of the most significant microclimate components associated with walking activity. While the magnitude of effects is often lower than that of rainfall (Cools et al., 2010; Sabir, 2010), a notable positive impact on pedestrian volume has been confirmed in European studies. In mild weather conditions, the walking volume increases as temperature elevates (Montigny et al., 2012; Vanky et al., 2017; Suminski et al., 2008). However, during hot weather conditions, its relationship becomes negative, leading to a reduction in pedestrian volume when the air temperature goes up or beyond a certain threshold (Attaset et al., 2010; Shaaban, & Muley, 2016). Many studies conclude this parabolic relationship has the point of heat threshold placed between 25°C and 30°C (Tu et al., 2004; Aultman-Hall et al., 2009; Miranda-Moreno & Lahti, 2013) Furthermore, the relationship could be dependent on the purpose of walking trip as well as the physical features of public space (Sharifi & Boland, 2018).

The intensity of the solar radiation (directly related to sunlight, shade and cloud cover) also has significant impacts on pedestrian volume in public spaces. Heavy clouds tend to reduce the pedestrian volume, while light cloud cover have positive relationships with the walking trip frequency and duration in Boston and San Francisco (Vanky et al., 2017). This is also supported by Attaset et al. (2010)'s study showing the lower pedestrian volume compared to an averaged time period when the cloud cover was heavy. Montigny et al. (2012) also reported that a 5% increase in sunlight area was correlated with a 2% increase over the mean number of pedestrians in nine Europe and North American cities. Interestingly, the impact of solar radiation on walking volume is highly dependent on air temperature (Watanabe & Ishii, 2016; Vanky et al., 2017). In the summer, with high temperatures, people tend to stay indoors or under the shade to avoid the sunlight while vice versa in the winter season.

With respect to wind speed and humidity, walking activity seems to be less influenced. Studies in Brisbane (Burke et al., 2006) and in Montpelier, Vermont (Aultman-Hall et al., 2009) have indicated that wind effect on pedestrian activity is not significant. Although a few studies point out that wind has a negative relationship in specific seasons such as winter, its degree of impact is found to be relatively minor. Higher wind speed was correlated with a lower pedestrian volume in two studies carried out in the Alameda County, California, U.S. and the City of Montreal, Canada (Attaset et al., 2010; Miranda-Moreno & Lahti, 2013.). Suminski et al. (2008) also supported this result by showing the decrease in the number of children walking to school as the wind speed increased. However, in most cases, the coefficient for wind speed was smaller compared to other microclimate components. Similar, humidity has not been shown to make a noteworthy impact on pedestrian volume (Attaset et al., 2010; Aultman-Hall et al., 2009).

2.2.1.2. Combined Effects

In actual outdoor environments, the effect of multiple microclimate components on human thermal comfort occurs concurrently, not individually. The increase in air temperature during mild seasons such as spring and fall may be perceived as pleasant for walking, whereas during the summer, especially when exposed to strong sunlight, people tend to feel uncomfortable as temperature and humidity increase. Moreover, low temperatures combined with strong wind or rainfall remove the heat from the skin surface of the body more efficiently due to convective cooling (Oke, 2017). Despite their key roles in determining the perceived and actual level of thermal comfort of a person, only a few existing studies considered this interaction effects of different microclimate factors on pedestrian activity.

Air temperature plays a key role in interaction effects. The combined effects of air temperature with sunlight or shade is relatively well explored in terms of the preference or presence of pedestrians associated with spatial features of public space. The air temperature’s effects on walking count significantly rely on the shading patterns. During sunny days, the positive effects of temperature decreased when it reached a higher degree (Montigny et al., 2012). Another similar study reported similar interaction effects between temperature and sunlight when studying pedestrian presence in urban plazas in San Fransisco and Montreal (Zacharias et al., 2001; Zacharias et al., 2004), or pedestrian behavior for searching shade in Japan (Watanabe & Ishii, 2016). When it comes to wind speed, Nikolopoulou & Lykoudis (2007) reported its positive relationship with the presence of pedestrians in a Greek plaza in an urban Mediterranean environment during the summer months, while the relationship become negative in the winter months. Moreover, the combined effects of wind and rainfall on pedestrian volume was greater during winter (Miranda-Moreno & Lahti, 2013).

There are two ways to consider the combined interaction effect of microclimate. One way is to use the interaction terms by introducing different compositions of microclimate factors in the model. Given that this method is local, site-specific, and empirically fitted, it is difficult to generalize the outcome of their relationships beyond the local study context. The other way is to adopt the heat index, which has long been used in diverse fields of study and practice. Among different types of indexes, the energy budget indexes are capable of estimating energy flux occurring between human body and the surround microclimate, thus reflecting their combined effects on the physiological thermal comfort level of a person. Since it is based on the principles of energy flux, it can be universally accepted and applied, and will not be confined to the local features. Therefore, the results from this approach can be easily transferrable and comparable.

2.2.2. Socio-cultural and Temporal Determinants

Walking sensitivity to meteorological conditions largely relies on the purpose of the activity (Vanky et al., 2017; Sharifi et al., 2016; Liu, 2016). Compared to utilitarian walking (i.e. walking to and from destinations), leisure walking for recreation, exercise and social puposes tends to be more responsive to the microclimate. In Sharifi et al. (2016)'s observational study, different purposes of pedestrian activity had different levels of resistance to weather conditions. Optional and social pedestrian activities had lower heat thresholds than utilitarian and necessary activities (Sharifi et al., 2016; Sharifi & Boland, 2018). Watanabe & Ishii (2016) also pointed out that pedestrian counts on weekdays are hardly influenced by changes in microclimate because mostly involved in their routine task and work. These results imply that individuals have greater flexibility in leisure walking than in utilitarian walking and they need stronger motivation to overcome unfavorable weather conditions to engage in leisure walking.

Temporal cycle is another key determinant of walking volume as it is associated with the daily and weekly routines of inhabitants (Montigny et al., 2012; Böcker et al., 2013). The pattern of pedestrian flow in the street is highly dependent the time frame such as working hours, commuting hours, and noontime as well as weekend versus weekday. On a weekday, the distribution of pedestrian volume often follows a non-linear shape with the peak time around noon. Therefore, weekday activities are likely to involve more utilitarian and routine walking and thus less sensitive to weather conditions. Meanwhile, on weekends, leisure and exercise activities are more dominant with more flexible schedules, which might explain the strong influences of meteorological conditions on the weekend pedestrian volume (Montigny et al., 2012; Aultman-Hall et al. 2009; Miranda-Moreno & Lahti, 2013).

For the socio-cultural aspect, weather attitude and expectation determine the climate-induced walking activity. Thermal neutrality can be defined as a thermal environment in which more than 80% of people feel neither warm nor cold (ASHRAE, 2010). Several studies argue that outdoor thermal neutrality can vary in different urban locations, climates, and seasons (Böcker et al., 2013). This is mainly due to the social and cultural context that plays a key role in forming these attitudes and expectation, and thus the way people respond to the given weather and thermal stimuli could be different. Thorsson's study (2007) supports this by comparing the survey results of weather attitude about outdoor thermal preference in a Japanese park with those in Swedish park. Their result indicated that, due to the difference in weather expectation, 80% of the park visitors preferred to stay in the shade in Japan, whereas only 14% did in Sweden, at temperatures higher than 20˚C. Suggested by these results, it is highly likely that the walking sensitivity to meteorological conditions of the population groups in different socio-cultural contexts is not identical.

2.3. Methods

2.3.1. Study Area

Seoul-lo 7017 at the center of Seoul, South Korea, was chosen as the study site. Seoul, the capital of South Korea, is home to 9,570,000 residents with a population density of 25,675 person/km² (https://data.seoul.go.kr). The city center where Seoul-lo 7017 is located features intense urban developments with mixed land uses containing residential, recreation, transportation, and commercial. This former highway overpass was redesigned as an elevated walkway to promote walking as part of a city renewal project. With its 1,024-meter length and 17 entrances, it connects three major urban

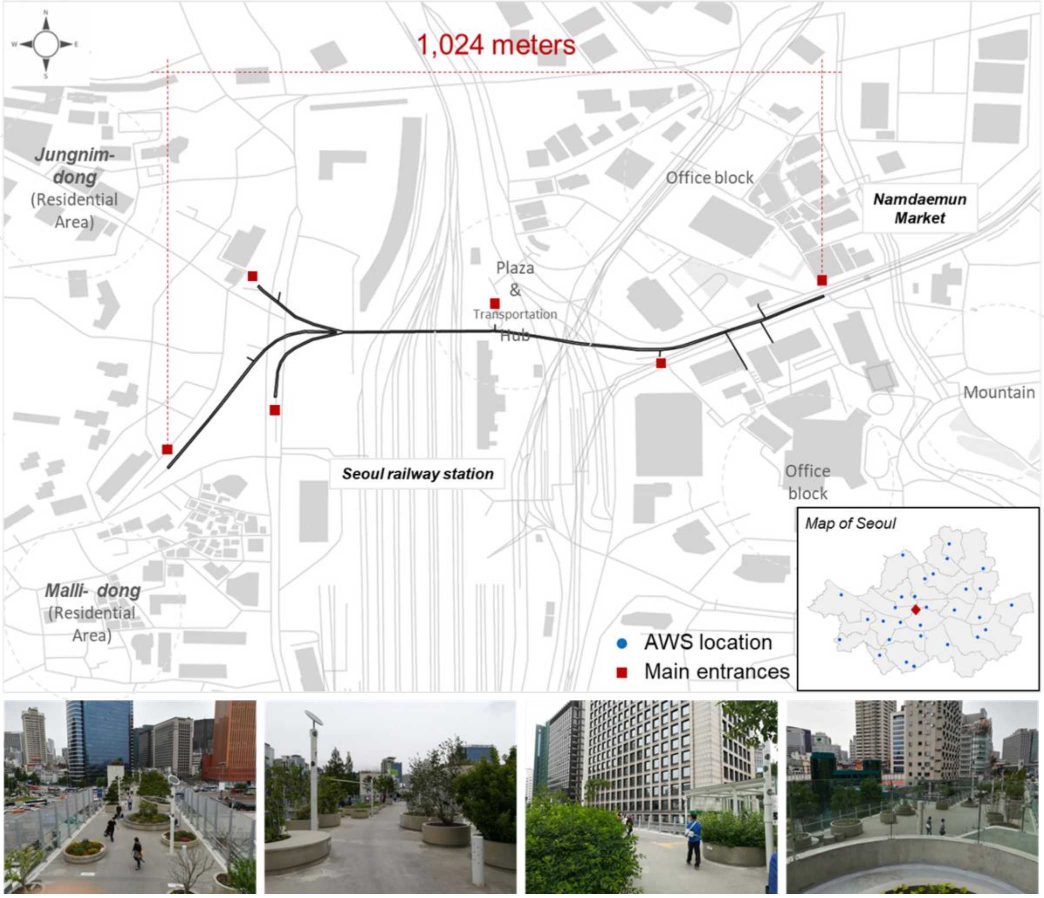


Figure 2.1 The context of Seoul-lo 7017, Seoul

activity hotspots previously isolated from one another, including “Seoul railway station,” “Namdaemun market,” and “Malli-dong” (Figure 1.1). Due to its location close to the main train station and surrounded by high-density offices and residential areas, it is one of the most crowded walkways in Seoul with a daily pedestrian traffic of approximately 14,000 in weekdays in 2018 (http://seoullo7017.co.kr/)

There were three reasons for selecting the Seoul-lo 7017 walkway. First, it is an elevated pedestrian walkway offering a semi-controlled environment for pedestrian observation. Since the potential confounding factors associated with pedestrian activities such as vehicles, crossings, building entrances, and walkway obstacles are restricted due to its elevated design, the effect of meteorological conditions can be detected more easily. Secondly, the primary purpose of using Seoul-lo 7017 is recreational or leisure (Na et al. 2017) which is an idea type of walking for studying the impact of microclimates as previously described. The main theme that guided the redesign of Seoul-lo 7017 was a “sky garden” that included multiple recreational and sociocultural amenities such as coffee shops, performing stages, playgrounds, and art galleries. Finally, according to the Köppen classification, Seoul (37° 31' N, 127° 1' E) has a humid continental climate with four distinct seasons, enabling the examination of walking under a wide range of meteorological conditions.

2.3.2. Data Acquisition

2.3.2.1. Walking Count Data

This study used twelve months of walking count data from July 2017 to June 2018 collected by the Seoul Metropolitan Government's Department of Parks and Recreation. This secondary data set consisted of the hourly pedestrian volume and the presence of people on the walkway, recorded by an in-person manual counting method. The Department of Parks and Recreation counted the number of pedestrians from 9:00 to 23:00 every day by watching the recorded video clips from multiple surveillance cameras located at the five major entrances of the walkway. This was supplemented by the short duration pedestrian count procedure to predict the hourly volume by multiplying six to ten-minute duration of the walking counts. The surveillance cameras were three meters above the walkway, which was high enough to look down on people to discriminate between them and avoid blockages.

Only the daytime data collected between 9:00 and 18:00 were selected for this study. The total number of pedestrian observation hours and counts were 3,524 hours and 6,042,459 people for the full year of data used in this study. Past studies using surveys and interviews experienced limitations in matching weather events with walking activity temporally given that those self-reported data are largely dependent on previous memories, diaries, notes, or subjective opinions. This makes it difficult to investigate the association between walking activity and weather conditions at the finer temporal scale. This study addresses this limitation by using objectively measured hourly walking data. Meanwhile, due to the availability of hourly walking count data, this study captures not only the immediate but also the delayed effects of weather events.

2.3.2.2. Weather and Microclimate Data

The meteorological data were acquired from two types of weather sensor stations to measure the different scales of meteorological conditions: The Automatic Weather Stations (AWS) for the mesoscale weather conditions and the Automated Synoptic Observing Stations (ASOS) for the on-site scale microclimate conditions. Both are publicly accessible via a web-based service managed by the Korean Meteorological Administration (KMA). To determine the weather condition, hourly mean values of twenty-nine AWS stations dispersed over the Seoul metropolitan area were spatially averaged, by taking the hourly data corresponding to the walking count hours. These included precipitation (mm), visibility (km), cloudiness (%), yellow dust (µg /m3), and daylight hours. For the microclimate, only one ASOS weather station closest to the study site, which was approximately 900 meters away, was used. The dataset included air temperature (°C), relative humidity (%), windspeed (m/s), wind direction, and solar radiation (W/m^2). As the elevation of meteorological station affects the windspeed, it was extrapolated to generate an estimation for the 10-meter height using the power-law which is the vertical profile of windspeed (Manwell et al. 2002).

2.3.2.3. Outdoor Thermal Comfort

Human thermal comfort is defined as “The condition of mind, which expresses satisfaction with the thermal environment” (ANSI/ASHRAE Standard 55, 2017). It is related not only to the microclimate components such as air temperature, relative humidity, windspeed, and solar radiation, but also to the physiological, physical, psychological and social and behavioral factors (Auliciems and Szokolay 2007; Chen and Ng 2012; Coccolo et al. 2016). To assess thermal comfort objectively, numerous indexes have been developed to generate a single value of estimated outputs by integrating meteorological and human physiological determinants of perceived thermal comfort. Although a gap remains between the actual and predicted estimation of perceived thermal comfort, this output value is widely used to indicate people's physiological, psychological, and behavioral responses to the given thermal stimuli in various industries and academic fields.

With a long history of development and applications, outdoor thermal comfort indexes can be broadly categorized into two types of thermal models: an empirical (or direct) and a rational (or analytic) model (Blazejczyk 2012; Parsons 2014; Havenith and Fiala 2015; Coccolo et al. 2016; Binarti et al. 2020). Given that the two models provide a mathematical description of human responses to the thermal environment, they have been used not only to calculate indexes but also to predict people's thermal responses (Parsons 2014). The empirical model was developed by exposing human subjects to a range of thermal environments and fitting empirical regression equations using the human response data obtained. Therefore, the estimation outputs operate well within the specific conditions used to develop the method. In contrast, the rational model provides a mathematical representation of the human body and its thermoregulation systems using the principles of thermal balance, transfer, and regulation. It adopts energy budget equations that rationalize the indexes, and thus universally applicable equation across the climates, regions, and seasons could be acquired with sufficient explanatory power (Jendritzky and Dear. 2009).

In this study, five different outdoor thermal comfort indexes were adopted to evaluate daytime pedestrian thermal comfort, which are validated and popularly used in the field (Staiger et al. 2011; Coccolo et al. 2016). These are Wet Bulb Globe Temperature (WBGT), Effective Temperature (TE), Comfort Formula (COMFA), Physiological Subjective Temperature (PST), and Universal Thermal Climate Index (UTCI) (Błażejczyk 2006; Błażejczyk et al. 2010; Jendritzky et al. 2012; Matzarakis et al. 2014; Vanos et al. 2012; Staiger et al. 2011; Havenith and Fiala 2015; Brown and Gillespie 1986). The WBGT and TE are empirical models, while COMFA, PST, and UTCI are rational models. Each index's estimated outputs were used to compare explanations of the variation in the walking count. The calculation was performed with the BioKlima 2.6 software package and the COMFA sheet (Brown & Gillespie, 1986; Vanos, Warland, Gillespie, & Kenny, 2010). To estimate the prevailing thermal comfort conditions, it was assumed that a person was walking in the middle of the walkway, which is an open space without shade. As a basic COMFA model parameter setting, the metabolic rate of a walking person of 190W/m^2, standard walking speed of 1.4m/s, and different sets of seasonal clothing insulation were selected.

2.3.3. Statistical Analysis

This study adopted a time-series regression to deal with the serial autocorrelation issues of the walking count datasets when estimating the time-lag effects of meteorological conditions. Serial autocorrelation occurs when error terms are serially correlated over time. It violates the assumption of the Gauss-Markov theorem stating that the errors in the model are uncorrelated with equal variances and an expectation value of zero, which should be met for the best linear unbiased estimates (Henri 1971). We assumed that this was mainly caused by the sequential and short interval observations of walking counts taken on the same day, which are subject to repeated measurement bias. Without a proper remedial measure, it could cause spurious regression outcomes accompanied by an underestimated standard error, inflated R-squared value, and inefficient estimate. The Cochrane-Orcutt model was therefore adopted, which is a time-series estimator adjusting a linear regression by taking a quasi-difference in the model (Cochrane and Orcutt 1949; Dufour et al. 1980). The equation was as follows:

$$y_t - \rho y_{t-1} = \alpha(1-\rho) + \beta(x_t - \rho x_t) + e_t$$

where $y_t$denoted the dependent variable of interest at time t, β was a column vector of coefficients, and x_t was a row vector of independent variables at time t. In this specification, e_t was white noise errors. Accordingly, the temporal trends, cycles, and variations in the walking count were considered using an iterative estimation process while removing the effects of serial autocorrelation to predict the delayed time effects of meteorological factors. To identify the combination effects of meteorological scale of climate, weather, and other microclimate components, we also estimated the interaction and delayed time effects of air temperature with those three scales of meteorology.

In addition to the Cochrane-Orcutt model, Bayesian Model Averaging (BMA) and Leave One Out Cross Validation (LOOCV) were each introduced to conduct an anterior and a posterior estimation. BMA is a variable selection approach using a time-varying parameter estimate obtained by averaging the estimates of the different set of models under consideration, which is weighted by its model probability (Fragoso et al. 2018; Hinne et al. 2020). It selects the most significant meteorological factors and social activity variables based on all possible scenarios of the model estimation rooted in the theory of Bayesian probability. The parameter of $\hat{\theta}_{BMA}$ can be estimated by

$$\hat{\theta}_{BMA} = \sum_{k=1}^{K} \hat{\theta}_k \, p \, (M_k \mid Z)$$

where $\hat{\theta}_k$ is the vector of parameters of the model M_k, M_k is the true model, Z is the given data, and $p \, (M_k \mid Z)$ is the prior density of the parameters under the model M_k (Hoeting et al. 1999; Viallefont et al. 2001). According to the BMA result, the variables of cloud cover, visibility, and rainy season were omitted in the model.

To evaluate model validity, LOOCV was used to test how accurately the five outdoor thermal comfort indexes would perform when explaining the variation of walking volume. LOOCV is a branch of cross validation method that is used to evaluate model validity and assess whether the results of statistical analysis could be generalized to an independent dataset using a machine learning algorithm (Efron 1982; Cheng et al. 2017). It measures the fitness of prediction to derive a more accurate estimate of model prediction performance by testing the model's ability to predict new data (testing set) that was not used during estimation (training set). Accordingly, by comparing their estimation outputs, the relative performance of five outdoor thermal comfort indexes in predicting the walking count can be measured. This was provided by

$$cv = \frac{1}{N} \sum_{i=1}^{N} e_{[i]}^{2}$$

where $e_{[i]}^{2}$ =$y_i - \hat{y}_{[i]}$,, the observations are given by y_1, ……, y_N and $\hat{y}_{[i]}$ is the predicted value obtained when the model is estimated with ith case deleted.

2.4. Results

2.4.1. Descriptive Statistics

Table 2.1 shows the seasonal variations in weather and microclimate conditions in the study site. The summer from June to August is hot and highly humid. Its hourly mean air temperature was 27.41°C, and the hottest day reached over 35°C. There was a month-long rainy season starting in mid-July, creating hot and muggy conditions. Meanwhile, the winter months from December to February are drier (Rh of 40.87%) and colder (Ta of - 0.81°C). The spring and fall are mild seasons with an hourly mean air temperature of 15.8°C and 17.8°C, respectively. On-site microclimate conditions showed a slight difference in air temperature and windspeed compared to the weather in Seoul. The temperature of the study site was recorded at 27.41°C in August, which was

2~3°C higher than the Seoul's suburban areas due to the urban heat island effects. The winter windspeed was 2.36m/s, which was also slightly higher than Seoul's average.

The walking count was strongly related to the month of the year, day of the week, and time of the day. The fall and spring covered over 70% of the yearly total walking count with the peak observations in October and March. The biggest daily difference occurred during these two months as well. October had the highest hourly mean count of 3,053 pedestrians, while January had the lowest at 1,071. Days of the week were also clearly linked with the walking count pattern. Regardless of the month, the weekend counts were much higher than weekdays, and their difference was most pronounced in September and October (Figure 2.2: upper plot). When investigating the time of the day, we found that 12.00 to 13.00 had the highest hourly mean count for most months, whereas the morning hours from 9.00 to 11.00 am were relatively lower (Figure 2.2: lower plot). Most seasons had a peak around noon, and steady or decreased walking counts in the afternoon.

Table 2.1 Summary Statistics for Hourly Mean Walking Count, Weather, and Microclimate by Four Seasons

	Spring		Summer		Fall		Winter	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Walking Count	1718.92	988.84	1502.14	932.67	2395.76	1665.55	1245.89	806.963
Weather								
Precipitation (mm)	0.19	1.45	0.54	2.94	0.02	0.19	0.02	0.42
Cloud cover (%)	5.19	4.15	7.24	3.13	4.61	3.86	3.99	4.07
Visibility (m)	1336.21	600.29	1398.44	581.35	1630.64	509.42	1479.37	599.68
Fine-dust (㎍/㎥)	42.95	20.48	26.13	10.82	31.78	13.35	43.62	17.48
Microclimate								
Air temp (°C)	15.78	6.48	27.41	3.28	17.79	8.22	-.81	5.44
Solar radiation (W/m^2)	438.24	269.90	388.26	245.45	265.50	193.39	210.79	164.10
Relative humidity (%)	49.12	21.89	61.71	18.07	46.90	15.35	40.87	17.88
Windspeed (m/s)	2.35	1.10	2.39	1.04	2.38	1.14	2.36	1.22

* Season: Spring (Mar ~ May 2018), Summer (Jun 2017, Jul & Aug 2018), Fall (Sep ~ Nov 2017), Winter (Dec ~ Feb 2017)

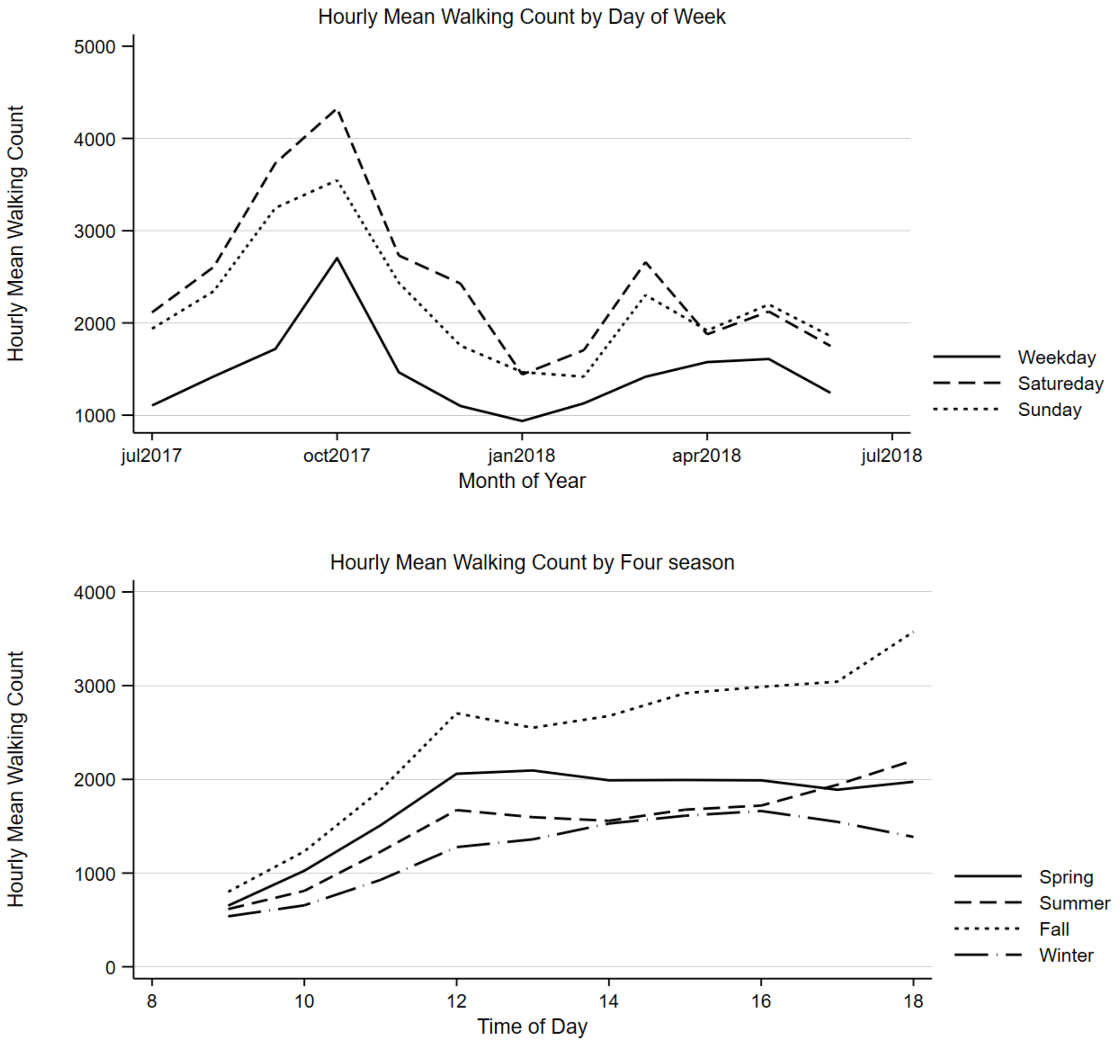


Figure 2.2 Hourly Mean Walking Count for Twelve Months by Day of Week (upper plot) and Hourly Mean Walking Count for Time of Day by Four Seasons (lower plot)

2.4.2. Regression Analysis

2.4.2.1. The Effects of Meteorological Condition on Leisure Walking Count

The time series analysis was adopted to estimate the impact of meteorological conditions on the leisure walking count. In Table 2.2, three nested models A, B and C are presented, which examined how meteorological and thermal comfort variables predicted the leisure walking count and how those variables contributed to the overall model fit. Model A was estimated as a baseline which only consisted of the control variables related to temporal cycles and social activity. Models B and C were estimated by adding the explanatory variables of meteorology and thermal comfort to Model A. In model C, the air temperature values were replaced by thermal comfort estimations calculated by five different outdoor thermal comfort indexes to test the indexes' capacities to predict walking count. The regression output shows that the adjusted R-squared increased by 15% when the meteorological and thermal comfort variables were added. The AIC and BIC test results also pointed out that Models B and C were parsimonious and preferred over Model A. This meant that meteorological and thermal comfort variables enhanced the predictive power of the suggested model significantly.

Above all, air temperature played a vital role in determining walking count patterns (Table 2.2). When all other variables were held at a constant value, a 1°C increase in air temperature was associated with a 0.56% rise in the square root of the hourly mean walking count. This variable had the largest effect explaining 5.48% of the variation in the walking count. Its relationship followed a parabolic shape, which indicated that the pedestrian count sharply increased until it reached a breaking point referred to as the heat threshold and then declined. Meanwhile, precipitation and windspeed had a negative linear correlation with the walking count outcome that decreased by 3.29% when it was raining as well as reduced by 0.42% for every 1% increase in windspeed. On top of that, precipitation had a one-hour delayed impact in summer and winter, which meant that its effect remained for an hour after the rainfall.

Considering the time-lag and interaction effects, Table 2.3 illustrates the output of time series regressions. The models presented in Table 2.3 are built upon on Model B shown in Table 2.2. In other words, it is an extension of Model B to further examine the air temperature's effect on walking count, which is dependent on the season, weather, and other microclimate variables. To introduce the quadratic relationship of air temperature with walking count, the term Ta * Ta was used as an interaction effect. A full year model in Table 2.3 shows that the predictive power of the full model increased up to 32% when considering these two effects. The degree of its impact relied on the two seasons of spring and fall. For the microclimate, solar radiation and relative humidity had synergetic effects on air temperature. Specifically, relative humidity had significant interactions in summer with a negative coefficient of 36.57. Solar radiation also interacted with a negative coefficient of 2.81 and 4.53 for the spring and fall seasons, respectively. These outputs indicated that the higher the relative humidity and the more intense the solar radiation, and that the hotter the air temperature and the greater the negative impact on walking count.

Table 2.2 Time Series Regression Output: The Effects of Microclimate and Thermal Comfort on the Walking Count

		Model A		Model B		Model C									
		b	SE	b	SE	b	SE	b	SE	b	SE	b	SE	b	SE
Temporal cycle	Day of the week														
	Weekday	-15.01***	1.47	-13.88***	0.97	-13.98***	0.99	-13.87***	0.97	-14.23***	1.08	-13.97***	0.97	-13.98***	1.01
	Sunday	-1.52	1.85	-1.73	1.22	-1.77	1.24	-1.76	1.22	-1.66	1.36	-1.81	1.23	-1.67	1.27
	Part of the day														
	Morning	-1.60**	0.59	-2.32***	0.55	-2.35***	0.55	-2.37***	0.55	-2.50***	0.56	-2.51***	0.55	-2.41***	0.56
	Noon	1.89***	0.39	1.45***	0.37	1.42***	0.37	1.44***	0.37	1.26***	0.38	1.31***	0.37	1.29***	0.38
Social activity	Holiday	18.04***	2.52	16.85***	1.66	16.88***	1.69	16.86***	1.65	17.44***	1.84	17.00***	1.66	17.14***	1.73
	Event	12.38***	1.73	6.39***	1.17	6.60***	1.19	6.55***	1.17	7.58***	1.30	6.41***	1.18	6.88***	1.22
	Break season	-1.51*	0.66	-2.03***	0.49	-2.32***	0.51	-2.01***	0.49	-1.38*	0.54	-1.90***	0.49	-1.67**	0.51
Climate	Season														
	Spring			6.05***	1.15	7.08***	1.24	6.38***	1.16	1.17	1.22	6.00***	1.15	4.31***	1.19
	Fall			11.61***	1.14	12.46***	1.19	11.86***	1.14	8.34***	1.22	11.72***	1.14	10.37***	1.17
	Winter			6.41***	1.79	6.27***	1.85	6.15***	1.75	-5.77***	1.56	5.78***	1.74	1.59	1.75
Weather	Precipitation			-3.29***	0.73	-3.31***	0.73	-3.39***	0.73	-3.42***	0.74	-3.32***	0.73	-3.29***	0.73
	Precipitation - 1hr lag			-2.31***	0.64	-2.32***	0.64	-2.33***	0.64	-2.37***	0.65	-2.23***	0.64	-2.27***	0.65
Micro climate	Wind speed (m/s)			-0.42**	0.15	-0.47**	0.15	0.23	0.16	-0.33	0.18	0.58**	0.18	0.19	0.18
	Relative humidity(%)			-0.07***	0.01	-0.12***	0.01	-0.07***	0.01	-0.06***	0.01	-0.10***	0.02	-0.08***	0.02
	Solar radiation (W/m^2)			-0.01***	0.01	-0.00***	0.01	-0.01***	0.01	-0.01	0.01	-0.01***	0.01	-0.01***	0.01
Thermal comfort	Air temp (°C)			0.56***	0.05										
	WBGT					0.72***	0.07								
	ET							0.54***	0.053						
	PST									0.074*	0.034				
	UTCI											0.403***	0.04		
	COMFA													0.034***	0.01
	Constant	56.70***	1.38	45.01***	2.18	43.70***	2.33	46.96***	2.05	58.15***	1.89	51.87***	1.83	59.56***	1.75
	Adj.R^2	0.11		0.26		0.25		0.26		0.22		0.26		0.24	
Durbin-Watson statistic		1.91		1.90		1.91		1.90		1.90		1.91		1.90	

* p < 0.05, ** p < 0.01, *** p < 0.001

| * Reference group: Saturday (Day of week), Afternoon (Part of the day) and Summer (Season)

Table 2.3 Time Series Regression Output Considering Interaction Effects: The Time-lag Effect of Precipitation and Interaction Effect of Air temperature on Walking Count by Four Season.

	A year		Spring		Summer		Fall		Winter	
	β	SE	β	SE	β	SE	β	SE	β	SE
Time-lag effect										
Preci * 1hr	-0.688***	0.14	-0.564*	0.26	-0.473*	0.21	-0.373	0.45	-1.111*	0.56
Preci * 2hr	-0.283*	0.13	-0.459	0.26	-0.124	0.19	0.023	0.41	-0.059	0.50
Interaction effect with air temperature										
Microclimate										
T*a* * T*a*	-13.165***	1.97	-16.777***	3.35	-3.993	15.29	-13.247***	2.97	5.33	4.40
T*a* * Rh	2.000	1.10	1.977	2.67	36.573***	8.75	2.002	3.17	5.704	4.34
T*a* * Ws	0.006	0.46	2.889	1.74	-3.421	3.05	1.152	1.25	-2.596	1.63
T*a* * Sol	-1.845***	0.50	-2.810*	1.37	0.173	0.90	-4.534***	1.16	0.972	2.58
Weather										
Ta * Preci	-0.071	0.35	-0.116	0.93	-3.17	2.16	1.026	1.40	-3.715	3.41
Season										
T*a* * Spring	6.261***	1.87								
T*a* * Summer	7.480	4.90								
T*a* * Fall	7.154***	2.11								
T*a* * Winter	Ref									
Adj.R^2	0.323		0.302		0.187		0.430		0.368	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

* Abbreviation: Air temperature (Ta), Relative humidity (Rh), Solar radiation (Sol), Wind speed (Ws), Precipitation (Preci)

* Note that the regression outputs are built upon the Model B in table 2.2. Only time-lag and interaction effects are reported in this table.

2.4.3. The Predictive Capacity of Outdoor Thermal Comfort Indexes

The predictive capacity of outdoor thermal comfort was examined by using air temperature as an alternative indicator of pedestrian heat stress. To estimate outdoor thermal comfort, five indexes including WBGT, TE, COMFA, UTCI, and PST were used. As shown in Table 2.2, their contribution to the overall model fit was almost identical, all with an increase in the adjusted R-squared values of less than 4%. Due to the minimal difference in the model performance, no evidence was found as to which index was a superior to others in predicting the walking count outcome. It was also notable that, except for the UTCI and TE, their predictive capacities were slightly lower than the air temperature at 26%, which contradicted our assumption that empirical and rational model indexes would be better predictors than the simple air temperature.

Moreover, we further evaluated the predictive capacities of the five indexes by exploring seasonal variations of their performance in model prediction. Table 2.4 shows the predictive capacities of the five indexes of WBGT, TE, COMFA, UTCI, and the PST for all four seasons. While their capacities varied according to what indexes were used and what seasons they belonged to, the regression output indicated that estimated thermal comfort values of the five indexes had consistently positive linear relationships with walking counts except during the summer season. TE, COMFA, and UTCI estimations were all statistically significant throughout the year, suggesting their significant roles for all seasons. However, the WBGT and PST did not predict walking during summer and spring. Their predictive capacities greatly varied according to the seasons, with over 15% of seasonal differences in the adjusted R-squared values across the five indexes. Their overall predictive capacities peaked in the fall and were lowest in the summer.

Table 2.4 shows the results of model validity tested using the LOOCV method. This method examined how accurately the suggested models using five different indexes performed. The output result indicated that the five heat indexes performed similarly in their prediction accuracy of the walking count outcome. Although the WBGT had a slightly higher Pseudo-R squared value at 59.1% than other indexes, overall variations in the Pseudo-R squared values across the indexes were less than 6%. Moreover, the RMSE and MAE output values of all indexes were around 7.0 and 5.5, respectively, meaning that their regression outputs had a similar fit and association with the dependent variable. Accordingly, the results indicated that the WBGT had a slightly better performance, but the overall predictive power of the five indexes was almost identical.

2.4.4. Heat Threshold of Walking Activity

The heat threshold of walking activity for each season is shown in Figure 2.3. This threshold indicated the breaking point of the relationship between heat and the walking count due to the pedestrian's thermal adaptation limit. To estimate the threshold, a segmented regression was used to examine the statistical significance of the heat threshold in the nonlinear curve shapes. The results demonstrated that spring and summer had a quadratic relationship, while fall was linear and winter was exponential.

Table 2.4 The Outdoor Thermal Comfort Indexes’ Predictive Capacity and Model Validity

	WBGT			TE			COMFA			UTCI			PST		
	b	SE	Adj.R^2	b	SE	Adj.R^2	b	SE	Adj.R^2	b	SE	Adj.R^2	b	SE	Adj.R^2
Predictive Capacity															
A Year	0.720***	0.075	0.259	0.540***	0.053	0.266	0.074*	0.034	0.240	0.403***	0.040	0.264	0.034***	0.005	0.244
Spring	0.459***	0.103	0.234	0.358***	0.077	0.236	0.025***	0.007	0.223	0.288***	0.061	0.237	0.061	0.048	0.205
Summr	-0.377	0.251	0.154	-0.513*	0.234	0.156	-0.089***	0.017	0.2	-0.616***	0.173	0.17	-0.153*	0.071	0.159
Fall	0.737***	0.117	0.384	0.583***	0.086	0.393	0.051***	0.008	0.388	0.457***	0.064	0.395	0.284***	0.063	0.353
Winter	1.639***	0.141	0.359	0.970***	0.089	0.345	0.090***	0.009	0.316	0.857***	0.078	0.341	1.233***	0.157	0.282
Model validity (Output of LOOCV)															
RMSE	6.851			7.064			7.295			7.049			7.407		
MAE	5.247			5.416			5.531			5.379			5.723		
Psd-R2	.591			.573			.548			.574			.537		

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Summer and spring had an inverse U-shaped curve because the walking count stopped increasing or began to decrease when it reached the heat thresholds, which were 24.4°C for spring and 27.88°C for summer. The summer heat threshold was higher as expected, and its slope was steeper than the spring values. In the fall, the walking count increased proportionally as the temperature rose. Conversely, winter had a U-shaped curve as walking counts climbed exponentially as temperature increased.

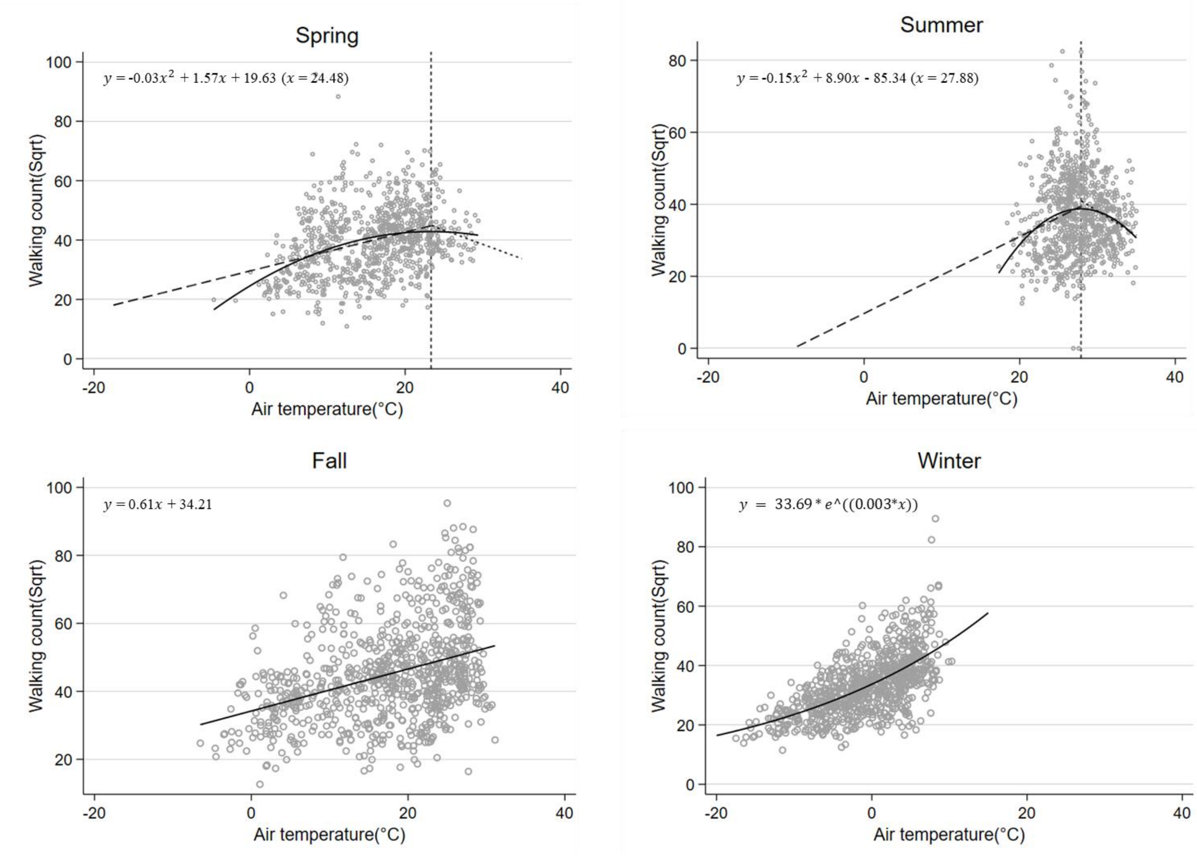


Figure 2.3 Heat Thresholds of Four Seasons: Spring (24.48 °C), Summer (27.88 °C), Fall (none) and Winter(none)

We also investigated that the heat thresholds during the weekends versus weekdays. We assumed that the weekend heat threshold would be higher than the weekday threshold. This is because leisure walking would be more dominant on weekends (Na et al. 2017), as it is more flexible and a voluntary practice often resulting in lower heat threshold. The regression result on summer daytime walking count clearly indicated that the heat threshold was strongly associated with the day of the week. The heat thresholds for the weekdays and the weekend were observed between 18°C and 21°C. While the regression coefficient, the degree of temperature effects on the walking count, was around -0.15 regardless of the day of the week, the heat threshold on weekdays was lower at 18.98°C than on weekends at 20.55°C. This result contradicted previous study results presenting that utilitarian walking's heat sensitivity was higher than leisure one at the study site.

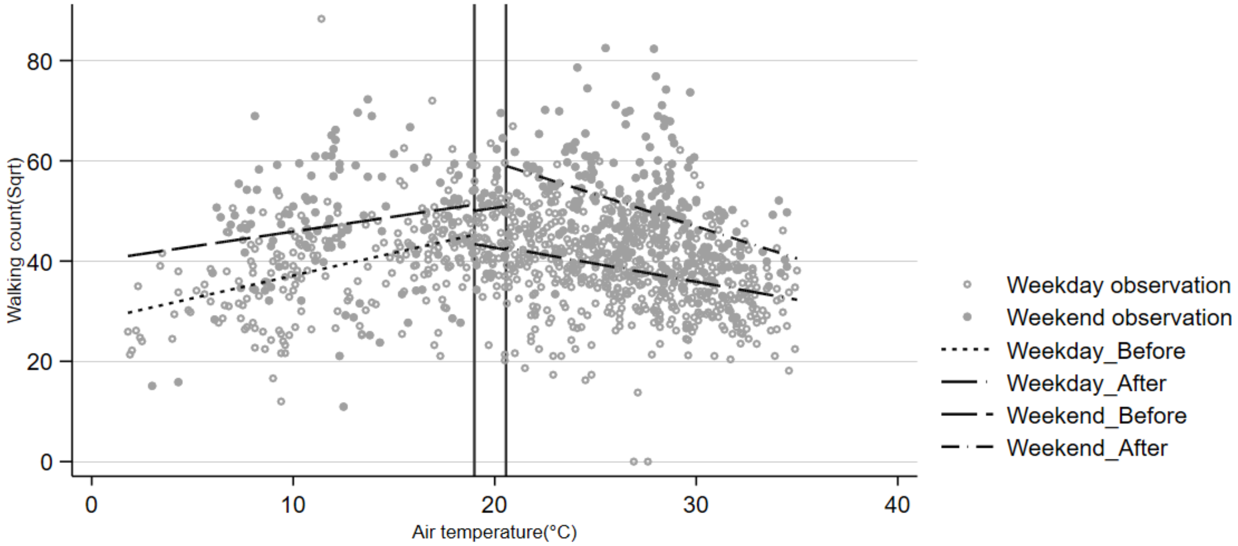


Figure 2.4 Heat Thresholds of Weekday (18.98 °C) and Weekend (20.55 °C) for Spring and Summer

Weekday_Before and Weekend_Before is the slope when air temperature is less than heat threshold. Weekday_After and Weekend_After is the change in the slope as a result of being heat threshold or higher.

2.5. Discussion

Meteorological condition has modest, but significant effects on walking activity (Böcker et al. 2013; Miranda-Moreno and Lahti 2013; Aultman-Hall et al. 2009; Suminski et al. 2008; Shaaban and Muley 2016; Watanabe and Ishii 2016). This study corroborated these findings while presenting new discoveries. It contributed new knowledge to the field by analyzing the effects of urban meteorological conditions and outdoor thermal comfort on leisure walking count by considering the different scales of season, weather, and microclimate. It further identified the heat thresholds of walking activity and exploring the predictive capacity of outdoor thermal comfort indexes.

The different meteorological scales of season, weather, and microclimate were clearly associated with the leisure walking count. As shown in Table 2.2 and 2.3, our results indicated that their impacts on the walking count were determined not only individual intensity, but also by other scales of meteorological conditions. In other words, the impact and types of relationship between weather and microclimate were largely influenced by the seasonal context. Past studies also reported that weather effects were confined by seasonal and microclimatic contexts (Aultman-Hall et al. 2009; Attaset et al. 2010). Considering the interaction and time-lag effects, as shown in Table 2.3, the adjusted r-squared value of our suggested “full-year model” was around 34%, which was comparable to earlier studies (Attaset et al. 2010; Prins et al. 2015; Shaaban et al. 2016). However, inconsistency remains about their relative degree of impact according to study locations. It could be caused by the additional confounding factors not included in the models such as sociocultural context (weather expectations and attitudes, demographics, walking attitudes) and street and roadside' characteristics (aesthetics, accessibility, amenities, and land use).

The study results illustrate that heat conditions play a key role in determining the leisure walking count. It was observed that air temperature had a nonlinear parabolic relationship with walking counts, showing an inverse U-shaped curve in spring and summer. A similar pattern had been observed in multiple studies where it often appeared on hot summer days (Tu, et al. 2004; Aultman-Hall et al. 2009; Lin et al. 2012; Sharifi and Boland 2018). We further investigated the combined effect of air temperature with other meteorological factors and found that the actual feeling of thermal comfort was determined by different combinations of these components (Brown and Gillespie 1986). Interestingly, the air temperature had considerable synergetic effects when combined with strong solar radiation. Several studies supported this finding by reporting the negative combined effects of high temperature and strong solar intensity on walking activity (Montigny et al. 2012; Watanabe and Ishii 2016).

The time-series analysis indicated that rainfall had a negative one-hour time-lag impact on the walking count (Table 2.3). This means that there was a delayed impact that remained one hour after rainfall. A similar outcome has been found in several studies that observed one or two-hour time-lag for both cycling and walking activity (Miranda-Moreno and Fernandes 2011; Miranda-Moreno and Lahti 2013). However, it remains unclear which factors determine the length of the effect and how they might be associated with different types of precipitation such as snow, hail, and sleet. Further, this study demonstrated that the standard coefficient and the magnitude of its impact ranged between -0.89 and -1.46. This figure is much lower than other studies' results. This inconsistency may be caused by the methodological differences in the treatment of precipitation variable for the model fit (Attaset et al. 2010). Moreover, we also suspected that the weather forecast would offset the degree of its impact by affecting decision-making and planning of outdoor activities ahead of time.

This study investigated the heat threshold of walking activity by the day of the week. We assumed that the weekend heat threshold would be lower than the weekday one. This is because leisure walking activity is more dominant on the weekend, and more susceptible to heat stress than utilitarian considering its voluntary nature. Several studies indicated that leisure walking is more sensitive to heat conditions than utilitarian walking (Sharifi et al. 2016; Sharifi and Boland. 2018). However, as shown in Figure 2.4, the segmented regression output demonstrated that the weekend threshold of 20.55°C was slightly higher than the weekday one of 18.98°C, which contradicted our assumption and the results from the previous studies. One possible explanation is that weekend walking could be slower, people can take more breaks, and therefore they are able to tolerate higher temperatures.

The predictive capacities of five outdoor thermal comfort indexes were examined as indicators of leisure walking count. While there were some seasonal variations, the adjusted R-squared values of the models using the five different indexes were between 0.24 and 0.27 (Table 2.4). Unlike our initial assumption that rational indexes would be superior to empirical ones, thermal comfort estimated by those five indexes versus the empirical ones showed similar levels of predictive power for walking count. One feasible explanation is that we evaluated the prevailing conditions of thermal comfort that did not consider spatial variations in walkway determined by the physical features of street design such as building geometry, tree shading, and built materials. Given that the microclimate determines pedestrian's decision about where and when to rest, which route to take, and how long the walk will be, we hypothesized that a rational index such as COMFA, UTCI, and PST would improve the model's predictive power if they were applied to studies on thermal behavior of pedestrians.

2.6. Conclusion

This study examined the effects of meteorological conditions and outdoor thermal comfort on the number of people who chose to walk. Specifically, the different scales of climate, weather, and microclimate impacts on the leisure walking count were investigated in the pedestrian-only urban walkway named Seoul-lo 7017 in Seoul, South Korea. The emphasis was on revealing the combined interaction effects of meteorological factors by exploring the predictive capacity of outdoor thermal comfort and identifying relevant heat thresholds. Methodologically, the time-series analysis was used to obtain these results while account for the serial autocorrelation of the models and the time-lag effects of weather conditions. Although this study uses pedestrian counts in only one urban pedestrian-only walkway, the wide range of meteorological conditions of the local environment and the hourly walking count data of a full year provide rich data for robust analyses.

The results of this study are consistent with previous studies confirming that season, weather, and microclimate had a significant impact on the leisure walking count. In terms of climate, there was a clear seasonal pattern with the highest volumes in the fall, a secondary peak in the spring, and the lowest volumes in the summer. For weather and microclimate, the air temperature had the largest effect explaining 5.48% of the variation in the walking count. In the spring and summer, the temperature had a parabolic relationship with the walking count peaking between 24.4°C and 27.8°C, which was the heat threshold. The combined effects of temperature and relative humidity had the largest impact throughout the year, and a one-hour time-lag effect of rainfall was observed. For the predictive power of outdoor thermal comfort indexes, the rational models explained around 33% of the variation in the walking count. This finding indicated that, considering a portion of variability, it is high and the application of indexes as an indicator in walking levels might be worthwhile. Moreover, to further improve the model estimations, the future work may employ surveys and interviews to consider individual behavioral motivations behind pedestrian trip-making.

For the meteorologists and urban planners, these findings are useful in several ways. First, the study results suggest that outdoor thermal comfort indexes are feasible to evaluate the physical street environment where non-sedentary behavior is dominant. It supports the potential applicability of rational model indexes for improving existing walkability audits to better assess the thermal characteristics of the street. Those indexes can also be incorporated into the quality assessment efforts for unban public spaces, which may be of interest to researchers and professionals in the environmental planning and design fields. Secondly, the outputs provide empirical evidence that can be used to develop the behavioral thermal adaptation models that predict the walking activity and its optimal ranges of heat stress. In the age of climate change, these can be used to provide operational guidance on how to manage and operate the streets and public spaces as well as organize outdoor social events during extreme weather events.

In summary, this study showed that different meteorological scales affected leisure walking significantly but differently. The volume of pedestrian activities differed across seasons. Within each season, pedestrians appeared to consider the weather conditions, primarily the air temperature to decide whether or not to go out. Once they were outside walking, pedestrians tend to consider the microclimate to determine the location and duration of their walk.

3. MULTILEVEL SPATIAL APPROACH FOR ASSESSING THE EFFECTS OF MICROCLIMATIC URBAN DESIGN FEATURES ON DAYTIME PEDESTRIAN THERMAL COMFORT

3.1. Introduction

Due to global warming and rapid urbanization, the frequency and intensity of extreme heat events and urban heat islands in the United States have sharply increased over the past several decades (Central, 2019; Hardin, Liu, Cao, & Vanos, 2018; Lowe, 2016). This ongoing trend has not only caused significant thermal discomfort, but also altered the patterns of outdoor physical and social activities in urban public spaces (Coates, Haynes, O'Brien, McAneney, & de Oliveira, 2014; Johansson & Emmanuel, 2006; Li, Liu, Dong, & Shi, 2015; Sharifi & Boland, 2018). Particularly for pedestrians, excessive heat stress has been reported as a critical barrier to walking activity, which, in turn, can deteriorate walkability, street livability, and urban vitality (Sharifi & Boland, 2018; Tumini, Higueras García, & Baereswyl Rada, 2016). In this regard, as a part of sustainable development, designing thermally comfortable street environments has become a major concern in urban design and microclimate studies.

Thermal conditions of urban streets are primarily determined by two spatial levels of urban design: street- and block-scale features. Cities are generally composed of a series of interfaces with continuity and diversity. These interfaces inhibit multiple and dynamic spatial scales that constitute spatial structure, urban form, and surface texture (Fazia Ali-Toudert & Mayer, 2006; Jiang, Han, Shi, & Song, 2019; Nouri, Costa, &

Matzarakis, 2017). Accordingly, in order to improve the thermal conditions, the relationships of urban design with microclimate have been explored at the neighborhood, block, and street scales. Especially for pedestrian thermal comfort, the effects of street- and urban block-scale design features have been of major concern in previous studies. While street-scale factors were explored in terms of geometry, greenery, and building materials (Andreou, 2013; Kong et al., 2017; Lee & Mayer, 2018), the impact of urban morphology, layout, and ground surface has been examined at the block-scale (Erell, Pearlmutter, & Williamson, 2010; Jamei et al., 2016; Lin, Gou, et al., 2017). However, to date, the multiscale effects of these design factors on pedestrian thermal comfort have received less attention.

Therefore, by using a multilevel spatial approach, the present study investigates the combined effects of microclimatic urban design features on daytime pedestrian thermal comfort. Specifically, it uses detailed on-site field measurements and estimates how different scales of street- and block-scale design factors impact the physiological thermal comfort of pedestrians using an urban walkway. First, the key focus is evaluating pedestrian thermal comfort by using an energy budget model to identify the spatial distributions of thermally uncomfortable street spots. Second, the correlation of individual microclimatic urban design factors with thermal comfort is explored. Finally, the effects of street- and block-scale design factors on thermal comfort are estimated by using hierarchical linear mixed model. The High Line of New York City was selected as a study site and a traverse field measurement was conducted for data collection in July 2019. It is expected that the findings of this study will help city planners and designers choose effective design strategies to improve the thermal comfort of urban streets and therefore promote pedestrian use of urban streets.

3.2. Literature Review

To date, two spatial units of urban design has been addressed in the previous literature on microclimatic urban design: the street-scale and block-scale. At the street-scale, the effects of street geometry, tree presence, and the optical properties of materials on thermal comfort have been examined. Street geometry, also referred to as “canyon geometry,” is often measured by the height-to-width (HW) ratio, and sky view factors (SVFs). Deep street canyons with a high HW ratio or high SVFs have been shown to improve thermal comfort by reducing air and surface temperatures, mainly due to the limited exposure of the canyon surface to direct solar radiation (F. Ali-Toudert & Mayer, 2007; Andreou, 2013; Emmanuel, Rosenlund, & Johansson, 2007). Tree presence also plays a crucial role in regulating thermal conditions. Specifically, it provides tree canopy shading, which leads to reduced solar radiation and lower air temperature (Holst & Mayer, 2011; Kong et al., 2017; Lee, Mayer, & Chen, 2016). In addition, surface materials with high albedo significantly decrease thermal stress, since they reduce the terrestrial radiative loadings on the human body by lowering the surface temperature of building walls and ground pavement (Erell, Pearlmutter, & Kutiel, 2014; Taleghani, Kleerekoper, Tenpierik, & Dobbelsteen, 2015; Lee & Mayer, 2018).

At the block-scale, the impact of block morphology, building layout, ground surface, and the proximity to bodies of water and green spaces on thermal environment has been investigated. Urban block morphology has the most significant impact on microclimate by modifying solar access and wind ventilation, which are primary measured by block density and volume (Haapio, 2012; Hachem, Athienitis, & Fazio, 2011; Perini & Magliocco, 2014; Shareef & Abu-Hijleh, 2020; Lin, Gou, et al., 2017). Moreover, block density and high volume results in deep and enclosed urban canyons, which exacerbate the urban microclimate for the following reasons: 1) more solar radiation is trapped, due to multiple reflections within the deep canyon; 2) less longwave radiation escapes into the sky, due to constrained visible fraction; and 3) dense urban structures block wind flow within the urban block, resulting in reduced ventilation cooling (Lin, Gou, et al., 2017; Erell et al., 2010; Lin, Lau, Qin, & Gou, 2017; Perini & Magliocco, 2014). The same density can also include various building configurations, with low-rise dense urban blocks associated with larger thermal amplitude than high-rise ones (Assis & Frota, 1999)

Block configuration has a noticeable effect on thermal conditions by altering the shading, wind speed, and ground albedo. It includes building layout, block orientation, and block building height variation. In this regard, taller buildings intensify solar reflection and absorption between building surfaces (Hang, Li, Sandberg, Buccolieri, & Di Sabatino, 2012; Lin, Gou, et al., 2017; Ratti, Raydan, & Steemers, 2003; Shareef & Abu-Hijleh, 2020). Moreover, several high-rise buildings placed in a canyon or in the middle of a block can increase the shading effect and wind speed, ultimately improving outdoor thermal comfort (Lin, Gou, et al., 2017; Rajagopalan & Wong, 2005). Building height variation is another determinant of microclimate modification. Specifically, non-uniform building height can promote better urban ventilation. However, it can also promote a hotter environment because it creates a rougher overall surface, thus leading to increased absorption of solar radiation (Erell et al., 2010; Lin, Gou, et al., 2017). Meanwhile, uniform building height can result in higher ground albedo, impeding reflective radiation from other surfaces (Kondo, Ueno, Kaga, & Yamaguchi, 2001; Lin, Gou, et al., 2017).

As for the surface features of blocks, they modify solar radiation, turbulent diffusion, and ventilation capacity. They are usually determined by the site coverage (openness), green spaces, and distance to geological features. Petralli (2014) reported that a 10% increase in the building coverage ratio increased the temperature from 0.30°C to 0.66°C. Green spaces, quantified by the green cover ratio, the tree canopy cover ratio, and the lawn cover ratio, are often found to be negatively related to air and surface temperatures (Hamada & Ohta, 2010; Perini & Magliocco, 2014; Wong et al., 2011). Additionally, the distance to geological features, such as bodies of water, parks, and woods, influences the thermal conditions of blocks. Regarding air temperature and spaces, those downwind of bodies of water are 1°C–2°C lower than nearby areas, mainly due to their capacity for heat storage and evaporation (Coutts, Tapper, Beringer, Loughnan, & Demuzere, 2012; Hathway & Sharples, 2012; Saaroni & Ziv, 2003; Shafaghat et al., 2016). Meanwhile, the cooling effect of parks and woods relies on the size, spatial structure and distribution of the geological features, which can decrease the air temperature in their surrounding areas (Jamei et al., 2016). However, since the cooling benefits of bodies of water and parks are highly localized, they sharply diminish as the distance grows from their boundaries (Jamei et al., 2016; Spronken-Smith, 1994; Yan et al., 2014).

For the evaluation of pedestrian thermal comfort, previous studies have primarily focused on the mono-spatial scale effects of urban design features. Specifically, they have mostly relied on the street-scale geometrical descriptors of SVFs and the HW ratio, only reflecting two-dimensional sections of the linear space and single-design objects at the pedestrian level (Erell et al., 2010; Lin, Gou, et al., 2017). There has been a limited consideration of the three-dimensional area features of the streets at the urban block-scale. It has also failed to capture the modified solar geometry and wind ventilation at the block-scale caused by neighboring buildings, morphological configurations, and nearby bodies of water and green spaces. Given that pedestrian thermal comfort is shaped by a feature of the built environment at multiple spatial scales, it is important to investigate the effects of multiscale urban design factors.

3.3. Methods

3.3.1. Study Site

The High Line in New York City was chosen as the study site (40.7483° N, 74.0050° W). Located on Manhattan's West Side, it is a 2.33 km elevated walkway and linear park, built on a former New York Central Railroad spur. It provides a wide range of microclimate conditions, coupled with diverse urban design features. It also offers a semi-controlled environment for microclimate assessment, due to 10-meter high elevation isolated from the ground level-artificial heat sources (e.g., vehicles and building ventilation equipment). This setting allows to better observe the effects of the urban design features on thermal conditions by controlling other heat sources. The spatial unit of analysis is the street segment, which is defined as a segment between two intersections by the allies and streets or by building faces. Thus, if one street block contains two buildings, there will be two street segments (Figure 3.1). This ensured homogeneity in urban design and microclimatic conditions within each segment. In total, 30 street segments were identified for this study, after excluding the ones (10 segments) under construction or closed for maintenance.

The 30 street segments were further classified into eight block design types, according to their morphological characteristics (Figure 3.2). Types 1–3 are open layout blocks with high exposure to direct solar radiation with higher SVFs, since they have building façades on one or neither side of the walkway. Types 4–6 are low- to high-density blocks with building façades on both sides of the walkway. Types 7 and 8 are enclosed blocks surrounded by wall façades on three sides (i.e., north, east, and west) or a tunnel walkway through a building. Most urban blocks have trees and vegetation on the walkway except for Types 7 and 8.

3.3.2. Data Collection

3.3.2.1. Microclimate Measurement

On-site microclimate measurements were conducted over six days in July 2019, which were mostly clear and hot without heavy clouds or wind. In order to cover the entire range of daytime heat conditions, microclimate conditions were collected every

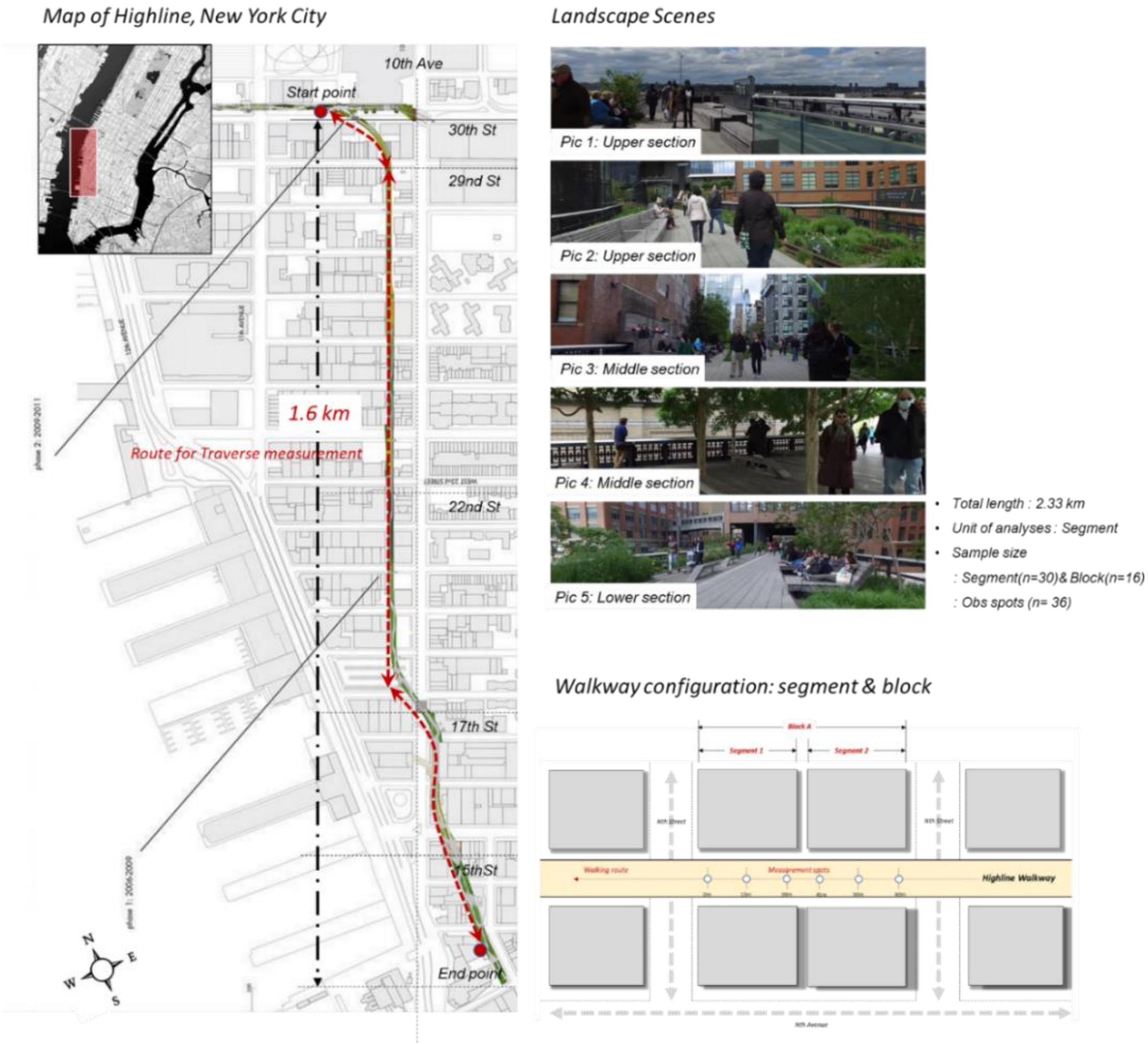
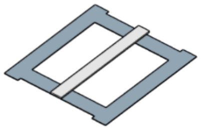
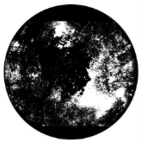
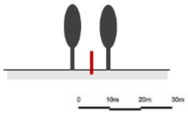
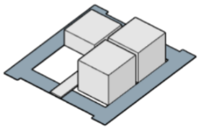
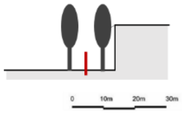
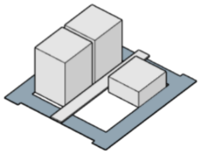
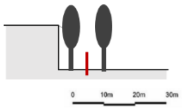
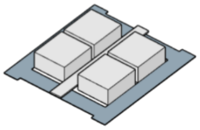
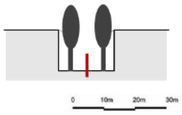
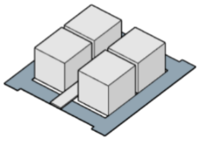
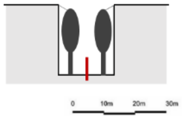
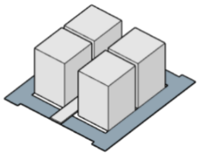
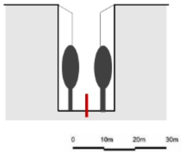
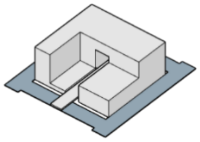
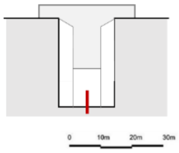
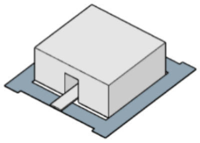
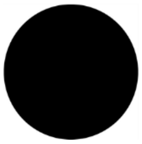
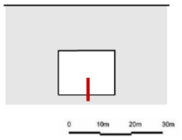


Figure 3.1 Context of the High Line, New York City

	Block Type	Segment No.	SVF	Section diagram
	Type 1 : Open walkway No building on both side of walkway	29, 30	 (Low)	
	Type 2 : Open to East Lower height building on westside of walkway	6, 25 26	 (Med-High)	
	Type 3 : Open to West Lower height building on eastside of walkway	19	 (High)	
	Type 4 : Low density Walkway with Low H/W ratio (< 1.5)	2, 7 8	 (High)	
	Type 5 : Med density Walkway with Medium H/W ratio (1.5 < < 2.5)	4, 9 14, 15 16, 17 18, 20, 22	 (Low-Med)	
	Type 6 : High density Walkway with High H/W ratio (2.5 <)	1, 3 5, 10 11, 12 13, 21	 (Low)	
	Type 7 : Enclosed walkway Walkway surrounded by building in three directions	28	 (Low)	
	Type 8 : Tunnel walkway Tunnel walkway go through middle of building mass	23, 24 27	 (Low)	

"Low SVF = (< 25)" "Med SVF = (25 < < 40)" "High SVF = (40 <)" | = Observation Spot

Figure 3.2 Eight Types of Block-Scale Design Features in the High Line

hour between 9:00 a.m. and 18:00 p.m. (UTC). The traverse measurement method was applied to obtain the microclimate components at the pedestrian level (Figure 3.3). With its advantage of measuring the actual street thermal conditions, it also captured the finer spatial and temporal resolution datasets, thus measuring the subtle spatial variations and strong heterogeneity of the microclimate components over the walkway (Timothy R. Oke, Mills, Christen, & Voogt, 2017; Ali & Patnaik, 2019; Lau, Shi, & Ng, 2019; Nakayoshi, Kanda, Shi, & de Dear, 2015; Tsin et al., 2016). To apply this traverse method, a lightweight, all-in-one backpack-type mobile weather sensor was developed to not hamper any walking activity. This sensor included a shielded thermometer, a humidity sensor, a two-dimensional anemometer, a radiation sensor, and a data logger.

The field work was performed by two trained surveyors. The first surveyor, equipped with a backpack-type weather sensor including a GPS tracker (Figure 3.3), moved along the centerline of the walkway at a moderate walking speed of 1.4m/s. The recording interval of the microclimate was 10 seconds, distanced at approximately every six meters. The second surveyor led the trajectory route to avoid a possible collision with nearby pedestrians. This approach reduced potential noises in the microclimate collection caused by shadow cast, body temperature, and hampered wind speed from other pedestrians. Concurrently, thermal infrared (IR) images of the building façade and ground pavement were taken by the second surveyor using an IR camera. A total of 15,050 microclimate records and 6,423 IR images were collected and aggregated by hourly mean values for use in the quantitative analysis.

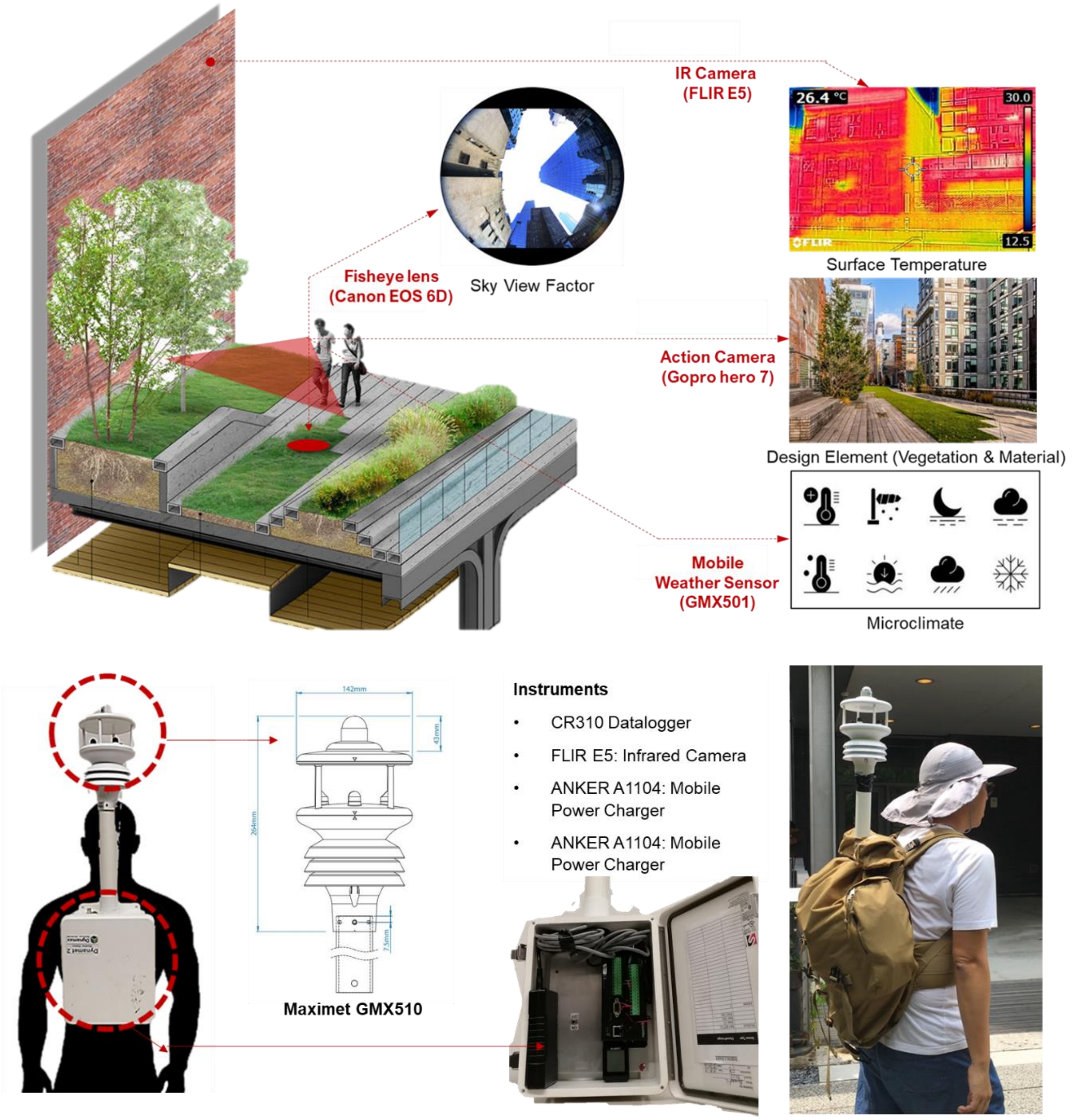


Figure 3.3 Traverse Field Measurements (Upper) and Backpack-type Weather Sensor System (Bottom)

3.3.2.2. Urban Design Measurement

The physical features of urban design were examined according to two different spatial scales: the street-scale and block-scale. For the street-scale design measurement, primary data captured from the fieldwork (conducted over three days in July 2019) were used. For the street geometry, SVFs, building view factors (BVFs), and tree view factor (TVFs) were measured using hemispheric images taken by the fisheye lens of a digital camera. These images were taken at 1.2 meters above the ground from the center of each street segment. The conditions of the street trees and surface materials were also taken by a digital camera. Additionally, during the fieldwork, the physical street conditions were filmed using a body-action camera mounted on the left shoulder and oriented toward the walking direction.

For measuring the block-scale design features, publicly available secondary data was used. Such data included open-access Geographic Information Systems (GIS) data, plan drawings, and aerial photos, from OpenStreetMap (https://www.openstreetmap.org) and NYC open datasets (https://opendata.cityofnewyork.us/). All the data obtained for the design variables were then digitized, mapped, and stored as separate geodatabase layers (using ArcGIS) for the evaluation of the outdoor thermal comfort associated with urban design features at different spatial scales.

3.3.3. Estimation of Outdoor Thermal Comfort

Human thermal comfort has been defined as “the condition of mind, which expresses satisfaction with the thermal environment” (ANSI/ASHRAE_Standard_55, 2017). It is not only determined by microclimate components, but also by one's physiological, physical, psychological, social, and behavioral factors (Auliciems & Szokolay, 2007; Chen & Ng, 2012; Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016). To estimate the level of pedestrian thermal comfort, the COMFA index (Brown & Gillespie, 1986) was selected, due to its capability of considering the diverse physical design elements in its thermal estimation. It also includes the following five-point scale classification: cold (<−150W/m^2), cool (−150 to −50W/m^2), neutral (−50 to 50W/m^2), warm (50–150W/m^2), and hot (>150W/m^2). The energy budget equation employed in the COMFA index is a generalized thermal balance model (first proposed by Gagge,1936), which is described as follows:

$$\Delta \mathrm{E} = M + R - C - K - E$$

where ΔS is the change in heat storage (W/m^2), which is 0 at energy balance, >0 at energy surplus, and <0 at energy deficit. In addition, the major energy streams are convective heat loss (C), evaporative heat loss (E), conductive heat loss (K), radiative exchange (R), and metabolic heat production (M) (Brown & Gillespie, 1986; Vanos, Warland, Gillespie, & Kenny, 2010). (R) is further divided by absorbed solar radiation (Kabs) and absorbed terrestrial radiation (Labs). Since it considers street design elements and pedestrian activity levels to estimate physiological thermal comfort, it can distinguish the individual design components and determine how they contribute to the thermal loadings of human body in terms of the energy flux principle.

The modification of the COMFA index was made to capture the radiation heat gain produced by the built materials in three-dimensional aspects. Specifically, it was developed to calculate the amount of terrestrial radiation emitted from vertical versus horizontal street objects separately. The measured surface temperature of the building façade and ground pavement was also used as the input parameters to estimate the amount of longwave terrestrial radiation that pedestrian can absorb, while standing in the centerline of the walkway. Thus, with this new version of the COMFA index, it was feasible to determine how much each side of the building façade, and the ground pavement contributed to pedestrians' thermal load. In order to achieve this, we processed 6,423 thermal images and extracted each surface temperature of the building façade and ground pavement across the High Line’s 30 street segments using Matlab’s computer vision techniques. Meanwhile, the Stefan-Boltzmann law was adopted to covert the measured surface temperature into the thermal radiation emitted from the walls and the ground. Its equation is as follows:

$$Rt = \varepsilon \frac{(5.67037441 \times 10^{-8})W}{m^{-2}} \cdot K^{-4}$$

where Rt is the amount of terrestrial radiation emitted(W/m^2), ε is the surface emissivity, and K is Kelvins.

Finally, the energy budget values of outdoor thermal comfort estimated by the COMFA index were analyzed to identify the spatial distribution of the daytime heat vulnerable street segments. These thermally uncomfortable hot spots of the High Line were further evaluated by mapping their intensity and duration of thermal loading that the pedestrian receive. Moreover, we estimated the individual contribution of each design factor to the thermal loading by calculating four components of energy flux –

absorbed solar radiation (Kabs), absorbed terrestrial radiation (Labs), convective heat loss (C), and evaporative heat loss (E) – to determine each share of net energy budget values over daytime hours. As a basic COMFA index setting, the metabolic rate of a walking person of 190W/m^2 (at a standard walking speed of 1.4m/s) and light summer clothing insulation options (t-shirt, shorts, socks, running shoes: clothing resistance = 32.78s/m, clothing vapor resistance = 46.46s/m) were selected.

3.3.4. Multilevel Analysis: Hierarchical Linear Mixed Model

The hierarchical linear mixed (HLM) model was adopted to estimate the multiscale spatial effects of urban design factors on pedestrian thermal comfort on the High Line. This approach allowed us to conceptualize the multilevel models, including the micro level and macro level factors, as well as the cross-level interactions (Hox, 2010). The HLM is an ordinary least square (OLS) regression-based analysis by taking the hierarchical data structures into account. Accordingly, we analyzed the variations in the explanatory variables at the individual and group levels, while considering their structural relationship and effectively decomposing the intra- and inter-group differences. The application of the HLM model in this study was particularly important, since it provided precise estimates accounting for any grouping effects from the multiscale urban design factors on thermal comfort with improved explanatory power (Figure 3.4).

Two separate HLM model estimation techniques were used in this study: fixed and random effects. Fixed effects are analogous to standard regression coefficients that are directly estimated, whereas random effects are not directly estimated but are summarized in terms of their estimated variances and covariances. Hence, random effects may take the form of random intercepts or random coefficients. We specifically chose a three-level HLM model since our collected microclimate observation data included two nested levels of spatial clustering for the street segments and urban blocks. The equation of the three level-model is as follows:

$$y_{jk} = x_{jk}\beta + Z_{jk}^{(3)}u_k^{(3)} + Z_{jk}^{(2)}u_{jk}^{(2)} + \epsilon_{jk}$$

For $i = 1, \ldots., n_{jk}$ first-level observations nested within $j = 1, \ldots., M_k$ second-level groups, which are nested within $k = 1, \ldots., M$ third-level groups. Group j, k consists of n_{jk} observations, so y_{jk}, x_{jk}, and ϵ_{jk} each have row dimension n_{jk}. $Z_{jk}^{(3)}$ is the $n_{jk} \times q_3$ design matrix for the third-level random effects $u_k^{(3)}$, and $Z_{jk}^{(2)}$ is the $n_{jk} \times q_2$ design matrix for the second-level random effects $u_{jk}^{(2)}$.

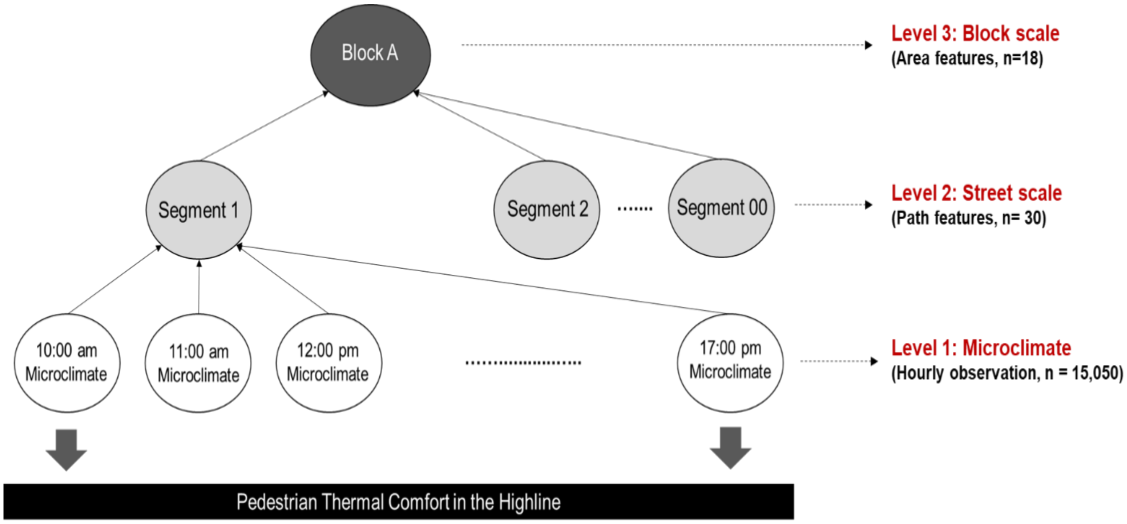


Figure 3.4 Multilevel Analysis: Hierarchical Linear Mixed Model

During the model fitting process, Pearson's correlation matrix and the variance inflation factor were used to check the potential multicollinearity issues, while the AIC and BIC tests were used to select the best-fitting model by comparing their overall performances. As a null model test, the intraclass correlation coefficient (ICC) was also estimated to measure how individuals share common microclimate conditions due to their similar conditions of street segments and urban blocks.

3.4. Results

3.4.1. Thermal Comfort Evaluation

3.4.1.1. Spatio-temporal Pattern of Pedestrian Thermal Comfort in the High Line

The pedestrian thermal comfort on the High Line was estimated by using the COMFA index, which measured the energy budget value (W/m^2) on a five-point scale, ranging from cold to hot. With the estimated COMFA value, the spatial distribution of thermally uncomfortable hot spots on the walkway was identified, and their changes in intensity over the daytime hours were examined. Moreover, to estimate the contributions of the urban design factors to the pedestrians' thermal loadings, four energy flux components produced by each urban design factor were estimated.

The spatial distribution of the thermally uncomfortable hot spots on the High Line is presented in Figure 3.4. According to the net budget map, the upper section of the High Line includes large clusters of thermally uncomfortable hot spots whose hourly mean energy budget value was greater than 150W/m^2. Meanwhile, the lower section of the High Line included two small clusters of cool spots with their values ranging from −50 to 50W/m^2. The evaluation map for Kabs and Labs showed similar distribution patterns of thermal loadings with the net budget map. This pattern confirmed that these two radiation loadings have the largest share of the net energy budget values.

Figure 3.5 presents the contour line of the daytime pedestrians' thermal comfort. This figure shows the daily pattern of energy budget values between 9:00 a.m. to 18:00 p.m. for the 30 street segments. The contour line also showed that the segments with thermally uncomfortable hot spots began to emerge at 10:30 a.m. By noon, 80% of the segments reached energy budget values of 150W/m^2, considered a high thermal stress level. Additionally, the contour line identified several clusters of thermally hot and cool segments. Segments 4–6, 8–10, and 16–21 belonged to hot clusters, while Segments 24–28 were cool clusters.

Figure 3.6 illustrates the amount of thermal loadings for the four energy flux components to which pedestrians are exposed. These include evaporative heat loss (−E), convective heat loss (− L), absorbed solar radiation (+ Kabs), and absorbed terrestrial radiation (+ Labs). Kabs and Labs comprised the largest proportion of the net energy budget, leading the overall increase in daytime thermal comfort. The amount of total absorbed radiation had the highest value of 180W/m^2 at 14:00 p.m. Individually, Labs had the highest value of 130W/m^2 at 16:00 p.m., which was the largest share of thermal loading among the components. Moreover, Kabs had the highest value of 105W/m^2 at noon, and then sharply declined to 43W/m^2 in the afternoon. Meanwhile, the amount of total heat loss – the sum of evaporative heat loss (E) and convective heat loss (L) – remained constant, ranging from −85 to −70W/m^2.

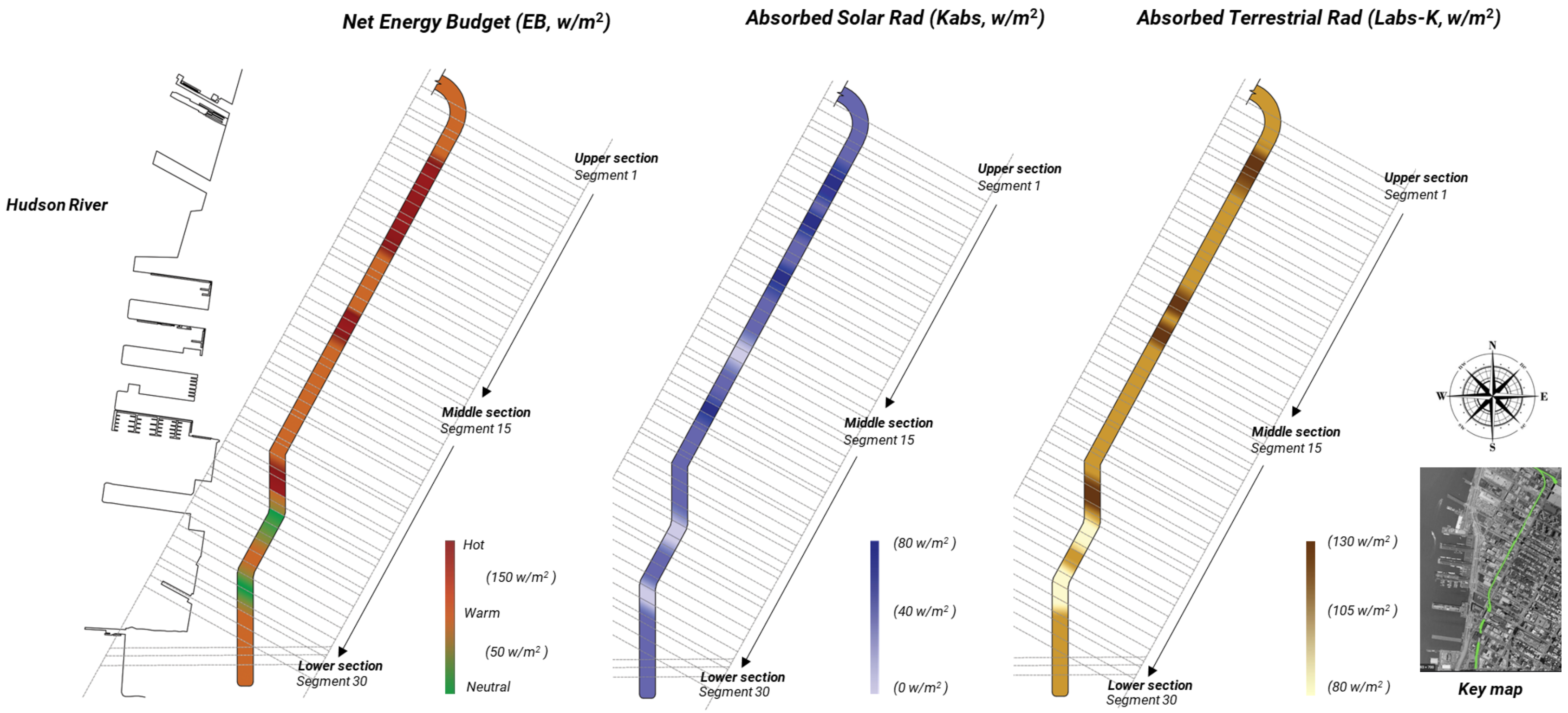


Figure 3.5 The Spatial Distribution of Thermally Uncomfortable Hot Spots in the High Line

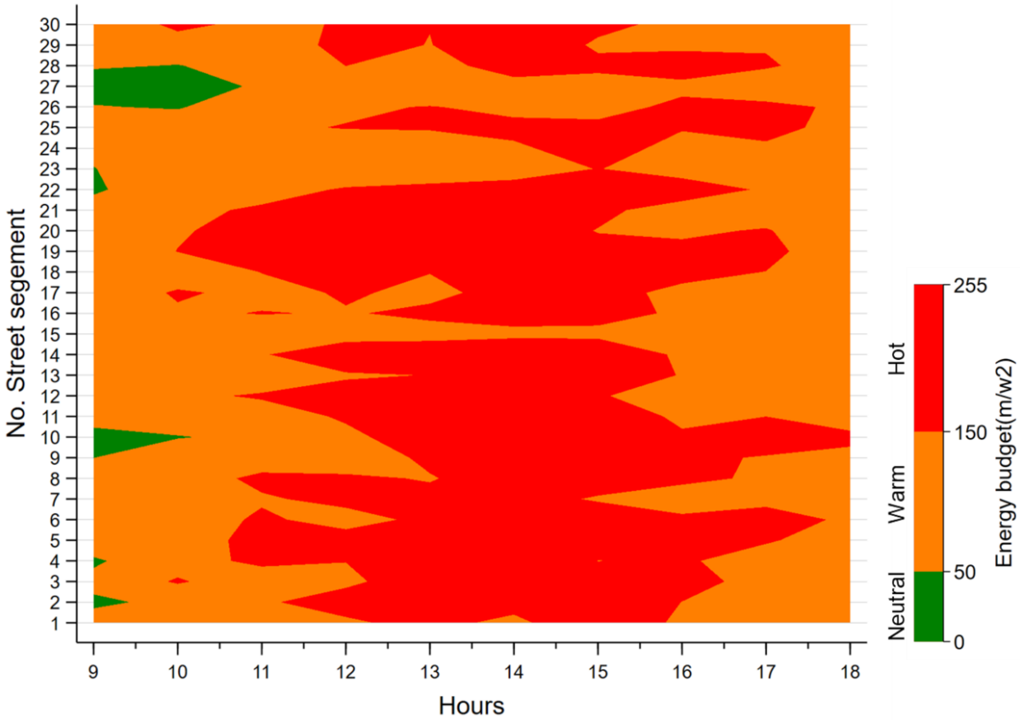


Figure 3.7 The Contour Line of Daytime Pedestrian Thermal Comfort for Thirty Street Segments

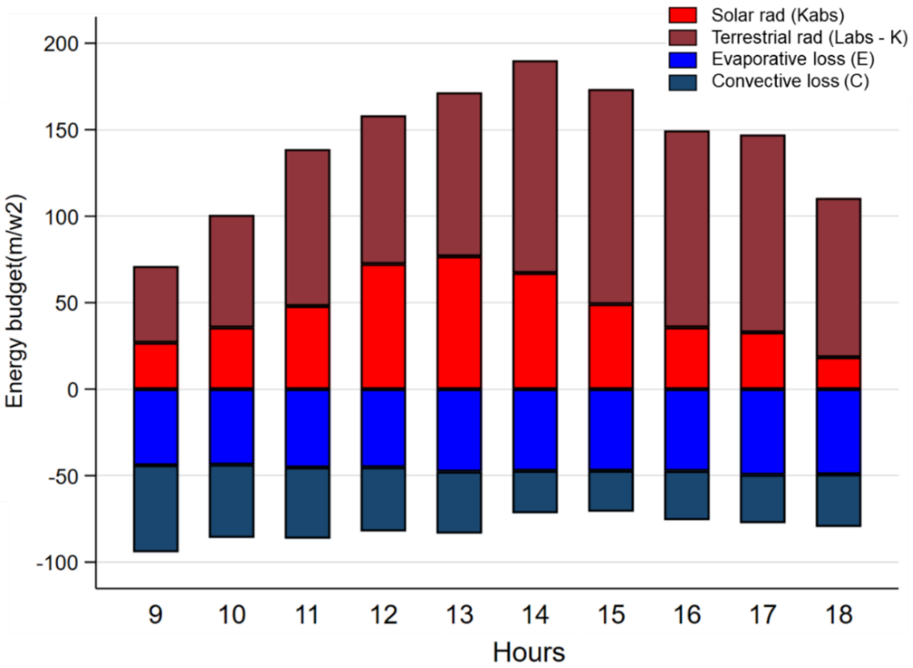


Figure 3.6 The Daytime Contribution of Four Energy Flux Component to Pedestrian Thermal Comfort

Figure 3.6 illustrates the amount of thermal loadings for the four energy flux components to which pedestrians are exposed. These include evaporative heat loss (−E), convective heat loss (− L), absorbed solar radiation (+ Kabs), and absorbed terrestrial radiation (+ Labs). Kabs and Labs comprised the largest proportion of the net energy budget, leading the overall increase in daytime thermal comfort. The amount of total absorbed radiation had the highest value of $180W/m^2$ at 14:00 p.m., while it had the lowest value of $60W/m^2$ at 9:00 a.m. Individually, Labs had the highest value of $130W/m^2$ at 16:00 p.m., which was the largest share of thermal loading among the components. Moreover, Kabs had the highest value of $105W/m^2$ at noon, and then sharply declined to $43W/m^2$ in the afternoon. Meanwhile, the amount of total heat loss – the sum of evaporative heat loss (E) and convective heat loss (L) – remained constant, ranging from −85 to $-70W/m^2$.

3.4.1.2. Correlation of Urban Design Features with Pedestrian Thermal Comfort

The relationship between pedestrian thermal comfort and urban design features was also explored. Regarding the block-scale features, the mean energy budget values for the eight block design types were compared by considering the effects of tree presence. For the street-scale features, changes in Kabs, as a function of street geometrical and greenery features, and the dependence of Labs on the albedo of the building facade materials were investigated.

As for the block-scale features, Figure 3.7 shows the hourly mean energy budget value for the eight block types. In this regard, the large variation of the budget value across the eight types were identified, showing a decrease in their values as it moves from low- (Type 4) to high-density (Type 6) block types. Except for Type 2, 3, and 7, their mean values were less than 150W/m^2, which falls under the neutral thermal conditions. Meanwhile, Types 2, 3, and 4 had higher mean values of approximately 160W/m^2, as they had more open conditions. Additionally, Type 8 had the lowest value of 95W/m^2, since it included enclosed streets such as a tunnel space. It should be noted that the decrease in energy budget values did not proportionally decrease as a function of the morphological densities because tree presence was not considered in this classification.

Regarding the street-scale features, we further examined the correlation of street geometry, greenery, and materials' albedo with Kabs and Labs. Figure 3.8 shows the relationship between street geometry and Kabs. SVFs had a positive linear relationship with Kabs while the HW ratio had a native one. This means that pedestrians are more likely to be exposed to direct sunlight when the SVF is higher and the HW ratio is lower. The degree of geometrical impact also became smaller when there was trees presence. Specifically, the coefficient slope of the HW ratio for a non-vegetated street was −5.77, which was steeper than that of the HW ratio for a vegetated street (−1.25). A similar (but inverse) pattern was also found for the correlation of SVFs with tree presence. This implies that the cooling performance of a highly dense street environment could be mitigated by dense vegetation.

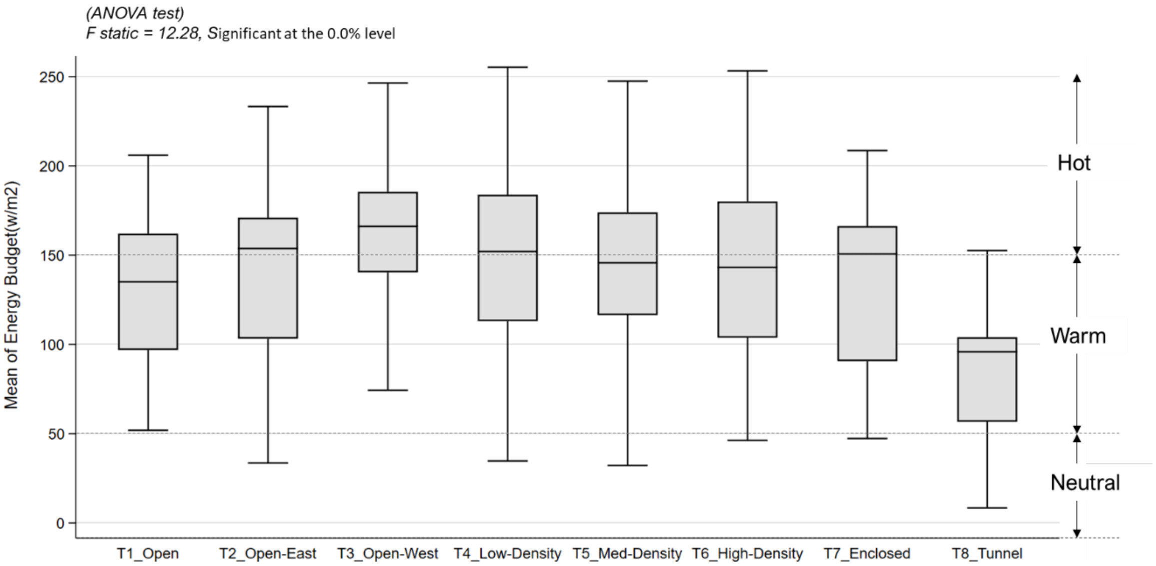


Figure 3.9 Mean Energy Budget Value for Eight Block Design Types

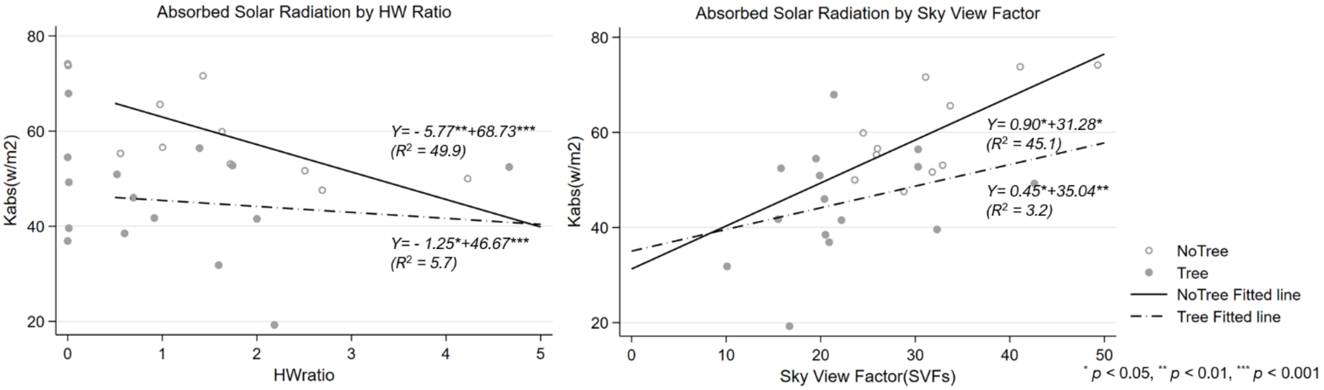


Figure 3.10 Correlation of Absorbed Solar Radiation (Kabs) with SVFs and HW ratio

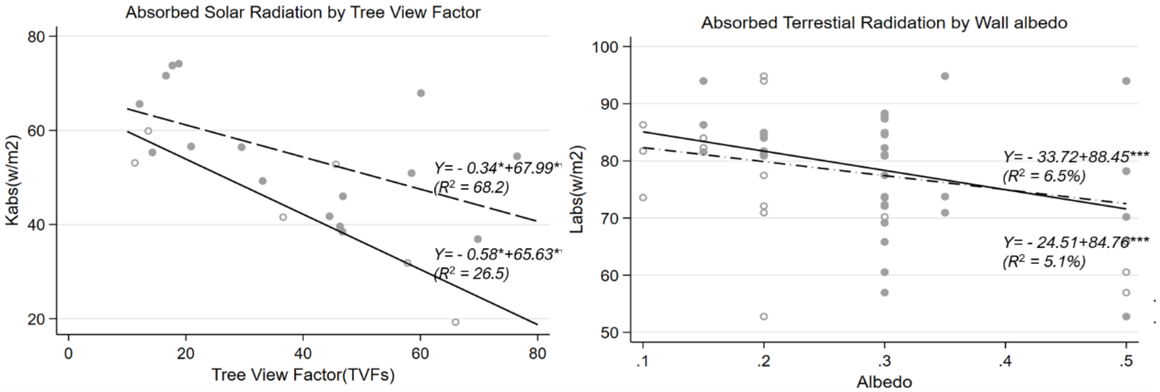


Figure 3.8 Correlation of Absorbed Solar Radiation (Kabs) with TVFs, and Absorbed Terrestrial Radiation (Labs) with Albedo of West and East Wall Façade

The correlation of Kabs with street greenery is illustrated in Figure 3.9. TVFs had a negative correlation with Kabs. Meanwhile, as the values of TVFs increased and the density of the trees increased, the amount of direct solar radiation that the pedestrians absorbed diminished. Furthermore, their effects on Kabs were more likely to grow as the HW ratio increased, while the effect of TVFs became more pronounced when combined with the high HW ratio of street. These results imply that the higher TVFs associated with deep street canyons provided a much cooler thermal environment. As for the effects of materials' albedo of building wall façade on Labs, they had a negative relationship, regardless of the wall direction (i.e., west and east). Accordingly, the higher the reflectivity of the materials used for the wall façades, the lower the value of Labs the people received.

3.4.2. Hierarchical Linear Mixed Model Analysis

3.4.2.1. Null Model: Interclass correlation coefficient (ICC)

As the first step of HLM analysis, the interclass correlation coefficient (ICC) was estimated to determine whether there was a hierarchical difference in the determinants of pedestrian thermal comfort between the different scales of microclimatic urban design factors (Table 3.1). Since ICC represents the share of variance accounted for by the random effect of the intercept component in the null model (Garson, 2019), we can effectively estimate the effect size of the street-scale design factors (Level 2) and the urban block-scale design factors (Level 3) when there are no other random or fixed effects in the three-level model. As shown in Table 3.1, the ICC result indicated that the estimated thermal comfort was significantly correlated with both spatial scales of the urban design factors. In other words, both street- and block-scale design factors affected the intercept (mean) of the estimated thermal comfort value in the microclimate measurement (Level 1). Conditional on the fixed effects covariates, the coefficient of the block-scale factors' random effects captured approximately 4.9% of the total residual variance, while the street- and block-scale factors' random effects combined consisted of 12.99% of the variance. This result confirmed that these two scales of urban design factors were significantly clustered, suggesting that the three-level model was an appropriate choice.

3.4.2.2. Full Model: Impact of Street and Block Scale Design on Thermal comfort

Table 3.2 presents the effects of the microclimate and microclimatic urban design factors on the estimated pedestrian thermal comfort at different spatial scales. The degree of impact, sign, and direction on the energy budget values were estimated by using the HLM model to identify the difference in effects while considering the nested structures of the microclimate measurement. Accordingly, the three models were used to determine the individual effect of each variable group and measure their contribution to the overall model improvement. Specifically, Model A was the baseline model with only the microclimate variables, Model B was estimated by adding the street-scale design factors to Model A. Model C was the full model further adding the block-scale design factors to Model B.

Table 3.1 Intraclass Correlation Coefficient (ICC)

Scales	ICC	SE	95% Conf. Interval
Block scale factors	0.0490	0.0698	0.3358
Street & Block scale factors	0.1299	0.0667	0.3428

The first column in Table 3.2 is the baseline model without considering the effects of urban design factors. This model only estimated the genuine effects of the microclimate variables on pedestrian thermal comfort. Resulted showed that all the microclimate variables of air temperature, wind speed, and relative humidity were strongly associated with thermal comfort. Considering the standardized coefficients of each variable's value, air temperature had the largest impact among all three models. In addition, when all of the other variables were held constant, a 1°C degree increase in air temperature was associated with a 11.99% rise in the mean energy budget values. Wind speed also had a significant impact on thermal comfort. This is an expected result given the High Line's proximity to the Hudson River and the high-rise buildings nearby, which often lead to a greater convective heat loss among the pedestrians on the walkway. Meanwhile, the impact of relative humidity was relatively minor.

The inclusion of street-scale design factors greatly increased the explanatory power of Model B, as shown in the AIC and BIC values in Table 3.2. At the street level, the HW ratio, TVFs, and albedo of the west wall façade had negative impacts on the energy budget values, while the ground pavement material had a positive relationship. Especially, the HW ratio and ground materials played a vital role in determining the thermal comfort. When all of the other variables were controlled, a 1% increase in the

HW ratio was associated with a −5.55% rise in the mean energy budget value. Regarding the ground material, the energy budget value in the case of wood pavement was 69.16W/m^2 higher than that of concrete. As for the TVFs, they had a significant negative impact, but it was relatively minor, given its coefficient of −0.47. Regarding the albedo of the wall materials, that of the west facing wall material was only significant in the model. We assume that this was largely because the amount of solar radiation that each side of the wall could receive largely depended on solar path. Accordingly, the direction that the walls faced caused the difference in the total amount of solar radiation they absolved during daytime hours.

At the block level, block density and volume variables were significantly associated with the estimated pedestrian thermal comfort. Specifically, every 1% increase in block density led to a −1.203% decrease in the energy budget values. Similar outcomes were reported in previous studies in which block density was a key factor that regulated the amount of direct solar radiation from the sun (Lin, Gou, et al., 2017; Perini & Magliocco, 2014; Erell, E, 2010; Lin, Lau, Qin, & Gou, 2017). Moreover, the block volume effect was statistically significant, but relatively small compared to block density, whereas block orientation and proximity to the river were not statistically significant in the final HLM model.

Finally, regarding the comparison of the three HLM models, the estimation shows overall consistency in terms of sign, effect size, and significance for the microclimate and street-scale design variables. As shown in the AIC and BIC output, there was not a significant model fit improvement between Model B and Model C.

Table 3.2 HLM Regression Output: The Effects of Urban Design Factors on Pedestrian Thermal Comfort

	Model A (Base HLM: Microclimate)		Model B (Partial HLM: Street design)		Model C (Full HLM: Block design)	
	beta	SE	beta	SE	beta	SE
Fixed effect						
Level 1: Microclimate						
Air temperature (°C)	11.990***	(0.367)	11.613***	(0.360)	11.637***	(0.360)
Windspeed (m/2)	-13.334***	(0.884)	-11.170***	(0.952)	-11.427***	(0.957)
Relative humidity (%)	-0.668***	(0.094)	-0.709***	(0.092)	-0.710***	(0.092)
Level 2: Street scale						
HWratio			-5.555***	(1.275)	-4.275***	(0.128)
Tree view factor (%)			-0.476***	(0.100)	-0.533***	(0.122)
Tree Canopy Cover Ratio (%)			0.128	(0.102)	0.062	(25.464)
Albedo of East wall mat			-8.864	(21.566)	5.464	(14.491)
Albedo of West wall mat			-41.830**	(13.509)	-48.898***	(0.360)
Ground material						
- Wood surface			28.945**	(8.797)	25.299**	(9.354)
Level 3: Block scale						
Block density					-1.134*	(0.490)
Block volume					0.076*	(0.039)
Proximity to river					0.020	(0.015)

	Model A (Base HLM: Microclimate)		Model B (Partial HLM: Street design)		Model C (Full HLM: Block design)	
	beta	SE	beta	SE	beta	SE
Impervious surface ratio (%)					-0.063	(0.242)
Openness of configuration						ref
- Presence of open square					0.775	(4.276)
Orientation						ref
- NW direction					6.068	(4.523)
_cons	-171.845***	(13.976)	-130.242***	(18.811)	-127.596***	(23.439)
Random effect	Estimate	SE	Estimate	SE	Estimate	SE
Level 3: Block scale						
Var (_cons)					3.16e-17	1.15e-15
Level 2: Segment scale						
Var (_cons)			32.684	12.978	18.626	18.591
Var (Residual)	1324.197	39.647	1178.005	36.586	1177.951	49.542
Sample size (n)		2,231		2,231		2,231
adj. R^2		-		-		-
chi2(2)		0.0000		0.0000		0.003
AIC / BIC test	22378.98	/22407.54	20864.77	/20932.57	20869.32	/20976.67
LR ratio test		-11184.492		-10420.38		-10415.7

Standard errors in parentheses || * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

This implies that, although block design factors were significant in the model, introducing them did not necessarily increase the explanatory power of the variation in the estimated thermal comfort values.

3.5. Discussion

Previous research has shown that the microclimatic features of urban design have a significant impact on pedestrian thermal comfort (Fazia Ali-Toudert & Mayer, 2006; T. R. Oke, 1988; Ratti et al., 2003; F. Ali-Toudert & Mayer, 2007; Emmanuel & Fernando, 2007; Erell et al., 2014; Jamei et al., 2016; Lee & Mayer, 2018; Lin, Gou, et al., 2017; Pearlmuttera, Berliner, & Shaviv, 2007; Perini & Magliocco, 2014; Shareef & Abu-Hijleh, 2020; Yang et al., 2018). The present study corroborates these findings, while presenting new discoveries. Based on a traverse measurement for the High Line in New York City, we analyzed the combined effects of street and block-scale design factors on pedestrian thermal comfort by using a hierarchical model.

The thermal comfort evaluation indicated that terrestrial radiation was the most significant contributor to the increased thermal stress received by pedestrians. As described in Figure 3.5, during the afternoon, the amount of terrestrial radiation emitted from the ground and wall façade sharply increased and peaked around 14:00 p.m. We assume that its largest share of thermal loading on the pedestrians attributable to its street geometry and materials. As for the High Line's geometrical features, it is a narrow and deep street canyon with relatively low SVFs and high HW ratio. It effectively regulates the direct solar radiation, but increases the terrestrial radiation gains from the building wall and ground pavement. This result is consistent with several previous studies (Erell, Boneh, Pearlmuttez, & Bar-kutiel, 2013; Lee & Mayer, 2018). Moreover, the terrestrial radiation effect significantly depends on the materials' albedo values. In this regard, the usage of high albedo materials for reducing the terrestrial radiation may result in greater pedestrian thermal stress, due to the increase in reflective solar radiation by such materials (Lee & Mayer, 2018).

According to the HLM result, air temperature was a major determinant of thermal comfort. As shown in Table 3.2, all of the microclimate variables considered were significant, and their sign and coefficients were generally consistent across the three models. Importantly, air temperature had the largest positive impact on the estimated energy budget values. Similar studies have indicated that air temperature had a positive linear relationship, and its effects became more pronounced when combined with strong solar radiation during the summer (Blazejczyk, Epstein, Jendritzky, Staiger, & Tinz, 2012; Pantavou, Lykoudis, Nikolopoulou, & Tsiros, 2018; Zare et al., 2018). Meanwhile, despite the proximity to the Hudson River, wind speed and relative humidity had relatively small effects, which is contradictory to previous studies. We assume that the major reason was that the duration of high wind speeds was relatively short during our study period, limiting its ability to increase the overall effect of wind ventilation. Additionally, convective heat loss was most likely minimized, especially when the climate was hot and humid (Sobolewski, Mlynarczyk, Konarska, & Bugajska, 2021).

Regarding the urban design features, the street-scale design factors played a significant role in determining thermal comfort. The HW ratio, TVFs, and the ratio of canopy cover had a negative linear relationship with thermal comfort, whereas SVFs had a positive impact. These results are supported by previous studies (Fazia Ali-Toudert & Mayer, 2006; F. Ali-Toudert & Mayer, 2007; Emmanuel et al., 2007; Andreou, 2013; Holst & Mayer, 2011; Kong et al., 2017; Lee, Mayer, & Chen, 2016), However, the impact of these variables varied, depending on the study location and regional climate features. Furthermore, they have mutual interaction effects as illustrated in Figures 3.8 and 3.9. Specifically, with the presence of trees, the cooling effects of the HW ratio and SVFs increased. Meanwhile, TVFs had synergy effects when combined with the streets with high HW ratios. Conversely, the ratio of tree canopy cover did not create cooling benefits in the streets with low HW ratio, which contradicted previous studies (Lee, Mayer, & Chen, 2016; Kong et al., 2017). This discrepancy is mostly like due to our methods of measuring tree canopy cover ratio. We examined all the tree canopy cover areas within the segments, even if the trees were located away from the pathway.

The effects of the block-scale design factors were significant, but their impact was relatively small, compared to the street-scale factors. As illustrated in Table 3.2, only the morphological factors of block density and block volume were negatively correlated with the energy budget values. The descriptive statistics in Figure 3.7 also indicated that the variation of solar radiation largely relied on block morphologies, which is consistent with prior studies (Erell et al., 2010; Lin, Gou, et al., 2017; Perini & Magliocco, 2014). However, except for solar radiation, minor variations in the microclimate conditions relied on the block morphologies. For example, if the observation spots were close enough to a large sized park with dense trees or bodies of water, a larger variation in air temperature and wind speed would have been observed by the different block morphologies. However, previous research has indicated that their cooling effects sharply disappeared as the distance between the observation spots and their boundaries increased (Jacobs et al., 2020; Jamei et al., 2016), suggesting their impact to be relatively limited and highly conditional.

3.6. Conclusion

This study investigated the impact of microclimatic urban design features on pedestrian thermal comfort by using a multilevel approach. Its purposes were: 1) to evaluate the spatial-temporal changes in physiological thermal comfort by using COMFA index; 2) to identify the correlation between individual urban design factors and thermal comfort; and 3) to estimate the effects of microclimate and street- and block-scale urban design factors on thermal comfort by using a HLM model. It used 30 street segments of the High Line in New York City as the study sites.

Results suggested that walking in the High Line is subject to high thermal stress, with the hourly energy budget values for 76% of the street segments being higher than than 150W/m^2. In addition, the upper section of the High Line included clusters of hot spots, while the middle and lower areas had sparsely distributed cool spots. As expected, most of the thermally uncomfortable hot spots were spatially matched with the street segments with high SVFs, a low HW ratio, less greenery, and low-density blocks. As for the radiation loading on thermal comfort, Labs was a critical determinant, resulting in increased pedestrian thermal comfort during the daytime hours.

The urban design features at both the street- and block-scales were highly correlated with the estimated pedestrian thermal comfort. At the block-scale level, the mean energy budget value largely depended on block density and tree presence, which were classified by the eight morphological block types in this study. At the street-scale level, SVFs had a positive linear relationship with Kabs, whereas TVFs and the ratio of tree canopy cover had a negative one. Additionally, the wall albedo had a negative impact on the Labs emitted from the building wall façades. This study also suggested that cooling effect of streets with densely vegetated or high albedo pavement materials could be diminished in highly dense street environments.

Finally, the HLM results revealed that the combination of urban design factors at the street- and block-scale levels significantly impacted pedestrian thermal comfort. By controlling for the microclimate conditions, the block-scale factors explained 4.9% of the variation in the energy budget values, while street- and block- scale factors combined accounted for 12.99%. This was largely because the street- and block-scale design features were spatially connected to one another and the microclimate conditions were clustered at these two different spatial scales. The AIC and BIC test results also supported this finding, indicating that the Model C considering the microclimate and design factors at the street- and block-scale levels was the best fitting model.

There are several limitations in this study. First, our data included a limited sample size for the block-scale variables, which might have reduced the explanatory power of the HLM model. Second, assigning a proper albedo value to different wall façade materials is challenging since most wall facades were heterogeneous with a mixture of diverse construction materials. This can make it difficult to estimate the albedo effects on surface temperature and calculate terrestrial radiation based on such temperature. Third, the COMFA index is a non-stationary outdoor thermal comfort index which estimates the physiological thermal comfort for a given time and spot. Given that it did not consider steady state conditions and the heat accumulation effects that the pedestrian received along the walkway, future studies should use a stationary index.

Overall, the findings of this study imply that the appropriate combination of street- and block-scale design factors can improve thermal comfort. It can help planners and designers decide what multiscale urban street design strategies and options to use for the effective regulation of summer thermal stress in daytime hours.

4. EFFECTS OF MICROCLIMATIC STREET DESIGN FEATURES ON THE HEAT-PEDESTRIAN ACTIVITY RELATIONSHIP: CASE STUDY OF THE HIGH LINE, NEW YORK CITY

4.1. Introduction

In the age of climate change, summer heat stress poses a threat to the health and well-being of citizens. Since frequency and intensity of extreme heat events and urban heat islands are increasing in most US cities, heat-related disease has sharply increased over the last decades (Taylor et al., 2018; Vaidyanathan et al., 2019). Furthermore, heat stress affects outdoor activities. Uncomfortable thermal conditions have often been recognized as a significant barrier that deters individuals from engaging in outdoor physical and social activities. Accordingly, severe thermal stress conditions could decrease urban vitality by altering the pattern of trip demand, travel distance, and attendance in urban public spaces (Böcker, Dijst, & Prillwitz, 2013; Cools, Moons, Creemers, & Wets, 2010). Moreover, poorly designed urban public spaces with little consideration of microclimatic features are likely to amplify the heat-related risk of visitors and lead to reduced visits and usage. Therefore, thermally-comfortable urban design is increasingly crucial for achieving a safe, favorable outdoor environment (Sharifi & Boland, 2018).

Studies on heat-related pedestrian activity have two behavioral focuses: walking and sitting. With regard to walking, studies have focused on which meteorological factors affect whether individuals choose to walk or not. Air temperature is a key meteorological determinant of walking. Air temperature has a positive relationship with walking volume in mild seasons, whereas during hot summers, its relationship is likely to be negative or parabolic with a heat threshold between 25 and 30 ○C (Montigny, Ling, & Zacharias, 2012; Suminski, Poston, Market, Hyder, & Sara, 2008; Vanky, Verma, Courtney, Santi, & Ratti, 2017). With regard to sitting, the effects of sunlight intensity on visitors' selection of preferred location and duration of stay at their chosen location have been the major concerns (Zacharias, Stathopoulos, & Wu, 2001) (T.-P. Lin, Tsai, Liao, & Huang, 2013; Klemma et al., 2017). Attendance in shaded areas has been strongly correlated with sunlight exposure (Martinelli, Lin, & Matzarakis, 2015; Huang, Lin, & Lien3, 2015). More individuals selected shaded areas and had longer stays as the temperature and solar radiation increased in summer (Huang et al., 2015; Kántor & Unger, 2010).

The relationship between thermal conditions and pedestrian activities can be conceptualized by the theory of behavioral thermal adaptation (Brager & Dear, 1998). This theory offers s basic idea of how people adapt to thermal stimuli by adjusting their behavior. It involves all the processes that individuals go through to improve the fit between the environment and their requirements (Chen & Ng, 2011; M. Nikolopoulou, Baker, & Steemers, 1999). Particularly, behavioral adjustment—spontaneous reactions of physical adaptation—is a key process in determining whether individuals choose to walk, and where they choose to stay. This adaptation process determines the acceptable ranges of thermal conditions, indicating the level of thermal stress that pedestrians can endure. Although this range has been significantly associated with the microclimatic street design features (de Freitas, Scott, & McBoyle, 2008; T.-P. Lin, Tsai, Hwang, & Matzarakis, 2012; C.-H. Lin, Lin, & Hwang, 2013), their empirical relationship has rarely been examined. To contribute to this area of research, this study addresses the following questions and hypothesis:

Research Questions:

What impact do meteorological conditions have on pedestrian activity, especially on walking and sitting? How could this relationship be modified by microclimatic street design features in a context of behavioral thermal adaptation?

Hypothesis:

A well-designed and thermally comfortable street space sustains the daytime pedestrian activity better, with a higher acceptance level of thermal stress during hot summer.

This study aimed to explore the effects of microclimatic street design features on the heat-pedestrian activity relationship. Specifically, the influence of sky view factors (SVFs) on the acceptable ranges of thermal conditions for pedestrian activity was investigated in the High Line, New York City. To achieve this goal, we set three objectives: (1) estimate the physiological thermal comfort of walking and sitting among individuals in the five selected observation spots in the High Line, (2) measure the impact of meteorological conditions on the activity while considering the street design features, and (3) identify the changes in heat threshold by SVF levels for each activity. For data collection, on-site microclimate measurements and an unobtrusive pedestrian observation method were used. Panel data were adopted to analyze the meteorological effects on pedestrian activity on streets with different SVF levels. We expected the findings of this study to provide practical knowledge and deepen the understating of designing heat-resistant street spaces that support pedestrian activities during hot summers.

4.2. Literature Review

The relationship between thermal conditions and pedestrian activity can be described by the theory of thermal adaptation (Brager & Dear, 1998). This theory provides a conceptual framework of how people adapt to given thermal stimuli by adjusting their inner and outer conditions (Chen & Ng, 2011; Marialena Nikolopoulou, Baker, & Steemers, 2001). Particularly, the behavioral adjustment - spontaneous reactions of physical adaptation - is considered as a key process determining whether people choose to walk and where they choose to stay. These behavioral reactions are often accompanied by changing their clothing, location, time of exposure, and types of

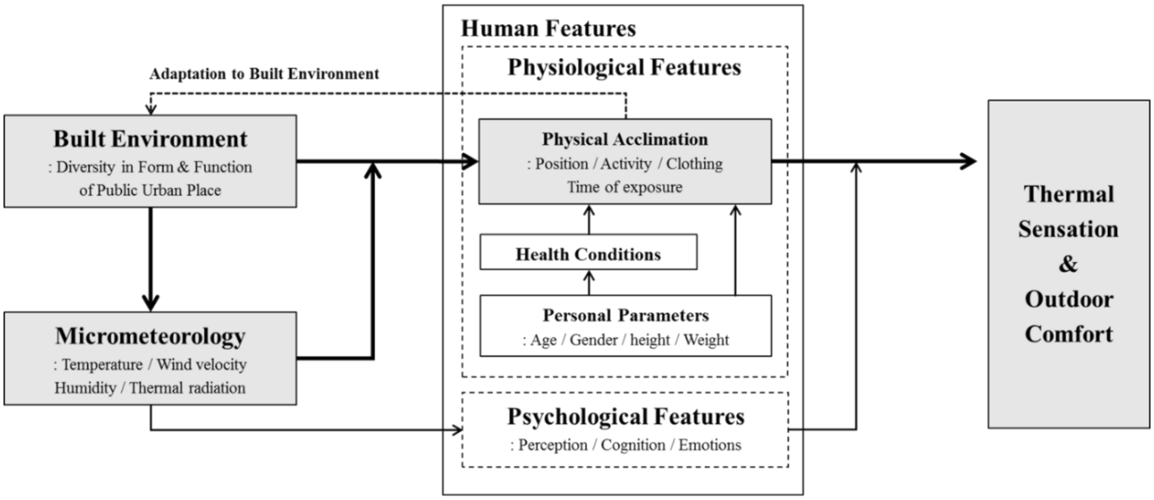


Figure 4.1 Conceptual Framework: Behavioral Thermal Adaptation

activity (Kántor & Unger, 2010). Furthermore, this adaptation process determines the acceptable ranges of thermal conditions, indicating the level of thermal stress pedestrians can endure. While this range is significantly associated with the microclimatic street design features (de Freitas et al., 2008; C.-H. Lin et al., 2013; T.-P. Lin et al., 2012), their empirical relationship has rarely been examined.

4.2.1. Meteorological Effects on Walking and Sitting Activity

The studies on heat-related pedestrian activity have two different focuses: the meteorological effects on walking and sitting. The studies on walking activity focused on how the weather affects people's decision to walk outdoors. For sitting activity, how the microclimate impacts the use of space, specifically for the preferred location to sit and stay, has been explored.

Regarding walking activity, air temperature and solar radiation are the most significant factors. In mild weather conditions, the walking volume increases as air temperature elevates (Suminski et al., 2008; Montigny et al., 2012; Vanky et al., 2017). Meanwhile, during hot summer, this relationship is likely to be negative, showing a reduction in the volume (Attaset, Schneider, & Arnold, 2010; Shaaban & Muley, 2016). In a full range of air temperature, walking volume often has a parabolic relationship with the point of heat threshold placed between 25 and 30 ○C (Tucker & Gilliland, 2007; Aultman-Hall, Lane, & Lambert, 2009; Miranda-Moreno & Lahti, 2013). Furthermore, the intensity of the solar radiation directly related to sunlight, shade, and cloud cover significantly affects walking volume in public spaces. Heavy clouds tend to reduce the volume, while less cloudy days positively correlate with the walking trip frequency and duration in Europe and North American cities (Attaset et al., 2010; Montigny et al., 2012; Vanky et al., 2017).

In an actual outdoor environment, meteorological effects on walking activity occur concurrently. Specifically, the air temperature has interaction effects with other meteorological factors such as season, weather, and microclimate. The increase in air temperature during mild seasons such as spring and fall may be perceived as pleasant for walking. Contrary, when exposed to strong sunlight, people tend to feel as highly uncomfortable as temperature and humidity increase during the summer. The combined effects of air temperature with shading have been reported in several studies. The air temperature effects on walking count largely rely on shading, and the positive impact of shading tends to be amplified during hot summer sunny days (Montigny et al., 2012; Zacharias et al., 2001, 2004). Despite its key role in determining the perceived actual level of thermal comfort of walking people, only a few studies consider this meteorological interaction's effects on walking activity.

When it comes to sitting activity in public spaces, the effects of meteorological conditions on visitors’ selection of activity locations and duration of stay at their chosen locations were the primary concerns (Klemma et al., 2017; C.-H. Lin et al., 2013; Zacharias et al., 2001). A visitor’s selection of sitting locations was mainly explored to see if whether they choose the shading and sunlight in given thermal conditions. The attendance in shaded areas is strongly correlated with thermal states, especially for sunlight exposure. The majority of visitors were observed sitting under shaded areas during hot summer at San Silvestro square in Rome and a plaza of the NMNS in Taichung City (Martinelli et al., 2015; Huang et al., 2015). Zacharias's study (2001) supports this finding by reporting that people prefer to be in sunlight areas as the temperature decreases and shows a tendency to move into shade areas at a higher temperature (>20 C) in Montreal, Canada. A similar result is also found in Watanabe's (2016) study on urban street space by showing the rate of selecting a shaded area increased when stopping at the traffic signal as the thermal comfort of UTCI grows. These studies confirm that choosing shaded areas to avoid sunlight is the most dominant and preferred method, especially when exposed to high thermal stress.

Furthermore, stay duration for sitting was investigated by measuring the amount of time people remained at their chosen locations. Past studies conducted in Taiwan and Hungary showed that more people selected shaded areas with longer stays as the temperature and solar radiation grew in summer (Huang et al., 2015; Kántor & Unger, 2010). However, at some cases, no significant correlation between stay duration and the temperature was found across a temperature range from 16.7°C to 23°C in a study of Fremont Plaza at San Francisco (Zacharias et al., 2004). Several studies also highlighted that the stay duration could be affected by the length of time people are exposed to specific heat conditions, their voluntariness of stay, and the activity type they engage (Cheung & Jim, 2018; Kántor & Unger, 2010; Zacharias et al., 2004). Specific activities such as ongoing conversation, lunch with another person, and reading material would lead to longer stays (Zacharias et al., 2004). The thermal conditions might have accumulated, and delayed effects on stay duration as thermal discomfort occurs after staying in that location for a certain amount of time (Cheung & Jim, 2018). Furthermore, people become more tolerant of the thermal environment and stay longer if they expose themselves voluntarily to that environment and can leave when they wish (Kántor & Unger, 2010).

4.2.2. Other Determinants for Heat - Pedestrian Activity Relationship

The heat - pedestrian activity relationship can be influenced by function of place, user's population, and socio-cultural context. The function of public spaces, which can be divided into route/passage and resting place, modifies the thermal impact on pedestrian activity in public spaces. Thorsson (2007) reported that the usage of parks and squares showed non-identical patterns of spatial behavior associated with microclimate mainly caused by their different functions of route and resting place. Similar study results also found in the Watanabe (2016) study indicated that the number of pedestrians in streets on weekday was hardly affected by thermal conditions as the streets were used as route space. Zeng's (2015) study also imply that different functions of streets generate varying correlations between the thermal environment and numbers of pedestrians, which reflects the complex usage of outdoor open spaces. These studies highlighted that the people in the resting place, whose purposes of visit is to relax, exercise, become refreshed, and eat lunch, has higher sensitivity to thermal conditions compared to a route place where commuting people pass through during daytime on their way home or to or from work and school. This is because the activities of the resting place require people to spend a longer time in the place. Thus, it leads them to avoid using thermally uncomfortable the place for their activity, spend less time in it, or adjust their thermal conditions by moving in or out of the shade.

The socio-cultural context and demographic population affect the heat-related pedestrian activity. One good example is Thorsson's study (2007). He compared the results of outdoor research in Japanese parks with those in Swedish parks and indicated that 80% of park visitors prefer to stay under the shade in Japan, whereas only 14% visitors choose to do that in Sweden at a temperature higher than 20 C. The difference between the countries with regards to the behavioral attitudes toward the sun and shade, and the time spent outdoors can be explained by socio-cultural contextual differences (Eliasson, Knez, Westerberg, Thorsson, & Lindberg, 2007). Furthermore, the physical body conditions and performance ability in outdoor environments are largely determined by age, gender, body weight, and health status. The range of thermal neutrality also depends on different population categories, local climate conditions and their weather expectations (Chan, Ryan, & Tudor-Locke, 2006; Marialena Nikolopoulou & Lykoudis, 2007; Yang, Wong, & Zhang, 2013). Gender and body weight are the mediating factors for the impact of thermal comfort on outdoor physical activities. Therefore, individual health status and population demographics affect pedestrian activity associated with meteorological conditions.

Pedestrian activity is majorly determined by physical environment of the streets. This includes physical design, safety, aesthetic, amenities, Land use, density and destination (Table 4.1). The former four factors belong to path characteristics while the latter three are area characteristics. The path characteristic is microscale street design features at the pedestrian level, whereas the area characteristic is related to density, volume, land use, zonings and key facilities nearby at block and neighborhood level (Moudon et al., 2006) (Alfonzo, 2016; Ewing & Handy, 2009; Gallimore, Brown, & Werner, 2011; Lee & Moudon, 2006; Southworth, 2005). To date, only a few studies consider these street design features when measuring meteorological effects on pedestrian activities. Therefore, it is not obvious and largely unknown how path and area characteristics modify heat-pedestrian activity relationships.

Table 4.1 Microscale Street Design Factors Affecting the Pedestrian Activity & Use of Street Space

Category	Class	Sub-class	Variables
Path characteristic	Safety	Vehicle traffic	- Buffer zone, bollards, curb, signals, signages - Number of lanes, Presence of sidewalk
		Crime	- CCTV, lighting, security patrol,
	Aesthetics	Landscape	- Greenness, architecture (Historical)
		Maintenance	- Cleanness, lighting
	Accessibility	Network	- Connectivity, continuity, intersection density - Access for entrance (stair, elevator)
		Transportation	- Bus stops, subway station, parking (car, bicycle)
	Amenities		- Seating areas, benches, street furniture, shops, galleries, and scenic spots (types of views)

Category	Class	Sub-class	Variables
	Physical design	Street	- Levelness, slop, barrier & obstacles, path width, pavement material (surface) - Landscape architecture (grass, tree)
		Building	- Building wall material, building height - Building frontage
Area characteristic	Adjacent Land use type		- Residential, Commercial, Business office (Zoning category) - Residential & Non-residential - Floor area of specific land use
	Size & Density		- Block & segment size, Population Density
	Destination		- Proximity of Key facilities (schools, shopping mall, sports facilities, market, park, plaza) - Number of generators or attractors

* Measured by Size, Number, Proximity (Distance) and Existence

4.2.3. Study Gaps

In the previous studies on heat – pedestrian activity relationship, several study gaps have been found. Firstly, the effects of multiple meteorological scales on pedestrian activity have not yet been clearly addressed: the microscale, mesoscale, and synoptic scale (Dunn, 1994). The synoptic scale is related to ‘climate’, which refers to the weather conditions over a long period of time that are regionally distinctive. The mesoscale indicates the ‘weather’ that is states of atmosphere at any given time and place over a short time, while the microscale refers to the ‘microclimate’ as locally prevailing on-site weather conditions. Despite the fact that these different scales all have an integral or individual impact on pedestrian activities in the usage of public spaces, what factors and scales of meteorological conditions affect walking and sitting activity is not clearly understood.

Secondly, empirical studies examining the impact of microclimatic features of street design on pedestrian activity are limited. The physical street environments are evaluated in previous studies on walking environments (Ewing & Handy, 2009; Moudon et al., 2006; Southworth, 2005). In the fields of urban planning and design, the attributes of microscale street design that determines the pedestrian activity are extensively examined in terms of route choice, walking behavior, walking activity, and pedestrian volume (Alfonzo, 2016; Gallimore et al., 2011; Lee & Moudon, 2006; Zhu & Lee, 2008). These individual design features covered safety, aesthetics, accessibility, land use, block size & density, and destination. Moreover, its evaluation framework is often reflected in walkability audit tools that have been actively developed during the last two decades (Day, Boarnet, Alfonzo, & Forsyth, 2006; Pikora, Giles-Corti, Bull, Jamrozik, & Donovan, 2003). However, only a few attempts have been made to link pedestrian activities with microclimatic street design features of solar geometry, greenery and optical properties of materials while considering these streets' path and area features.

Lastly, it is widely agreed that a thermally comfortable public space maintains a wide range of outdoor activities during summer heat events. Some empirical studies support this by showing that the higher the thermal comfort that space has, the higher the heat threshold of outdoor activities the space exhibits (Sharifi & Boland, 2018; Sharifi, Sivam, & Boland, 2015). It represents the concept of spatial heat resistance, which is the ability of a space to support outdoor activity against high thermal stress conditions.

However, only a few studies attempt to explore the physical features of space in relation to this concept. In this regard, the effects of microclimatic street design features on the acceptance level of thermal conditions for walking and sitting activity requires further investigations to verify this concept.

4.3. Methods

4.3.1. Study Site

The High Line in New York City, a 2.33 km elevated walkway and linear park created on a former New York Central Railroad spur on the west side of Manhattan, was chosen for the study site (40.7483° N, 74.0050° W). The main reason we selected the High Line was that it provided diverse microclimate conditions coupled with the physical features of street design. These conditions allowed the effects of microclimatic street design features on pedestrian activities to be explored under a full range of thermal conditions. Furthermore, due to its 10-meter height elevation, this walkway offered a semi-controlled environment excluding ground-level artificial heat sources generated by vehicles, ventilation equipment, and building cooling systems. These sources of data noise collected during field measurement can be minimized. Six observation street spots in the High Line were selected for the fieldwork because they were major activity areas with a high volume of visitors (Figure 4.3). Walking and sitting were observed for all spots, except for spot D, which had two observation spots – D1 and D2 – to observe sitting only.

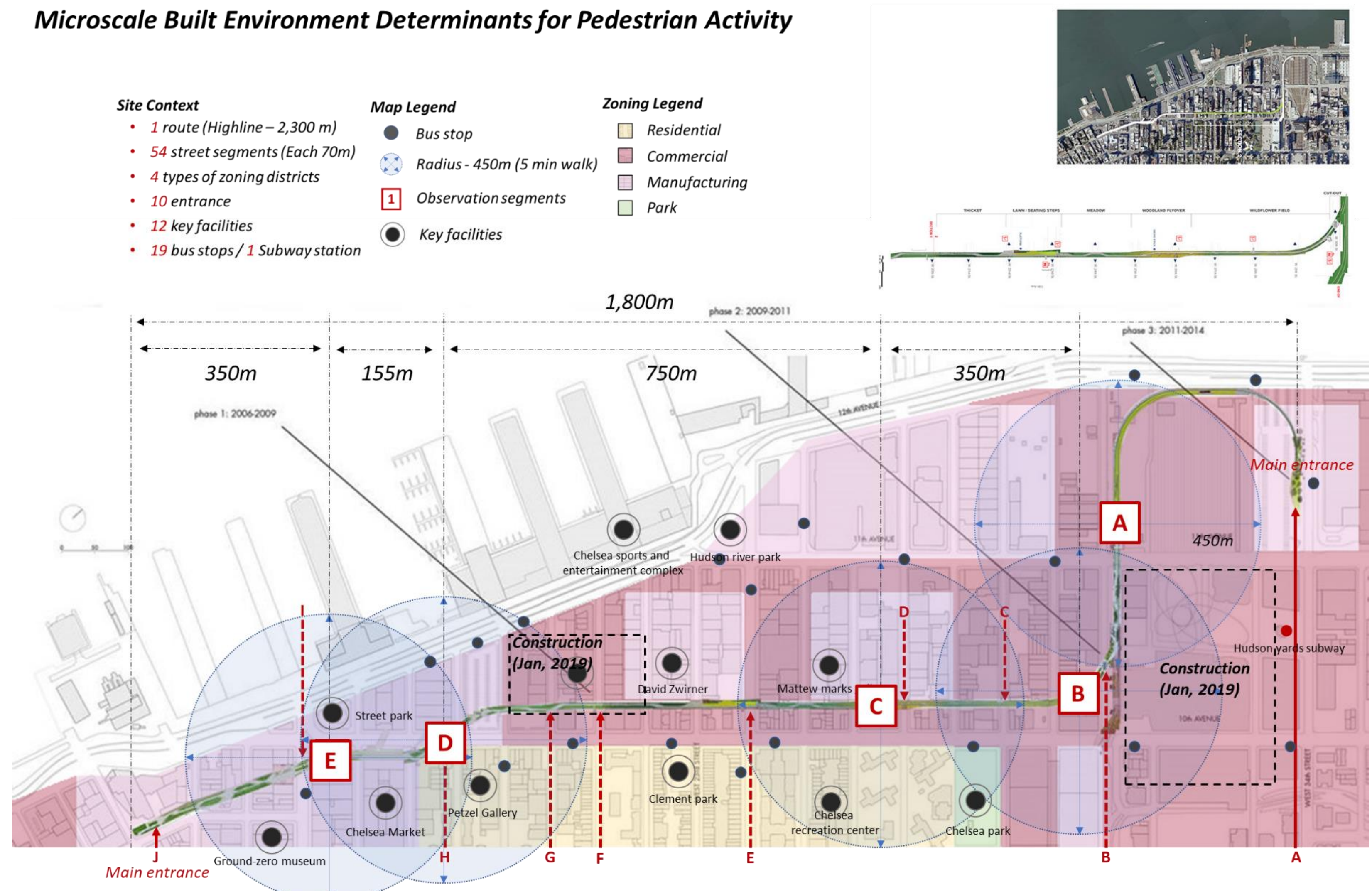


Figure 4.2 Context of the High Line, New York City

Regarding the microclimatic design (Table 4.2), spot A and spot D1 have relatively higher SVFs over 50%, while spot D2 and E have higher TVFs of 86% and 46% each. For the Path characters, spot B, D1, and D2 have the higher accessibility considering the number of the metro station and bus stops within 500 meters and street width. Meanwhile, spot B has the largest number of sitting benches with 152 in total, and spot C1 has both playground and viewpoint spots for sightseeing tours. Concerning area features, spot D1 and spot D2 have the highest block density with around 33. The number of key destinations within 500 meters is relatively higher for spot D1, D2, and E.

Table 4.2 Street Features for Five Observation Spots in the High Line

		Spot A	Spot B	Spot C	Spot D	Spot D1	Spot D2	Spot E
Sample size (n)		34	29	48	33	33	33	48
Activity type		W/S	W/S	W/S	W	S	S	W/S
Microclimatic								
SVFs (%)		63.6	25.9	26	12	9.5	43.7	32.3
TVFs (%)		0	14.3	20.9	86.5	86.5	12.3	46.3
HW ratio (%)		0	.36	1.44	2.06	2.06	2.06	.76
Path features								
Accessibility	- Entrance (m)	2	3	3	3	3	3	2
	- Bus stop	1	3	3	5	5	5	2
	- Metro station	0	1	0	0	0	0	0
	- Street width	0	47	18	33	33	33	25
Amenity	- Number of benches	32	152	69	118	87	31	53
	- Playground (Bi)	0	0	1	0	0	0	0
	- View point (Bi)	0	0	1	1	0	1	1
Greenery	- Impervious area (%)	0	65.17	48.5	5	12	0	46.21
	- Tree canopy cover (%)	0	0	7.81	40	85	0	14.26
Area features								
Density	- Block density	0	19.15	11.69	33.7	33.7	33.7	6.44
Destination	- Key facilities	0	1	2	3	3	3	3
Land use	- Zoning district	C	C/P	R/C	R/M	R/M	R/M	M

n = hours of daytime observation, m = within 500 m,
Activity type (W, walking; S, sitting), Zoning district (R, residential; C, commercial; M, manufacturing)

4.3.2. Data Collection

This cross-sectional time-series study used primary data collected from the fieldwork. In five observation spots in the High Line (Figure 4.3), unobtrusive observations and microclimate measurements were conducted every hour (between 10:00 am and 17:00 pm) for 15 days in July 2019. Before conducting the fieldwork, daily weather conditions and the social event schedule were checked to ensure diversity in daily activities, while avoiding unusual ceremonial events. A complete hourly set of 560 records were acquired from the microclimate and pedestrian observations.

The direct observation method was used to record the walking and sitting activities. Specifically, we used unobtrusive direct observation to avoid interference with any activities during the observation periods. Using a hidden video camera, a trained surveyor recorded the diverse types of pedestrian activities namely walking, exercising, standing, sitting, lingering, and eating. Simultaneously, every 15 minutes, the surveyor took a picture and manually marked the use of street space on the map, such as the occupation of street benches, positions of the individuals' stay, and sunlight exposure. Next, two surveyors counted the number of people walking and sitting by watching recorded video clips, to increase the intercoder reliability. This step was performed after the short-duration pedestrian count procedure that predicted the total counts per hour by multiplying 4 to 15 min of walking and sitting counts. These records were aggregated by hourly mean values and then matched with the corresponding meteorological data.

Two scales of meteorological data were collected: weather (mesoscale) and microclimate (microscale). Weather data were obtained from automatic weather stations

(AWS) dispersed over the mid-Manhattan areas; for the High Line's microclimate conditions, on-site measurements were conducted. The AWS weather data were publicly accessible by using a web-based service managed by Weather Underground (https://www.wunderground.com), a commercial weather information provider. The hourly mean weather values of six AWS stations were spatially averaged to reflect the weather conditions of the mid-Manhattan area. For the microclimate measurement, a portable meteorological station was placed using a tripod at the center of each of the five observation spots in the High Line. It collected solar radiation(W/m^2), relative humidity (%), wind pattern (m/s), and air and surface temperature (°C) every 5 s, which were used as input values to estimate the physiological thermal stress of pedestrians. Since the elevation of the meteorological station affects wind speed, we extrapolated them to a height of 10 meters by using the power-law, the vertical profile of wind speed (Manwell, McGowan, & Rogers, 2009).

Most of the street design features were obtained by on-site investigation. The two trained surveyors recorded street path features such as amenities, aesthetics, and physical design, by using a coding sheet, digital camera, and GPS tracker. The coding sheet was digitized for the analysis; and next, its internal consistency between the two surveyors was evaluated to increase the data accuracy and reliability. As a supplement, the secondary datasets provided by local and state governments were used to measure each observation spot's accessibility, adjacent land use, and destination. These are open access GIS data, plan drawings, and aerial photos, whose sources are OpenStreetMap and NYC open datasets (https://opendata.cityofnewyork.us/). To examine solar geometrical features of the High Line's street spots, we measured SVFs using hemispheric images taken by the fisheye lens of a digital camera, taken at 1.2 meters above the ground. All these design variables were collected from primary and secondary data sources and then digitized, mapped, and stored as separate geodatabase layers by using ArcGIS for further analysis.

Figure 4.3 Five Observation Street Spots in the High Line

4.3.3. Estimation of Outdoor Thermal Comfort

Human thermal comfort can be defined as “The condition of mind, which expresses satisfaction with the thermal environment” (ASHRAE, 2017). It is determined by microclimate components, but also human’s physiological, physical, psychological and social and behavioral factors (Auliciems & Szokolay, 2007; Chen & Ng, 2011; Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016). Numerous heat indexes have been developed to estimates outdoor thermal comfort objectively, which can be broadly classified into two types of thermal models: an empirical and a rational model (Binarti, Koerniawan, Triyadi, Utami, & Matzarakis, 2020; Blazejczyk, Epstein, Jendritzky, Staiger, & Tinz, 2012; Coccolo et al., 2016; Havenith & Fiala, 2015; Parsons, 2014). Given that the two models provide a mathematical description of human responses to the thermal environment, they have been used not only to calculate indexes but also to predict people’s thermal responses (Parsons, 2014). The empirical model was developed by exposing human subjects to a range of thermal environments and fitting empirical regression equations using the human response data obtained. The rational model offers a mathematical representation of the human body and its thermoregulation systems using the principles of thermal balance and regulation. Because it adopts energy budget equations that rationalize the indexes, universally applicable equations across the climate, region, seasons could be acquired (McGregor, Ebi, & Burton, 2009).

To estimate the pedestrian thermal comfort, a rational model of COMFA index (Brown & Gillespie, 1986; Kenny, Warland, Brown, & Gillespie, 2009a, 2009b) is selected due to its capability to consider the diverse physical design elements in its thermal estimation. The energy budget equation employed in COMFA is a generalized thermal balance model (first proposed by Gagge,1936). It was developed from heat transfer principles, which is also referred to as energy flux between human physiology and the surrounding environment. It is described as follows:

$$E = M + R - C - K - \Delta S$$

Where ΔS is the change in heat storage (W/m^2), which is 0 at energy balance, > 0 at energy surplus and < 0 at energy deficit. With the major energy streams being convective heat loss (C), evaporative heat loss (E), conductive heat loss (K), radiative exchanges (R), and metabolic heat production within the body (M) (Brown & Gillespie, 1986; Vanos, Warland, Gillespie, & Kenny, 2010). Given it considers the street design elements and pedestrian activity level to estimates physiological thermal comfort, it can distinguish what individual design components and how much they can contribute to the thermal loadings on human body in terms of energy flux principle. Accordingly, the diurnal pattern and the spatial distribution of thermal comfort for five High Line's observation spots are evaluated using COMFA model.

4.3.4. Statistical Analysis: Panel Data and Piecewise Regression

Panel data analysis, also called cross-sectional time-series data analysis, was adopted to estimate the effects of meteorological conditions and urban street design features on walking and sitting in the High Line. This statistical method analyzes two-dimensional panel data wherein the behaviors of entities are observed across time (Fitzmaurice, Laird, & Ware, 2004; Klenk et al., 2012). Our dataset of walking and sitting counts comprised entities repeatedly measured at multiple observation spots over time; thus, using the panel data analysis was a suitable approach (Allison, 2009; Torres-Reyna, 2007; Williams, 2015). First, it has more variability and efficiency to detect and measure statistical effects than the ordinal time series or cross-sectional data analysis. Second, compared to the OLS model, it has greater leverage in distinguishing cause and effect by exploiting the timing of their respective changes. Last, it considers variables at different levels of analysis suitable for hierarchical modeling. We used the linear regression panel model because we expected that walking and sitting count would be linearly dependent on meteorological conditions and street design factors.

Two techniques of panel data analysis can be used for the estimation: fixed effects (FE) and random effects (RE) models (Table 4.3). FE models estimate only the relationship between explanatory and outcome variables within individual differences because they discard information on differences between individuals but control for time-invariant variables. Therefore, this technique has an advantage: it allows for measuring the genuine meteorological effects on walking and sitting count while controlling the possible effects of physical street design factors on the activity. The equation is as follows (Allison, 2009):

$$Y_{it} = \beta_1 X_{it} + \alpha_i + \mathrm{u}_{it}$$

α_i (i=1….n) is the unknown intercept for each entity (n entity-specific intercepts), and Y_it is the dependent variable (DV) where i = entity and t = time. X_it represents one independent variable (IV), β_1 is the coefficient for that IV, and u_it is the error term.

In addition, RE models incorporate the time-invariant variables in their estimation. The meteorological or street design factors resulting in the difference between pedestrian activities can be measured. Since it considers the multi-scale effects of street design variables, we can estimate the differences across pedestrian activity observed at five street spots. However, since the RE model no longer controls omitted or confounding variables (Torres-Reyna, 2007; Williams, 2015), the variation across pedestrian activity in five street spots is assumed to be random and uncorrelated with the predictor or independent variables included in the model. The equation is as follows (Allison, 2009):

$$Y_{it} = \beta X_{it} + \alpha + \mathrm{u}_{it} + \varepsilon_{it}$$

α is the unknown intercept for each entity (n entity-specific intercepts), and Y_{it} is the dependent variable where i = entity and t = time. X_{it} represents one independent variable (IV), β is the coefficient for that IV, u_{it} is the between-entity error term and ε_{it} is the within-entity error term.

The regression outputs of FE and RE models were compared to identify whether missing time-invariant variables exist in the model. If the discrepancy occurs between two outputs, which missing fixed variables are suitable for further model development can be discussed. The Hausman test was conducted to determine whether the RE or FE model was preferred.

For appropriate model selection, three test methods were adopted in the model-fitting process: F test, Lagrange multiplier (LM) test, and Housman specification test (Hausman, 1978). The F-test was used to examine the FE model, and the LM test was adopted to test the RE model. The former compares the pooled OLS and fixed model to check how much the fixed model can improve the goodness-of-fit. The latter contrasts a RE model with pooled OLS. The pooled OLS is used if the tests do not reject the null hypothesis. The Housman specification test examines the similarity between FE and RE estimators. It uses that the covariance of an efficient estimator with its difference from an inefficient estimator is zero (Greene, 2017). If the null hypothesis that the individual effects are uncorrelated with other dependent variables in the model is not rejected, a RE model is selected over a FE model.

Table 4.3 Comparison of Fixed and Random Effect Model

	Fixed effect (FE) model	Random effect (RE) model
Aim	- The models are designed to study the cause of changes within a person or entity	- Difference across entities have some influence
Character	- Explore the relationship between explanatory and dependent variables within an entity. - Each entity has own individual characteristics that may or may not influence the predictor variables.	- Difference across entities have some influence on the dependent variables. - Need to specify those individual characteristics that may or may not influence the explanatory variables.
Assumption	- Something within the individual entities may impact or bias the explanatory or outcome variable. – confounding factor. - Relevant variables have been omitted from the model - There is correlation between entity's error term and explanatory variable: α_i(error term – vary across entity, but not across time) is correlated with the X_s (the time-varying explanatory variable)	- The variation across entities is assumed to be random and uncorrelated with the predictor or explanatory variables included in the model. - No time-invariant variables omitted or variables omitted are not corelated with the variables in the model. - There is no correlation between entity's error term and explanatory variable: α_i(error term – vary across entity, but not across time) is <u>uncorrelated with</u>

	Fixed effect (FE) model	Random effect (RE) model
	- Time-invariant characteristics are unique to the individual and should not be correlated with other individual characteristics.	the X_s (the time-varying explanatory variable)
Benefit	- Control for time-invariant variables that have not been measured but affect dependent variable. - Remove the effects of those time-invariant characteristics & Assess the net effect of the predictors on the dependent variable. - Add time effects – control for time effects whenever unexpected variation or special events may affect the outcome variable	- Estimate the effect of stable characteristics that is not changes over time (Time-invariant variables) - Time invariant variables can be included in the model. (in the fixed effect model, these variables are absorbed by intercept as they are constant) - It is possible to produce unbiased estimate of both the β_s and γ_s with lower standard errors than a fixed effects model generally if $\alpha_i$is uncorrelated with the X_s
Drawback	- The effects of time-invariant variables cannot be estimated for model (the coefficient of γ_s) - Doesn’t control for unobserved variables that changes over time (=the time-varying explanatory variable) - Cannot be used to investigate time-invariant cause of the dependent variable – time-invariant characteristics of the individuals are perfectly collinear with the person or entity dummies. - Cautious that in applications where the within-person variation is small relative to the between-person variation, the standard error of the fixed effects coefficient may be too large to tolerate.	- Some variables may not be available therefore leading to omitted variable bias in the model. - If relevant time-invariant variables have been omitted from the model, coefficient may be biased. - Suffered from omitted variable bias.

4.4. Results

4.4.1. Descriptive Statistics

4.4.1.1. Hourly Walking and Sitting Count – Attendance in the High Line

The daytime pattern of hourly mean walking count in five observation spots is illustrated in Figure 4.4. Except for spot A, all spots had M-shaped curve patterns with two peak hours approximately 12:00 and 15:00. In those four spots, the walking counts sharply increased in the morning and then reached the first peak at noon. During the afternoon, counts slightly decreased until 14:00 and then gradually returned until they reached the second peak at approximately 15:00. In addition, spot A had the least number of counts with an inverse-U shape, with the peak hour at approximately 13:00.

Figure 4.5 presents the daytime hourly mean sitting count for all, shaded, and sunlight areas. Unlike the pattern of walking count, overall sitting count had an S-shaped curve pattern. The total sitting count had almost identical curve patterns as the shaded area sitting count. This finding mainly occurred because the ratio of people sitting under the shade was far higher than that in the sunlight. Moreover, street benches of spots D and E were always shaded by trees. Under shaded area, the sitting count had a steep slope by noon and was relatively constant by 16:00. The number of people sitting in the sunlight was relatively small and had less variation during the daytime.

The occupancy rate (%) of street benches in five observation spots is presented in Figure 4.6. The block and gray bar in the bar chart are the occupancy rates under shade and sunlight individually. The overall patterns of this graph indicate that the occupancy ratio in the shaded area was much higher than that in sunlight for all five observation

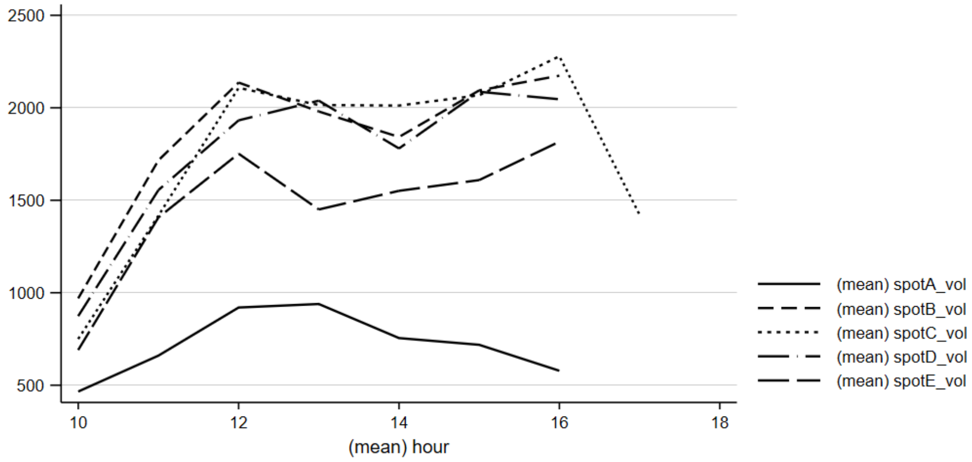


Figure 4.6 Hourly Mean Walking Count in Five Observation Spots

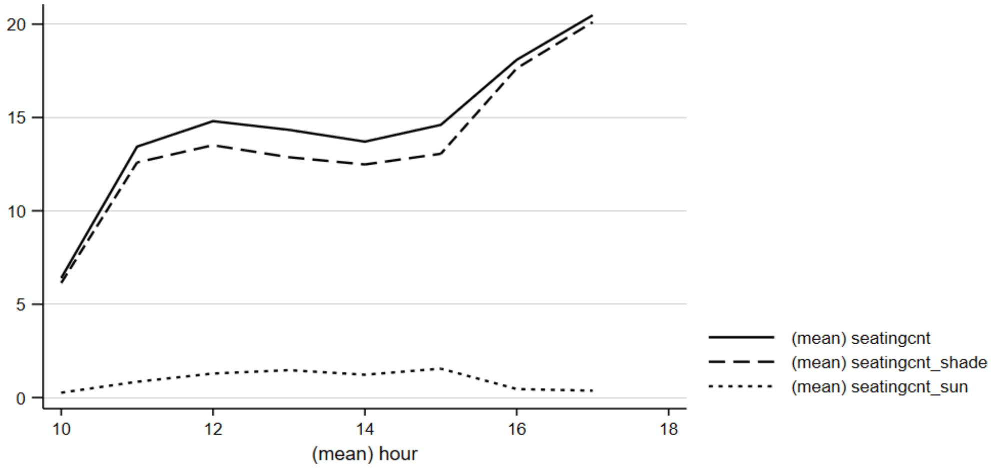


Figure 4.5 Hourly Mean Sitting Count under Shade and Sunlight

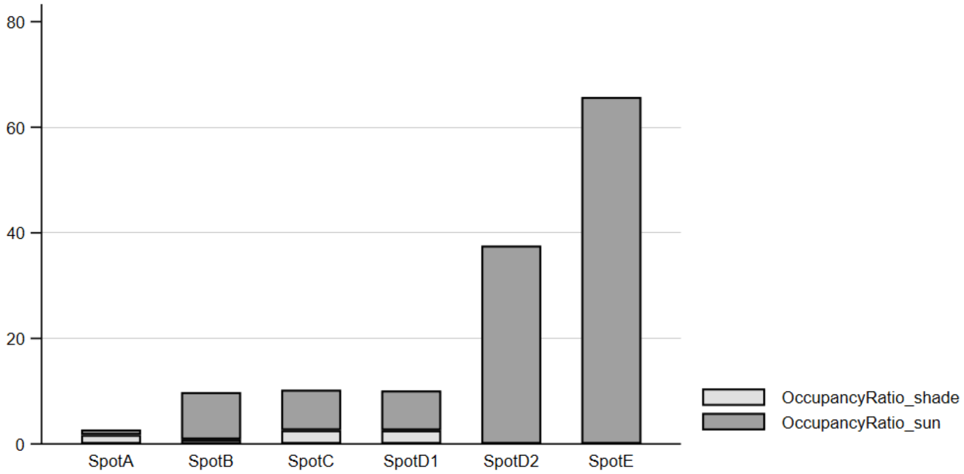


Figure 4.4 Hourly Mean Occupancy Ratio (%) for Each Observation Spot under Shade and Sunlight

spots. With regard to total occupancy rates, spots E and D2 were highest at 70% and 38%, whereas spot A was the least at less than 5%. All occupancy rates for spots D2 and E belonged to the shaded bar because they were always under tree-shaded areas. The ratio under sunlight for spots C and D1 were almost identical with 3%. Spot A had the least ratio with 3%, but its shade and sunlight ratios were similar at 1.5% each.

4.4.1.2. Meteorological conditions

Table 4.4 revealed the weather and microclimate conditions for five observation spots. For the weather, mid-Manhattan in New York City had scorching hot, muggy summer conditions. Hourly mean air temperature and solar radiation were 27.93°C and 678.84W/m^2 respectively. Hourly mean relative humidity was high at 53.94%, and windspeed was moderate at 1.04m/s.

The overall microclimate in the High Line was similar to the weather except for solar radiation and wind speed. A considerable variation in hourly mean solar radiation was found at the five observation spots. Spot A and D2 were the highest at 572.49W/m^2 and 543.07W/m^2 respectively, because those spots were open spaces. In addition, spot D1 and E had the least solar radiation values because those spots were under relatively dense tree canopy cover. Wind speed also varied according to the observation spots. Spot B had the highest wind speed at 1.85m/s, caused by the Venturi effect of tall buildings; spot A was the lowest despite its proximity to the Hudson River.

For thermal comfort, Figure 4.7 illustrated the hourly mean energy budget values of walking and sitting for six observation spots. For sitting, the energy budget value ranged from 40 to 60W/m^2 where belonged to the range between neutral and slightly warm comfort according to the COMFA classification. Specifically, spot A was the highest at 55W/m^2, and spot D1 and E were lower than that, at 47 and 49W/m^2. For walking, the energy budget value for all spots was between 90 and 130W/m^2. This range of values means that all spots' conditions were pretty warm if people walked at a moderate speed of 1.4m/s. Similar to the sitting, spot A had the highest mean value of 130W/m^2, and spot D had the least mean value of 85W/m^2 for walking. The difference between walking and sitting in energy budget values was mainly caused by the increases in metabolic rates from 90W/m^2 for sitting to 120W/m^2 for walking.

Table 4.4 Weather for Mid-Manhattan and Microclimate for the High Line

			Ta	Slr	Ws	Rh	EB
Weather		mean	27.933	678.845	1.004	53.946	63.5
(Meso)		sd	(0.813)	(159.148)	(0.063)	(2.937)	(13.254)
Microclimate	Spot A	mean	28.025	572.496	1.31	54.368	57.231
(On-site)		sd	(1.142)	(123.682)	(0.215)	(3.022)	(9.126)
	Spot B	mean	27.721	414.394	1.851	53.972	44.174
		sd	(1.135)	(210.059)	(0.473)	(3.43)	(12.164)
	Spot C	mean	28.051	429.118	1.637	52.891	47.05
		sd	(0.998)	(252.851)	(0.344)	(3.208)	(14.837)
	Spot D1	mean	27.846	219.021	1.665	53.993	33.974
		sd	(0.86)	(146.54)	(0.454)	(2.877)	(10.089)
	Spot D2	mean	27.846	543.076	1.665	53.993	54.362
		sd	(0.86)	(134.684)	(0.454)	(2.877)	(6.804)
	Spot E	mean	27.664	354.579	1.687	54.346	40.161
		sd	(0.905)	(145.485)	(0.47)	(2.832)	(12.7)

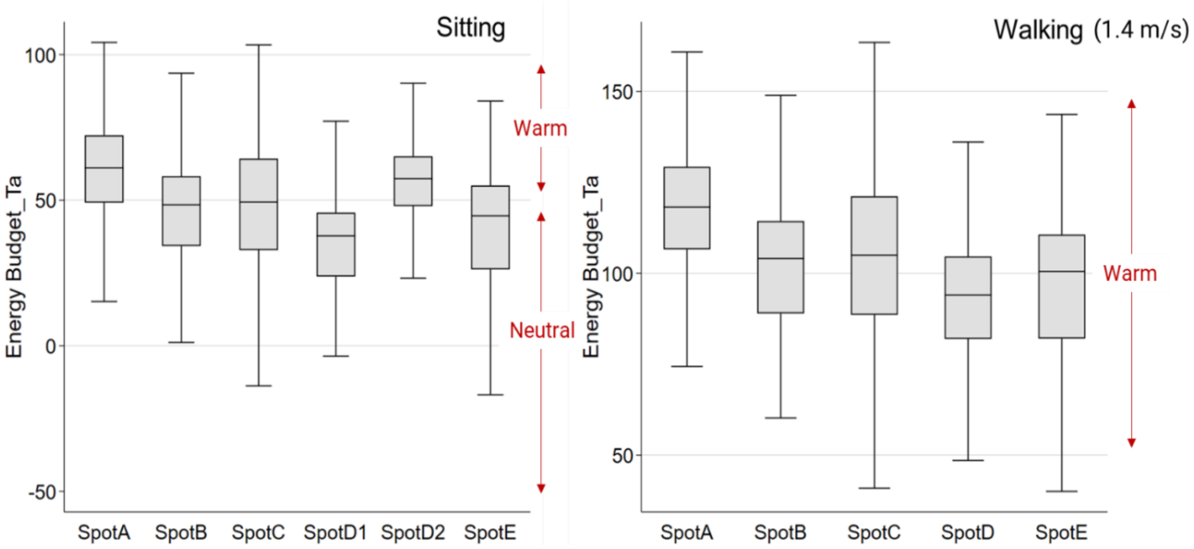


Figure 4.7 Hourly Mean Energy Budget Values of Sitting and Walking for Five Spots

4.4.2. Regression Analysis

4.4.2.1. Meteorological effects on walking and sitting count at different scales

Panel regression analysis (PA) was used to estimate the impact of weather, microclimate, and thermal comfort on walking and sitting count. Comparing model performances by using weather and microclimate variables enabled us to figure out what meteorological factors at different scales affect walking and sitting dominantly. The weather condition was the spatially averaged values of five different AWS over the mid-Manhattan area; microclimate data for each observation spot was collected using field measurement.

The upper row in Table 4.5 presents the PA results of the suggested walking model. Models 1, 2, and 3 used weather, microclimate, and thermal comfort each as independent variables while walking count was the dependent for all the models. Model

1 used the weather variable and had the largest adjusted R-squared values of 16.6%; thus, the weather variables explained the 16.6% variation in the walking account. Model 2, which used microclimate variables, and Model 3, which used thermal comfort variables, had similar explanatory power, ranging from 5% to 10%, which was lower than Model 1. This result implies that the walking count at the High Line was more influenced by the mesoscale meteorological condition of weather than the on-site condition of microclimate.

The sitting model was presented in the bottom row in Table 4.5. It used the occupancy ratio of benches as a dependent variable. The panel regression model results suggested that Model 5, which used microclimate variables, had the highest adjusted R-squared values at 51.2%, which was much higher than 3% of Model 4, which used weather variables. Model 6, which used thermal comfort variables, had an explanatory power similar to that in Model 4. The results indicated that sitting was mostly determined by microclimate conditions. Notably, the variable of the shaded cover ratio of benches was the most influential factor because it explained more than 30% of the variation in sitting count, controlling for other dependent variables. This result was consistent with the descriptive statistics as shown in Figure 4.5, wherein the occupancy ratio of benches was majorly affected by shading cover.

Table 4.5 Walking and Sitting Activity - Panel Regression Output by Weather, Microclimate and Thermal Comfort

	Model 1 - Weather (Mesoscale: Mid-Manhattan)				Model 2 - Microclimate (Microscale: High Line)				Model 3 - Thermal comfort (Microscale: Highline)			
Walking activity - Volume count												
	Pooled OLS model		FE model		Pooled OLS model		FE model		Pooled OLS model		FE model	
Ta	2470.527***	(570.200)	2589.473***	(436.575)	2057.216***	(494.065)	1781.390***	(376.940)	-	-	-	-
Ta* Ta	-42.742***	(9.990)	-45.509***	(7.655)	-35.790***	(8.749)	-31.397***	(6.673)	-	-	-	-
Rh	0.913	(5.980)	-5.172	(4.640)	-0.463	(6.190)	-0.133	(4.701)	-6.328	(5.816)	-3.263	(4.439)
Ws	763.309**	(250.286)	604.711**	(191.821)	241.438	(132.234)	-130.642	(107.558)	179.856	(134.556)	-178.928	(108.878)
Slr	-0.115	(0.273)	-0.359	(0.211)	0.059	(0.217)	0.641**	(0.195)	0.149	(0.289)	0.885***	(0.247)
EB	-	-	-	-	-	-	-	-	59.582***	(16.295)	51.437***	(12.265)
EB * EB	-	-	-	-	-	-	-	-	-0.287***	(0.078)	-0.257***	(0.058)
_cons	-3.5e+04***	(8270.019)	-3.5e+04***	(6323.703)	-2.8e+04***	(7083.885)	-2.4e+04***	(5392.276)	-1.5e+03	(1011.424)	-901.823	(772.208)
N		174		174		174		174		174		174
F-test (model)		7.47***		12.79***		6.10***		12.35***		4.99***		11.71***
F-test (fixed)		-		31.44***		-		33.21***		-		34.26***
adj. R^2		0.1575		0.1660		0.1285		0.0810		0.1035		0.0651
AIC/BIC test	2719.002	2737.956	2619.975	2638.929	2724.88	2743.834	2621.636	2640.591	2729.813	2748.767	2624.12	2643.074
Sitting activity - Occupancy ratio of benches												
	Pooled OLS model		FE model		Pooled OLS model		RE model		Pooled OLS model		RE model	
Ta	28.823	(21.202)	25.595**	(8.597)	24.619*	(11.501)	23.519**	(7.264)	-	-	-	-
Ta* Ta	-0.505	(0.368)	-0.451**	(0.149)	-0.453*	(0.202)	-0.417**	(0.127)	-	-	-	-
Rh	0.078	(0.229)	-0.127	(0.094)	-0.155	(0.140)	-0.134	(0.089)	-0.277*	(0.132)	-0.228**	(0.085)
Ws	17.771	(9.488)	5.309	(3.897)	-12.026***	(2.866)	-6.722***	(1.890)	-12.156***	(2.854)	-7.135***	(1.880)
Slr	-0.007	(0.008)	-0.005	(0.003)	0.003	(0.005)	-0.001	(0.004)	0.021**	(0.007)	0.008	(0.005)
Shade Cov	-	-	-	-	14.743***	(0.737)	6.300***	(1.184)	14.793***	(0.732)	6.095***	(1.179)
EB	-	-	-	-	-	-	-	-	-0.126	(0.197)	0.154	(0.126)
EB * EB	-	-	-	-	-	-	-	-	-0.002	(0.002)	-0.003**	(0.001)
_cons	-400.616	(311.297)	-331.417**	(126.273)	-332.718*	(165.999)	-310.170**	(105.040)	7.963	(10.774)	22.216*	(10.570)
N		226		226		226		226		226		226
F-test (model)		1.04***		4.26***		68.94***		-		70.44		-
F-test (fixed)		-		224.71***		-		-		-		-
LR chi2(6)		-		-		-		53.65***		-		56.31***
LR test		-		-		-		174.92***		-		174.38***
adj. R^2		0.0009		0.0120		0.6443		-		0.6493		-
AIC/BIC test	2120.573	2141.096	1707.283	1727.806	1888.116	1912.059	1717.193	1747.978	1884.911	1908.855	1714.535	1745.32

Standard errors in parentheses | * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4.4.2.2. Meteorological effects on walking and sitting count considering street design features

The pooled OLS model was used to estimate the effects of meteorological conditions while considering the physical features of street design. Since the F-test and B-P LM test null hypotheses were not rejected, the pooled OLS model was the most appropriate method. There were two sets of the model group for walking and sitting. According to the prior panel regression results, the weather (mesoscale of mid-Manhattan) and the microclimate variables (microscale of the High Line) were used for the walking and sitting model respectively. To check the model improvement when adding street design features, adjusted R-squared values and AIC and BIC values were estimated.

Table 4.6 represents the pooled OLS output for the walking model. In Model 1, the weather variable explained 16.00% of the variation in the walking count. In addition, when considering the street's path and area design feature variables, the adjusted R-squared value for Models 2 sharply increased to approximately 50.00%. The AIC and BIC test results also indicated that Model 2 was preferred over model 1. Thus, the variables of street design features increased the model explanatory power by 35%. This output implies that weather had a considerable impact on walking count due to its 16% R-squared values, although street design features were the main determinants of the variation in walking count.

When regard to the effects of individual variables, the significance, sign, and impact degree of weather variables were consistent over the two suggested models. Air temperature and wind speed had a positive relationship with walking count with significance at the .01 level. Specifically, the air temperature had quadratic relationships as an interaction effect for all three models. In Model 2, except for tree canopy cover, all street features had positive relationships with the walking count. The number of entrances had the largest impact, showing that an increase of one in entrance number was associated with a 413 increase in walking count when all other variables were controlled.

Table 4.6 Pooled OLS Outputs for Walking: number of Walking People

	Model 1 (Weather)			Model 2 (Design)		
	β	b	SE	β	b	SE
Weather						
Ta	2470.527***	7.405***	(570.200)	2651.574***	7.948***	(444.047)
Rh	0.913	0.014	(5.980)	-5.632	-0.089	(4.722)
Ws	763.309**	0.224**	(250.286)	612.205**	0.180**	(195.359)
Slr	-0.115	-0.033	(0.273)	-0.398	-0.113	(0.215)
(Interaction)						
Ta * Ta	-42.742***	-7.231***	(9.990)	-46.693***		(7.784)
Street design features						
Path characteristic						
Entrance				413.288***	0.318***	(85.211)
Street width				11.397***	0.260***	(3.138)
Tree canopy cover				-17.841**	-0.276**	(6.659)
Area characteristic						
Destination				122.089***	0.213***	(33.474)
_cons	-3.5e+04***		(8270.019)	-3.8e+04***		(6443.432)
N			174			174
F-test (model)			7.47***			22.04***
adj. R^2			0.1575			0.4932
AIC/BIC test	2719.002		2737.956	2633.43		2661.861

Standard errors in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4.7 illustrates the pooled OLS estimation for the sitting model, which used the occupancy ratio of benches as independent variables. In Model 1, the microclimate variables explained 65.18% of the variation in the occupancy ratio of benches. While considering street design features, the adjusted R-squared value grew to over 82% in Models 2. The AIC and BIC test outputs for Model 2 were almost identical at 1778.44, which was slightly lower than Model 1. Although Model 2 was preferred over model 1, the degree of model improvement was relatively minor compared with the walking model. This result indicated that, for the occupancy ratio of benches, the microclimate variable had a much larger impact than street design feature variables.

Among the microclimate variables, the shaded cover area of benches had a dominant impact on the occupancy ratio of benches. Controlling for all other variables, a 1% increase in the shaded cover area of benches was associated with an 18.93% increase in the occupancy ratio of benches. For binary regression output, this variable accounted for more than 35% of the variation in occupancy ratio. In Model 1, except for relative humidity, all the microclimate variables were statistically significant at the .1 level, and wind speed had a negative relationship with only occupancy ratio. When adding street design features, the weather variables' significance, sign, and degree of impact slightly changed, and solar radiation was no longer significant. Interaction effects were found between air temperature and air temperature, and between air temperature and the shaded cover area of benches, which were all significant across two models. For the street design features, entrance, street furniture, and presence of viewpoint had a positive

Table 4.7 Pooled OLS Outputs for Sitting: Occupancy Ratio of Benches

	Model 1 (Microclimate)			Model 2 (Design)		
	β	b	SE	β	b	SE
Microclimate						
Ta	25.903*	2.034*	(11.393)	21.714**	1.705**	(8.191)
Rh	-0.155	-0.057	(0.138)	-0.066	-0.024	(0.100)
Ws	-11.091***	-0.159***	(2.863)	-6.869**	-0.098**	(2.139)
Slr	0.031*	0.282*	(0.013)	-0.015	-0.140	(0.010)
Shade Cov	18.937***	1.066***	(1.907)	10.313***	0.581***	(1.494)
(Interaction)						
Ta * Ta	-0.476*	-2.104	(0.200)	-0.385**	-1.703	(0.144)
Shade Cov * Slr	-0.008*	-0.322	(0.003)	0.007**	0.295	(0.003)
Street design features						
Path characteristic						
Entrance				-25.030***	-0.463***	(2.359)
Street furniture				0.051*	0.073*	(0.026)
Playground				-0.878	-0.014	(2.671)
View point				7.514***	0.143***	(2.087)
_cons	-367.175*		(164.894)	-246.457*		(118.546)
N			226			226
F-test (model)			61.16			94.98***
adj. R^2			0.6518			0.8213
AIC/BIC test	1884.314		1911.678	1737.401		1778.448

Standard errors in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

relationship with occupancy ratio whereas the area of playground had a negative but not significant effect.

4.4.3. Heat Threshold and Microclimatic Street Design Features

SVFs were used to explore the effects of microclimatic street design features on heat-related pedestrian activity. SVFs are a descriptor of a street's solar geometrical features regulating the shading effects, which are the key determinants of pedestrian activity. The difference in acceptance level of thermal conditions for walking and sitting by SVFs was investigated.

In Figure 4.8, the upper three plots present the heat threshold of walking relied on SVFs. Air temperature had a quadratic relationship with walking count over three levels of SVFs. In Table 4.8, the segmented regression results indicated that, in their inverse-U shape relationships, all values of the threshold were statistically significant at the .01 level. The peak volume of walking count for SVFs was 575, 2,100, and 1,800. Notably, the slope coefficient before and after the heat threshold value was not identical. The decreasing slope (negative coefficient value) was relatively steeper than the increasing slope (positive coefficient value) regardless of the SVFs values. The heat threshold of medium and low SVFs was almost identical at approximately 28.00. Moreover, the high SVFs had relatively lower value at 27.34 compared to others. Thus, the higher SVF streets with more shaded area had a slightly higher heat threshold for walking count.

The lower section of Figure 4.8 illustrates the heat threshold of occupancy ratio by SVFs. Unlike walking, in the high SVFs, the air temperature had a linear relationship with the occupancy ratio of benches, relatively low R-squared values, and was not statistically significant (Table 4.8). This finding implied that, in high SVFs, sitting had a relatively weak relationship with thermal condition. Furthermore, medium and low SVF spots showed a quadratic relationship with the occupancy ratio. The peak occupancy ratio for medium and low SVFs was 11.00% and 60.00% respectively. Similar to walking, the decreasing slope (negative coefficient) was relatively steeper than the increasing slope (positive coefficient) regardless of the SVF level. The heat thresholds for medium and low SVFs were almost identical at approximately 28.00%. This result implies that considering the SVFs regulates the shading effects, and had a significant impact on the occupancy ratio. However, the level of SVFs (intensity and coverage of shading) rarely affected the heat threshold values of sitting.

Table 4.8 Segmented Regression Output for Heat Threshold of Walking and Sitting

	Low-SVFs		Med-SVFs		High-SVFs	
Location	(Spots A)		(Spots B, C and D1)		(Spots D2 and E)	
	β	SE	β	SE	β	SE
Walking activity						
Ta_(before)	182.858***	54.268	265.736***	56.624	184.830***	52.695
Ta_(after)	-295.594***	81.564	-496.917***	98.583	-298.834***	105.305
Int	-120.717	141.183	-105.004	198.293	-132.696	192.569
Constant	-4095.793***	1427.719	-5457.984***	1541.222	-3443.611**	1426.609
Prob > F	0.008		0.000		0.005	
Sitting activity						
Ta_(before)	-	-	1.625**	1.031	4.649*	2.713
Ta_(after)	-	-	-2.620**	1.266	-7.342**	3.551
Int	-	-	-0.676	2.644	-4.078	7.285
Constant	-	-	-32.933	27.243	-67.002	71.287
Prob > F	-	-	0.233		0.231	

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Ta_(before) is the slope when air temperature is less than the heat threshold. Ta_(after) is the change in the slope as a result of being the heat threshold or higher. Int is the predicted mean for air temperature that is just over the heat threshold minus the predicted mean for air temperature that is infinitely close to being the heat threshold.

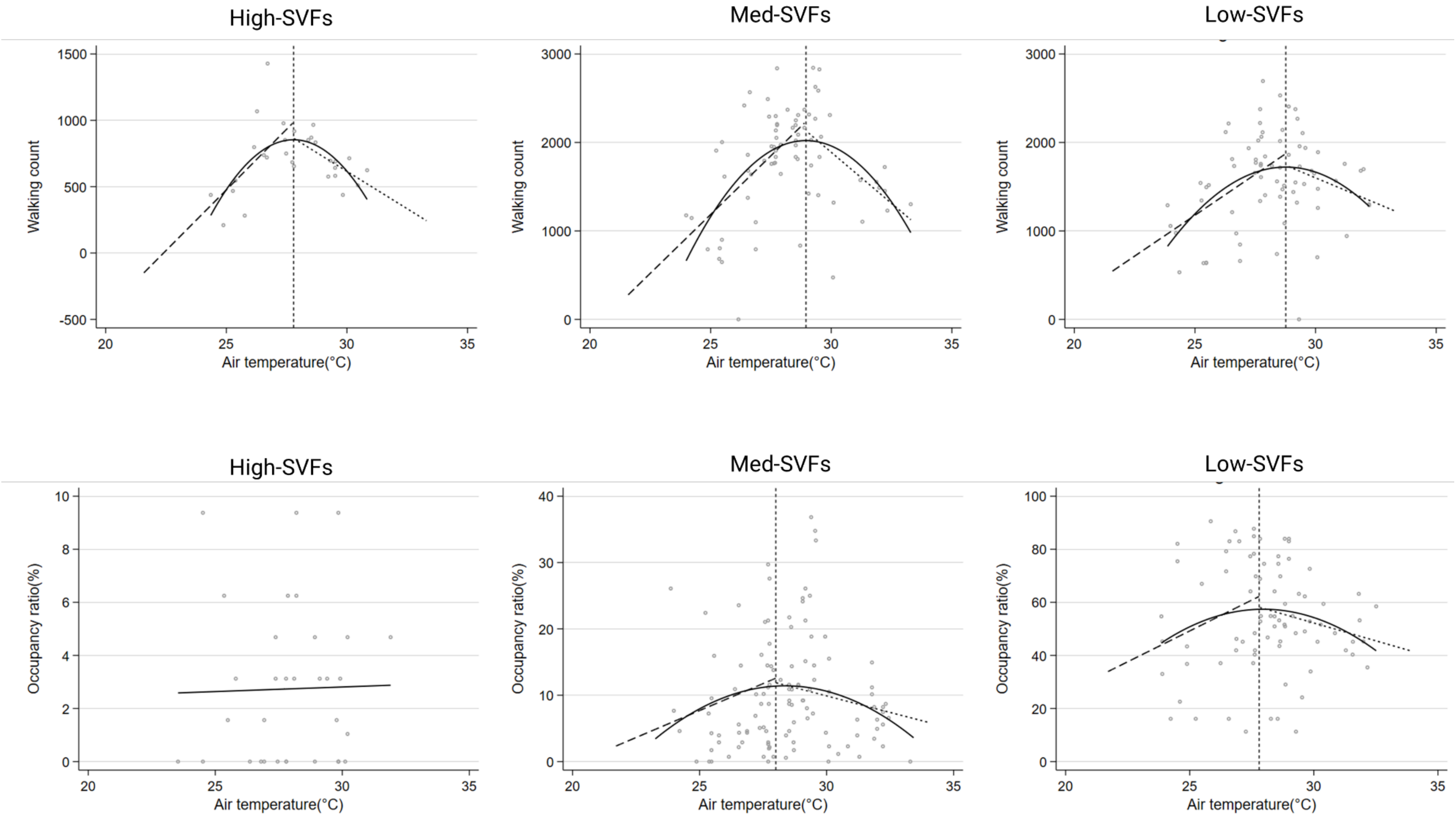


Figure 4.8 Heat Threshold of Walking and Sitting that Relies on Level of SVFs (Solar Geometrical Features of Street Design)

4.5. Discussion

The microclimatic street design had a significant impact on the heat-pedestrian activity relationship (Klemma, Hoveb, Lenzholzera, & Kramer, 2017; C.-H. Lin, Lin, & Hwang, 2013; Nikolopoulou & Lykoudis, 2007; Thorsson, Honjo, Lindberg, Eliasson, & Lim, 2007; Zacharias, Stathopoulos, & Wu, 2001). This study corroborated these findings while presenting new findings.

The meteorological conditions at two scales had different effects on walking and sitting activity. In Table 4.5, the walking count was influenced by weather conditions (mesoscale), and microclimate conditions (on-site microscale) determined the occupancy ratio of benches. These results were consistent with similar studies reporting that weather influences walking, which were related to walking trip demand, frequency, travel distance, and attendance in public spaces (Attaset, Schneider, & Arnold, 2010; Montigny, Ling, & Zacharias, 2012; Suminski, Poston, Market, Hyder, & Sara, 2008; Vanky, Verma, Courtney, Santi, & Ratti, 2017). In addition, sitting is majorly affected by microclimate conditions in terms of spatial distributions of visitors and stay duration (Klemma et al., 2017; C.-H. Lin et al., 2013; Nikolopoulou & Lykoudis, 2007). We assumed that this discrepancy in the effect of meteorological scale was caused by different decision-making levels, for example, strategic, tactical, and operational levels (Hoogendoorn & Bovy, 2004). Walking is mainly related to whether individuals choose to walk at a strategic and tactical level. These comprise departure time choice, activity scheduling, activity area choice, and route choice to reach the activity area, which are decisions usually made before the trip and are thus primarily affected by weather conditions or the forecast. Contrary, sitting is involved in where the people choose to stay and how long they remain in a given condition, whose decision is usually made at an operational level in the middle of the trip on the basis of on-site meteorological conditions.

The interaction effects of meteorological variables were found in the suggested models (Tables 4.6 and 4.7). Air temperature plays a crucial role in determining the walking and sitting count for the weather and microclimate conditions. The air temperature had a nonlinear parabolic relationship with both activities, showing an inverse U-shaped curve pattern. A similar pattern had been observed, where it often appeared on hot summer days (Aultman-Hall, Lane, & Lambert, 2009; T.-P. Lin, Tsai, Hwang, & Matzarakis, 2012; Sharifi & Boland, 2018) Especially for sitting, shading cover ratio of benches had a significant synergy effect with air temperature, which is also reported in several similar studies (Cheung & Jim, 2018; T.-P. Lin et al., 2012; Martinelli, Lin, & Matzarakis, 2015). This study found that the shading effects on the occupancy ratio of benches have a J-shaped curve illustrating that the occupancy ratio of benches grows exponentially as the shading cover ratio of benches increases, which can be supported by Zacharis' study (2004). Thus, shading is the most influential factor determining where people choose to stay, especially when the temperature is high during the summer season.

The degree of meteorological impact on pedestrian activity is relatively higher than that of the street's path and area characteristics. The standardized coefficient of the variables in the model was estimated to compare their relative degree of impact, indicating which variables have the largest impact on activity. Notably, the study output indicates that air temperature has the largest impact on walking and sitting count in the summer daytime. For walking count, the impact degree of other weather variables such as relative humidity, wind speed, and solar radiation is relatively smaller than path and area street characteristics (Table 4.7). Meanwhile, for sitting, with the air temperature, the variable of shading cover ratio of benches has a larger degree of effect compared to other street variables (Table 4.8). This result implies that proper modification of microclimate by urban street design promotes pedestrian activity during hot summers. To maximize the cooling benefits for pedestrians, designers should lower the air temperature and increase the shading effects, which are also critical determinants of a person's physiological outdoor thermal comfort.

SVFs affect the acceptable ranges of thermal stress for walking and sitting. SVFs are a descriptor of a street's solar geometrical design features, which regulates shading effects. Although the heat threshold of air temperature does not proportionally increase as the function of SVFs' values, its presence has significant effects on the changes in the heat threshold for walking and sitting count (Figure 4.8). Similar studies have revealed that shading effects, which are majorly determined by SVFs, HW ratio, and Tree Canopy Cover, are the key determinant of where and how long individuals prefer to stay in a given condition related to sedentary and leisure activities (Klemma et al., 2017; T.-P. Lin et al., 2012; Martinelli et al., 2015). An exemplary study conducted by Shafari (2018) supports this result by showing that the increase in street greenery density is related to the higher heat threshold of pedestrian activity. Thus, the thermally comfortable area with more shaded cover has higher spatial heat resistance that supports activities during high thermal stress conditions. However, this relationship would be highly flexible because the pedestrian's thermal sensitivity can vary by the walking purpose (optional, utilitarian, and social), weather attitude (socio-culture and local climate), and functions of public space (route/passage and resting place) (Sharifi & Boland, 2018; Watanabe & Ishii, 2016)

4.6. Conclusion

This study investigated the effects of microclimatic street design features on the heat-pedestrian activity relationship by using fieldwork data collected at the High Line, New York City. The aim was to (1) investigate the different spatial scales of meteorological effects on walking and sitting, (2) estimate the impact of meteorological conditions and their interactions on walking and sitting while controlling the street features of the five observation spots, and (3) identify the acceptable ranges of thermal stress for each activity in comparison of street spots with a different level of SVFs.

The different scale of meteorological conditions has different effects on walking and sitting. The walking count was heavily influenced by weather conditions, while microclimate conditions majorly determined the sitting count. The key reason for this discrepancy in meteorological scale effects was caused by different decision levels made before making the trip for walking and the middle of the journey for sitting. Furthermore, interaction effects were found between air temperature and temperature, and between air temperature and shade cover ratio of benches.

The pooled OLS regression output revealed the relative degree of the impact of meteorological conditions on walking and sitting while controlling street design features. With regard to walking, the weather variables only explained approximately16% of the variation in the walking count. In addition, when considering street design features, the adjusted R-squared value for suggested full models sharply increased to approximately 50%. For sitting, microclimate variables explain 65.18% of the variation in the occupancy ratio of benches. While accounting for street design features, the adjusted R-squared value increased to over 82%. This finding implied that sitting is largely determined by shading effects modified by microclimatic street design features.

The heat threshold of sitting and walking was significantly influenced by SVFs regulating the solar access and shading effects. Air temperature had a quadratic relationship with a walking count over three levels of SVFs. This curve pattern indicated that the thermally comfortable spots with more shaded areas had a slightly higher heat threshold, which proved our research hypothesis. Unlike walking, in the high SVFs, the air temperature had a linear relationship with the occupancy ratio of benches for sitting, and it had relatively low R-squared values that were not statistically significant. However, medium and low SVF spots showed a clear quadratic relationship with the occupancy ratio and had higher heat threshold values than low SVFs. This finding implied that sitting is largely determined by the presence of shading regulated by SVFs.

This study has several limitations. First, the low number of five observation street spots might have influenced the reliability of suggested models. Since the limited sample size of the street design measurement led to higher variability of pedestrian observation for walking and sitting count in each observation spot, bias in the estimation might have occurred. Second, the results on the heat threshold for walking and sitting count in this study might not apply to other study sites. This phenomenon would occur because value of heat threshold would be highly flexible as the pedestrian's thermal sensitivity can vary by the purpose of activities, weather attitude, and functions of public space. To address these issues, computer vision technologies needs to be developed and used, which able to record and analyze a large amount of pedestrian observation data in multiple spots at the same time. Currently, collecting and processing long-term, big sample size pedestrian observation data is challenging but critical to improving accuracy and reliability of study outputs.

In conclusion, a key finding of this study is that microclimatic street design features improve pedestrian thermal comfort and increase the acceptable range of thermal conditions for walking and sitting. Walking count was associated with weather conditions, while the sitting count was primarily determined by microclimate conditions, especially for the occupancy ratio of benches. SVFs had a considerable impact on the heat threshold for the occupancy ratio of benches. This finding is significant because the shading effect of solar geometry is the most influential factor that determines where pedestrians prefer to stay. We expect this study's outcome to provide empirical knowledge and deepen the understating of designing heat-resistant street spaces that support pedestrian activities and thus promote street vitality in the global warming.

5. CONCLUSION

5.1. Summary

This study explored the dynamic relationship between thermal comfort and pedestrian activities in relation to urban street design throughout three independents yet connected research topics. It highlighted the impact of physiological thermal comfort on pedestrian activities, especially walking and sitting. Accordingly, the study evaluated the association between thermal comfort and urban street design using the on-site microclimate measurements. Furthermore, the study investigated the influence of microclimate and thermal comfort on pedestrian activities and the usage of street spaces using the data captured through direct observations. Given that the process of thermal adaptation shaped the relationship between heat and pedestrian activities, particular attention was given to the heat threshold of walking and sitting, according to the specific microclimatic features of the street.

Chapter 2 examined the effects of meteorological conditions and outdoor thermal comfort on the number of pedestrians (walking primary for leisure purpose). Specifically, the study identified the different scales of meteorological conditions and their impact on leisure walking count in a pedestrian-only urban walkway named Seoul-lo 7017 in Seoul, South Korea. The findings indicated that walking count is correlated to climate, weather, and microclimate conditions. In terms of climate, a clear seasonal pattern was observed with the highest volumes in the fall, a secondary peak in the spring, and the lowest volumes in the summer. For weather and microclimate, air temperature exerted the largest effect, which explained 5.48% of total variation in walking count. In the spring and summer, the temperature displayed a parabolic relationship with walking count, which peaked between 24.4°C and 27.8°C. The combined effects of temperature and relative humidity exerted the largest impact throughout the year. The study noted a one-hour time-lag effect of rainfall. In terms of the predictive power of the outdoor thermal comfort indexes, the rational models explained approximately 33% of the variation in walking count.

Chapter 3 explored the combined effects of microclimatic urban design features on daytime pedestrian thermal comfort by using a multilevel model. Using on-site field measurement data, this study examined the impact of different scales of street- and block-scale design factors on the physiological thermal comfort of pedestrians on the High Line in New York City. Findings showed that the High Line experienced high thermal stress conditions with clusters of hot spots, particularly in its upper section. In addition, the urban design features at the street and block scales were highly correlated with the estimated level of pedestrian thermal comfort. The mean energy budget value was largely dependent on block density and volume at the block-scale level, whereas height-to-width ratio, tree view factors (TVFs), and the ratio of tree canopy cover exhibited a negative linear relationship with absorbed solar radiation at the street-scale level. Moreover, the findings indicated that the combination of urban design factors at the street- and block-scale levels significantly influence pedestrian thermal comfort.

Chapter 4 investigated the effects of microclimatic street design features on the relationship between pedestrian activities and outdoor thermal comfort. Five major pedestrian activity spots of the High Line in New York City were selected as study sites. Panel data analysis was used to estimate the impact of microclimatic street design and to identify associated heat threshold levels based on field measurements conducted in July in 2019. The results indicated that pedestrian activities were significantly determined by the meteorological conditions and thermal comfort, which are regulated by the features of microclimatic street design. Walking count was associated with weather conditions, whereas microclimate conditions primarily determined sitting count, especially for the shading cover ratio of benches. In terms of the walking activity model, the weather variables explained approximately 16.60% of variation in walking count. Meanwhile, for the sitting activity model, the microclimate variables explained 65.18% of variation in the occupancy ratio of benches. Regarding the features of microclimatic street design, sky view factors (SVFs) exerted a considerable impact on the heat threshold for sitting count. However, its impact on walking count was relatively minimal.

5.2. Implications for Research and Practice

Implication 1*: The different meteorological scales of season, weather, and microclimate are clearly associated with walking activity.*

The meteorological impacts of walking count were determined not only through individual intensity, but also through scales of season, weather, and microclimate conditions. The seasonal climatic context largely influenced their impact and types of relationship between weather and microclimate. In the case of Seoul-lo 7017, their dynamic relationships led to interaction impact, time-lag effects, and diverse relational functions, which are also subject to seasonal variations. Notably, inconsistency remained about their relative degree of influence on walking count according to study location. In other words, socio-cultural contexts should be included in future studies, which may include weather expectations, attitudes, demographics, and walking attitudes. Findings from this research can be utilized to develop behavioral thermal adaptation models for the prediction of walking activities and their optimal ranges of thermal conditions.

Implication 2*: Thermal conditions play a key role in determining pedestrian activities. However, its degree of impact relies significantly on the types of walking activity, days of the week, and features of street design.*

The case studies on Seoul-lo 7017 and High Line indicated that air temperature exerted the largest effect on walking and sitting activities among all meteorological variables. Moreover, air temperature had a non-linear relationship with walking count, which displayed the pattern of an inverse U-shaped curve in spring and summer, peaked between 24.4°C and 27.8°C. Thus, it led to considerable synergetic effects on walking count when combined with strong solar radiation in summer.

- Thermal effects are dependent on the types of pedestrian activity. Meteorological conditions at two scales differently influenced walking and sitting. Specifically, weather (mesoscale) influenced the walking count, whereas microclimate (on-site microscale) determined the occupancy ratio of benches, which is assumed to be caused by different decision-making levels at the strategic, tactical, and operational levels.

- The heat threshold for walking activity is dependent on the day of the week. Heat thresholds during the weekend would be lower than that during weekdays as indicated by the dominance of leisure walking activity during the weekend. This form of walking activity is more susceptible to heat stress than utilitarian walking given that it is a voluntary practice.
- The heat threshold for sitting and walking activities were significantly influenced by SVFs, which regulate solar access and shading effects. Air temperature had a quadratic relationship with walking count and occupancy ratio of benches over three levels of SVFs (low: 20% >, medium: 20% < < 40%, and high: 40% <). This curve pattern implies that thermally comfortable spots with more shaded areas exerted a slightly higher heat threshold.

These findings can be used to provide operational guidance on the management and operation of streets and public spaces, as well as the organization of outdoor events during daytime in hot summers. Moreover, they provide practical knowledge and a deep understating for designing heat-resistant street spaces that support pedestrian activities during the age of global warming.

Implication 3*: Physiological thermal comfort, estimated using the outdoor thermal comfort indexes, is highly related to pedestrian activities.*

This study explored the predictive capacities of five outdoor thermal comfort indexes, which were examined as indicators of leisure walking count. Given the association between microclimate and pedestrian activities, the study hypothesized that rational indexes such as COMFA, UTCI, and PST would improve the explanatory power of the model if these indexes were applied to studies on the thermal behavioral features of pedestrian presence on streets. Although the study observed several seasonal variations, the results indicated that the rational models explained approximately 33% of variation in walking count based on a full-year data. This finding implies that the application of indexes as indicators of variation in walking count is valid. Furthermore, outdoor thermal comfort indexes can be feasible tools for evaluating the pedestrian thermal environment. This finding suggest that these indexes can help improve existing walkability audits to incorporate thermal conditions for a more complete assessment of urban public spaces to support pedestrian activities.

Implication 4*: Urban design factors at the street- and block-scale levels significantly impacted pedestrian thermal comfort.*

The urban design features at the street- and block-scales were highly correlated with the estimated levels of pedestrian thermal comfort. At the block-scale level, the mean energy budget value was largely dependent on block density and tree presence, which were classified into the eight morphological block types in this study. At the street-scale level, SVFs had a positive linear relationship with absorbed solar radiation that a person receives (Kabs), whereas TVFs and the ratio of tree canopy cover exerted a negative effect. After controlling for microclimate conditions, the block-scale factors explained an additional 4.9% of the total variance, whereas street- and block- scale factors accounted for 12.99% of the total variation in energy budget values. This result implies that the design features at the street- and block-scale levels were spatially interconnected, and microclimate conditions were clustered at the two spatial scales. To effectively improve pedestrian thermal comfort, the study proposes the following design implications.

- First, planting trees in open street canyons instead of narrow and deep streets is more effective for cooling. The shade of nearby buildings, especially in high-density blocks, can considerably mask the effects of tree shading. Notably, however, extremely dense trees in deep canyons may produce lower ventilation and radiation blanket effects, leading to increased pedestrian thermal stress.
- Second, utilizing high albedo materials for building wall façades is important, especially for those that receive direct sunlight during the afternoon. This study found that the afternoon terrestrial radiation emitted from wall façades was the largest contributor to the increased thermal loading on pedestrians. However, the study noted that excessive high albedo materials may increase such loading due to the increase in reflective solar radiation.
- Third, enhancing variation in building heights in urban blocks is a promising strategy to promote thermal comfort. Specifically, non-uniform building heights could improve urban block ventilation, especially for streets near water and green bodies. However, the ventilation cooling of water and green bodies is highly limited to their distance and boundaries.

Appropriate modification of urban design factors at the street- and block-scales can effectively improve pedestrian thermal comfort. Moreover, these findings can serve as guidance for planners and designers when deciding which strategies are appropriate for urban street design to effectively regulate pedestrian thermal stress during daytime hours in summer.

Implication 5: *SVFs alter the acceptable ranges of thermal conditions for walking and sitting activities.*

SVFs describe the solar geometrical design features of streets, which regulate shading effects. Although the heat threshold of air temperature does not proportionally increase as a function of SVF values, its presence exerts a significant impact on the heat threshold for walking and sitting. Thermally comfortable areas often have lower SVFs values with increased shaded cover and spatial heat resistance, which support pedestrian activities during high thermal stress conditions. This finding suggests the importance of shading effects, which are regulated by the urban street design features, to promote pedestrian activities. Specifically, applying street trees for solar protection of street benches, facilities, and leisure spots is highly recommended with a careful consideration of the street orientation, building layout, and wind ventilation. However, the effects of shading on pedestrian activities will likely vary, as the thermal sensitivity of pedestrians differs according to the walking purpose (e.g., optional, utilitarian, and social), weather attitude (e.g., sociocultural and local climate), and the functions of public spaces (e.g., route/passage and resting place).

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