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# A Comprehensive Review of Thermal Comfort Studies in Urban Open Spaces

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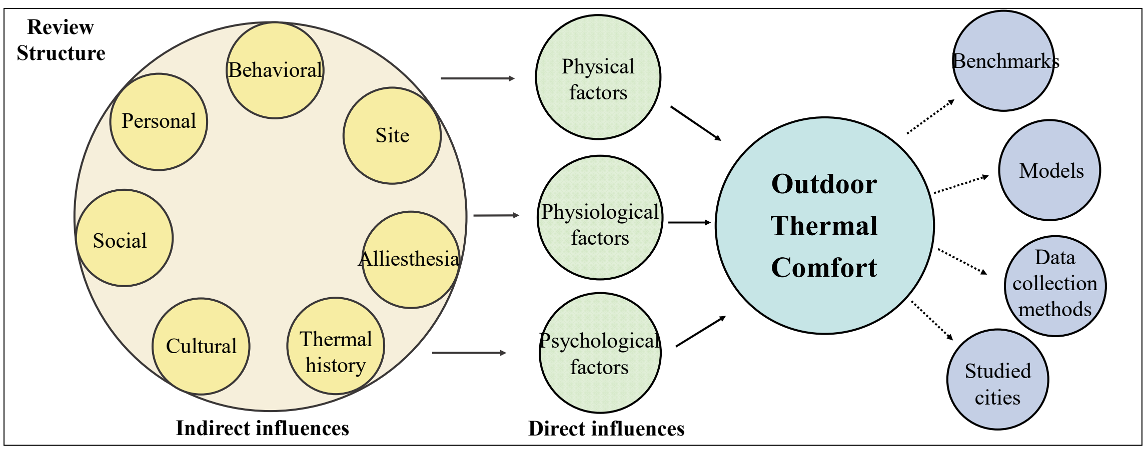
## Graphical Abstract




## Abstract:

Urban open spaces provide various benefits to large populations in cities. Since thermally comfortable urban open spaces improve the quality of urban living, an increasing number of studies have been conducted to extend the existing knowledge of outdoor thermal comfort. This paper comprehensively reviews current outdoor thermal comfort studies, including benchmarks, data collection methods, and models of outdoor thermal comfort. Because outdoor thermal comfort is a complex issue influenced by various factors, a conceptual framework is proposed which includes physical, physiological and psychological factors as direct influences; and behavioral, personal, social, cultural factors, as well as thermal history, site, and alliesthesia, as indirect influences. These direct and indirect factors are further decomposed and reviewed, and the interactions among various factors are discussed. This review provides researchers with a systematic and comprehensive understanding of outdoor thermal comfort, and can also guide designers and planners in creating thermally comfortable urban open spaces.

**Keywords:** Outdoor thermal comfort; Urban open space; Urban heat island; Adaptation; Human behavior; Urban planning

**Nomenclature**

AC, Air Conditioner
ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASV, Actual Sensation Vote, a linearly regressed thermal sensation model
COMFA, comfort formula, a human thermal budget index
DTS, Dynamic Thermal Sensation, a model that calculates thermal sensation
FI, Fluctuation Index, used to indicates the fluctuation of microclimate parameters
GOCI, Global Outdoor Comfort Index
HVAC, Heating, Ventilation, and Air Conditioning
H/W, Weight-to-Width ratio
IMEM, Instationary Munich Energy Balance Model
ITS, Index of Thermal Stress, a human thermal budget model
IZA, the thermal comfort Index for cities of Arid Zones
MOCI, Mediterranean Outdoor Comfort Index
OTE, Optimum Thermal Environment
OUT_SET*, Outdoor Standard Effective Temperature
PET, Physiologically Equivalent Temperature
PMV, Predicted Mean Vote
SET*, Standard Effective Temperature
SVF, Sky View Factor
TOCI, Turkish Outdoor Comfort Index
TSV, Thermal Sensation Vote
UEB, Underneath Elevated Buildings
UTCI, Universal Thermal Climate Index
WBGT, Wet Bulb Globe Temperature

## 1. Introduction

More than half of the world's population lives in cities (World Population Bureau, 2018). Urban open spaces provide physical, environmental, social, and economic benefits to citizens (Woolley, 2003). Thermally comfortable urban open spaces offer high-quality locations to residents and attract them to the outdoors (Lai et al., 2019a; Lai et al., 2014b; Lin et al., 2012; Nikolopoulou and Lykoudis, 2007), thus increasing the vitality of cities. Creating a comfortable thermal environment in urban open spaces requires a good understanding of outdoor human thermal comfort. As a result, an increasing number of studies have been conducted on the topic of outdoor thermal comfort.

These outdoor thermal comfort studies have addressed various activities in different kinds of outdoor spaces, and have been performed in cities with diverse climates. Although the studies have accumulated valuable knowledge about outdoor thermal comfort, conflicting conclusions have been reached. For example, while many studies have found the neutral temperature in the hot season to be higher than that in the cool season, two studies (Spagnolo and de Dear, 2003;

Yahia and Johansson, 2013) demonstrated the opposite results. The conflict may be due to the different methods used to obtain (Johansson et al., 2014), analyze, and interpret the data. For instance, the data collection process varied among three-point (Lai et al., 2014b), five-point (Nikolopoulou and Lykoudis, 2006), seven-point (Lin, 2009), and nine-point (Chen et al., 2018) scales for thermal sensation votes. Furthermore, data analysis relied on different thermal benchmarks, such as neutral temperature, preferred temperature, and acceptable temperature (Cheung and Jim, 2017; Shooshtarian and Ridley, 2016a), and the methods for obtaining these benchmarks may be different. When calculating neutral temperature, some studies have used the "bin" method (Lin and Matzarakis, 2008), while other investigations have employed "probit analysis" (Spagnolo and de Dear, 2003). In addition to distinctive methods, different models used in various studies may add to the complexity of outdoor thermal comfort. These models were developed by incorporating different influencing factors of outdoor thermal comfort, such as physical, physiological, psychological, social, cultural, behavioral, and personal factors. However, the above influencing factors are intertwined with one another, making outdoor thermal comfort a complex issue. At the same time, the number of outdoor thermal comfort studies were increasing. Therefore, to timely provide information for further researches, it is necessary to perform a critical review to comprehensively and systematically summarize the methods, models, and influencing factors in current outdoor thermal comfort studies.

This review is organized as follows. First, after a brief introduction of the benchmarks used for outdoor thermal comfort, we present a summary of current studies, including the climatic and geographical distributions of these studies, and the research methods and models that were employed. Next, as the main content of this paper, the direct and indirect factors influencing outdoor thermal comfort are reviewed. Finally, this study discusses the interactions among various factors, the frequently occurring adaptation phenomena, the practical implications of the studies' findings, and the outlook for future research.

## 2. Studying outdoor thermal comfort

To conduct the comprehensive review, this study first searched peer-reviewed articles published in databases such as Google Scholar, Scopus, Web of Science, ScienceDirect, Springer, and Wiley etc. Only studies that combined thermal environment conditions with subjective human responses were selected. If a study only analyzed the thermal environment, or only used thermal indices or models to assess human thermal comfort without actual perception data, it was not included in our review. If a set of data were used repeatedly in different papers to analyze the various aspects of outdoor thermal comfort, these papers were all included. The reviewed articles were conducted in different climatic regions all over the world, employed different methods to collect data, used different benchmarks for data interpretation, and they identified various influencing factors of outdoor thermal comfort. The following contents provide a review of the above issues.

### 2.1 Current studies

Researchers have studied outdoor thermal comfort in various cities located in different climatic zones. Figure 1 summarizes these cities on a world map according to Koppen climate classification. As shown in the figure, studies have been conducted in 107 cities, on all continents except Antarctica, among which 42 cities were in Asia and 22 in Europe. Although the cities include 20 in Africa, 16 of these were in Nigeria, as investigated by Eludoyin and Adelekan (2013). Some cities have been surveyed repeatedly. For example, Taichung was investigated eight times, and Hong Kong seven times. Tables 1 and 2 provide further information about these studies. This large body of outdoor thermal research reflects its global relevance and importance.

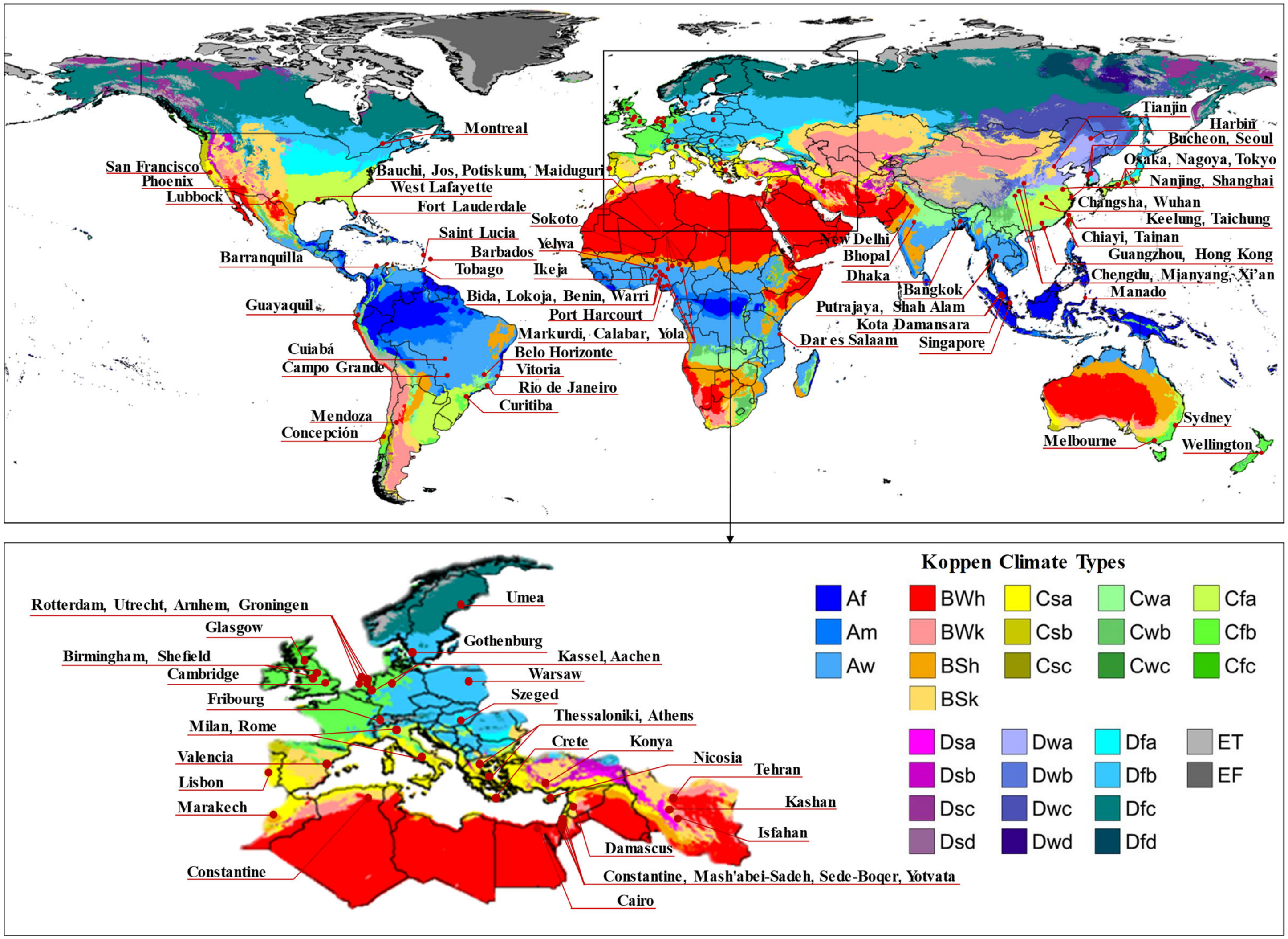



Figure 1. Studied cities on the world map according to Koppen climate classification. Map from Beck et al. (Beck et al., 2018).

## 2.2 Benchmarks of outdoor thermal comfort

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has defined outdoor thermal comfort as "the condition of mind that expresses satisfaction with the outdoor thermal environment (ASHRAE, 2017a)." To assess whether the state of thermal comfort in outdoor spaces has been reached, many different benchmarks are available in the literature. Since thermal comfort is defined as a "condition of mind," subjective judgements about thermal sensation, thermal preference, thermal comfort level, and thermal acceptability are important indications of thermal comfort (Cheung and Jim, 2017; Shooshtarian and Ridley, 2016a). According to these subjective benchmarks, outdoor space can be considered thermally comfortable if the occupants feel approximately neutral, do not wish to change the outdoor thermal environment, or directly regard the outdoor thermal environment as thermally comfortable or acceptable. Although differences among subjective benchmarks have been discussed by Spagnolo and de Dear (2003) and Cheung and Jim (2017), the benchmarks have been used interchangeably in some studies. For example, the neutral range was regarded as an acceptable range by Yahia and Johansson (2013) and Mahmoud (2011). However, Lai et al. (2014a) and Shooshtarian and Ridley (2016a) showed that it might be problematic to indirectly use thermal sensation vote to derive an acceptable thermal range when assessing the outdoor thermal environment. In a review of 24 outdoor thermal comfort studies, Cheung and Jim (2017) found that neutral or acceptable conditions were often mistaken for comfortable conditions.

In addition to subjective perceptions, outdoor space attendance been used as an indicator of thermal comfort, since people tend to "vote with their feet" and leave a space if they feel uncomfortable. For example, Huang et al. (2016) directly defined an optimum thermal environment (OTE) for Wuhan, China, by using the UTCI range corresponding to attendance of over 90%. Physiological responses such as skin and core temperatures, and sweat rate, may also serve as reasonable indices of outdoor thermal comfort. However, very few studies have tried to establish a link between physiological indicators and outdoor thermal comfort.

## 2.3 Approaches to data collection

The research data on outdoor thermal comfort have generally been collected by one of two methods, the traverse field survey and the longitudinal subject test, as shown in Tables 1 and 2, respectively. Most studies have used traverse field surveys. In this type of survey, researchers use a questionnaire to obtain a subjective evaluation of thermal comfort and other related information such as gender, age, clothing, and mood at the time of the interview. The collection of subjective votes is usually accompanied by monitoring of the surrounding microclimate. Some studies further recorded the activity in the areas investigated, such as the attendance in the sites, length of stay, and adaptive behaviors of occupants. Because the traverse field survey allows researchers to easily collect a large amount of real-world data, this has been the most common approach. However, in this type of survey, the perceptions of interviewees are collected only once at a specific time under uncontrolled thermal environmental conditions. Therefore, the dynamic influences of the thermal environment cannot be investigated. Furthermore, it is hard to minimize the uncertainty that arises from individual differences in traverse field surveys.

As a result, some researchers have carried out longitudinal tests on limited numbers of human subjects in selected or relatively controlled outdoor thermal environments. In a longitudinal subject test, many uncertainties, such as the thermal environmental parameters (air temperature, radiation, wind speed, etc.) and personal parameters (age, gender, thermal history, etc.) can be controlled. For example, Cheng et al. (2012) created four different combinations of outdoor thermal environmental conditions using a wind break and an umbrella, and investigated the thermal perception of eight subjects under these thermal conditions. Longitudinal subject tests have also made it feasible for researchers to record physiological parameters of subjects, such as skin and core temperatures, heart rate, pulse, and sweat rate. While the majority of studies have chosen either the traverse field survey or the longitudinal test, two studies (Cohen et al., 2019; Jeong et al., 2016) used a combination of these approaches in order to take advantage of both methods.

When it is not feasible to conduct on-site studies, models can be employed to assess human thermal response to certain thermal environments. For example, Katavoutas et al. (2015) used the two-node Instationary Munich Energy Balance Model (IMEM) to study the dynamic changes in skin and core temperatures and skin wetness of a typical subject who entered a hot outdoor environment from an indoor space.

Table 1. Summary of traverse field studies from the reviewed literature.

| No | Author, Year | City | Climatic Zone (Koppen Classification) | No. of Votes | Periods Investigated |
|---|---|---|---|---|---|
| 1 | (Nikolopoulou et al., 2001) | Cambridge, UK | Marine West Coast (Cfb) | 1431 | Spring, summer, winter |
| 2 | (Zacharias et al., 2001) | Montreal, Canada | Warm Summer Continental (Dfb) | N/a | April, May, June, September, and October |
| 3 | (Ahmed, 2003) | Dhaka, Bangladesh | Tropical Savanna (Aw) | 1500 | July, August |
| 4 | (Becker et al., 2003) | Yotvata, Israel | Tropical and Subtropical Desert (BWh) | 288 | July |
| 5 | (Spagnolo and de Dear, 2003) | Sydney, Australia | Humid Subtropical (Cfa) | 1018 | Summer, winter |
| 6 | (Gómez et al., 2004) | Valencia, Spain | Tropical and Subtropical Steppe (BSk) | 1500 | Four seasons |
| 7 | (Stathopoulos et al., 2004) | Montreal, Canada | Warm Summer Continental (Dfb) | 466 | Spring, autumn |
| 8 | (Thorsson et al., 2004) | Gothenburg, Sweden | Marine West Coast (Cfb) | 285 | From July to October |
| 9 | (Knez and Thorsson, 2006) | Tokyo, Japan | Humid Subtropical (Cfa) | 63 | March |
| | | Gothenburg, Sweden | Marine West Coast (Cfb) | 43 | April |
| 10 | (Nikolopoulou and Lykoudis, 2006) | Kassel, Germany | Marine West Coast (Cfb) | 824 | Four seasons |
| | | Athens, Greece | Mediterranean (Csa) | 1503 | Four seasons |
| | | Thessaloniki, Greece | Humid Subtropical (Cfa) | 1813 | Four seasons |
| | | Milan, Italy | Marine West Coast (Cfb) | 1173 | Four seasons |
| | | Fribourg, Switzerland | Marine West Coast (Cfb) | 1920 | Four seasons |
| | | Sheffield, UK | Marine West Coast (Cfb) | 1008 | Four seasons |
| | | Cambridge, UK | Marine West Coast (Cfb) | 948 | Four seasons |
| 11 | (Eliasson et al., 2007) | Gothenburg, Sweden | Marine West Coast (Cfb) | 1379 | January, April, June and October |
| 12 | (Hwang and Lin, 2007) | Taichung, Taiwan | Humid Subtropical (Cfa) | 3027 | Spring, summer, winter |
| | | Yunlin, Taiwan | Humid Subtropical (Cfa) | | Spring, summer, winter |
| | | Chiayi, Taiwan | Humid Subtropical (Cfa) | | Spring, summer, winter |
| 13 | (Kantor et al., 2007) | Szeged, Hungary | Warm Summer Continental (Dfb) | 844 | August, September |
| 14 | (Nikolopoulou and Lykoudis, 2007) | Athens, Greece | Mediterranean (Csa) | 1503 | Four seasons |

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|---|---|---|---|---|---|
| 15 | (Oliveira and Andrade, 2007) | Lisbon, Portugal | Mediterranean (Csa) | 91 | Spring, winter |
| 16 | (Thorsson et al., 2007) | Tokyo, Japan | Humid Subtropical (Cfa) | 1142 | March, May |
| 17 | (Walton et al., 2007) | Wellington, New Zealand | Marine West Coast (Cfb) | 649 | Over nine months |
| 18 | (Lin and Matzarakis, 2008) | Sun Moon Lake, Taiwan | Humid Subtropical (Cfa) | 1644 | Four seasons |
| 19 | (Metje et al., 2008) | Birmingham, UK | Marine West Coast (Cfb) | 451 | From August to February |
| 20 | (Lin, 2009) | Taichung, Taiwan | Humid Subtropical (Cfa) | 505 | From April to February |
| 21 | (Hwang et al., 2010) | Taichung, Taiwan | Humid Subtropical (Cfa) | 3837 | Four seasons |
| 22 | (Krüger and Rossi, 2011) | Curitiba, Brazil | Marine West Coast (Cfb) | 1654 | From January to August |
| 23 | (Mahmoud, 2011) | Cairo, Egypt | Tropical and Subtropical Desert (BWh) | 300 | June, December |
| 24 | (Kantor et al., 2012) | Szeged, Hungary | Warm Summer Continental (Dfb) | 967 | Spring, autumn |
| 25 | (Krüger et al., 2012) | Glasgow, UK | Marine West Coast (Cfb) | 763 | From March to July |
| 26 | (Makaremi et al., 2012) | Putrajaya, Malaysia | Tropical Rainforest (Af) | 200 | March, April |
| 27 | (Ng and Cheng, 2012) | Hong Kong, China | Humid Subtropical (Cfa) | 937 | August (pilot) |
| | | | | 2702 | From November to August |
| 28 | (Yahia and Johansson, 2013) | Damascus, Syria | Tropical and Subtropical Steppe (BSk) | 920 | January, February, August and September |
| 29 | (Cohen et al., 2013) | Tel Aviv, Israel | Mediterranean (Csa) | 1731 | Summer, winter |
| 30 | (Eludoyin and Adelekan, 2013) | Yelwa, Nigeria | Tropical Savanna (Aw) | 3600 | March to November |
| | | Sokoto, Nigeria | Mid-Latitude Steppe and Desert (Bsh) | | |
| | | Bauchi, Nigeria | Tropical Savanna (Aw) | | |
| | | Potiskum, Nigeria | Mid-Latitude Steppe and Desert (Bsh) | | |
| | | Maiduguri, Nigeria | Mid-Latitude Steppe and Desert (Bsh) | | |
| | | Yola, Nigeria | Tropical Savanna (Aw) | | |
| | | Markurdi, Nigeria | Tropical Savanna (Aw) | | |
| | | Ilorin, Nigeria | Tropical Savanna (Aw) | | |
| | | Lokoja, Nigeria | Tropical Savanna (Aw) | | |
| | | Bida, Nigeria | Tropical Savanna (Aw) | | |
| | | Jos, Nigeria | Tropical Savanna (Aw) | | |

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| | | Warri, Nigeria | Tropical Savanna (Aw) | | |
| | | Ikeja, Nigeria | Tropical Savanna (Aw) | | |
| | | Port Harcourt, Nigeria | Tropical Monsoon (Am) | | |
| | | Benin, Nigeria | Tropical Savanna (Aw) | | |
| | | Calabar, Nigeria | Tropical Monsoon (Am) | | |
| 31 | (Lin et al., 2013a) | Taichung, Taiwan | Humid Subtropical (Cfa) | 759 | From September to January |
| 32 | (Lindner-Cendrowska, 2013) | Warsaw, Poland | Marine West Coast (Cfb) | 553 | July, February, April and October |
| 33 | (Pantavou et al., 2013) | Athens, Greece | Mediterranean (Csa) | 1706 | July, October and February |
| 34 | (Yang et al., 2013b) | Singapore | Tropical Rainforest (Af) | 2020 | From August to May |
| | | Changsha, China | Humid Subtropical (Cfa) | 2052 | From June to August |
| 35 | (Lai et al., 2014a) | Tianjin, China | Hot Summer Continental (Dwa) | 1565 | From March to January |
| 36 | (Lai et al., 2014b) | Wuhan, China | Humid Subtropical (Cfa) | 490 | August, September, October and November |
| 37 | (Pearlmutter et al., 2014) | Sede-Boqer, Israel | Mid-Latitude Steppe and Desert (Bsh) | 319 | July |
| 38 | (Tsitoura et al., 2014) | Crete, Greece | Mediterranean (Csa) | 200 | Summer, winter |
| 39 | (Villadiego and Velay-Dabat, 2014) | Barranquilla, Colombia | Tropical Savanna (Aw) | 781 | January |
| 40 | (Chen et al., 2015) | Shanghai, China | Humid Subtropical (Cfa) | 596 | From November to January |
| 41 | (Trindade da Silva and Engel de Alvarez, 2015) | Vitoria, Brazil | Tropical Savanna (Aw) | 841 | Spring, summer, winter |
| 42 | (Klemm et al., 2015) | Arnhem, Netherlands | Marine West Coast (Cfb) | 184 | Summer |
| | | Utrecht, Netherlands | Marine West Coast (Cfb) | 181 | Summer |
| | | Rotterdam, Netherlands | Marine West Coast (Cfb) | 194 | Summer |
| 43 | (Martinelli et al., 2015) | Rome, Italy | Mediterranean (Csa) | N/a | August |
| 44 | (Ruiz and Correa, 2015) | Mendoza, Argentina | Tropical and Subtropical Desert (BWk) | 667 | Summer, winter |
| 45 | (Rutty and Scott, 2015) | Barbados, the Caribbean Islands | Tropical Monsoon (Am) | 216 | March, April |

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|---|---|---|---|---|---|
| | | Saint Lucia, the Caribbean Islands | Tropical Monsoon (Am) | 126 | |
| | | Tobago, the Caribbean Islands | Tropical Monsoon (Am) | 130 | |
| 46 | (Saaroni et al., 2015) | Tel Aviv, Israel | Mediterranean (Csa) | 300 | June, July |
| 47 | (Sharmin et al., 2015) | Dhaka, Bangladesh | Tropical Savanna (Aw) | over 700 | September |
| 48 | (Wu et al., 2015) | Taichung, Taiwan | Humid Subtropical (Cfa) | 392 | March, April |
| 49 | (Zeng and Dong, 2015) | Chengdu, China | Humid Subtropical (Cfa) | 255 | August |
| 50 | (Chow et al., 2016) | Singapore | Tropical Rainforest (Af) | 1573 | Summer, winter |
| 51 | (Elnabawi et al., 2016) | Cairo, Egypt | Tropical and Subtropical Desert (BWh) | 320 | June, July and December |
| 52 | (Giannakis et al., 2016) | Nicosia, Cyprus | Mid-Latitude Steppe and Desert (BSh) | 305 | June, July |
| 53 | (Hirashima et al., 2016) | Belo Horizonte, Brazil | Humid Subtropical (Cfa) | 1693 | March, July |
| 54 | (Huang et al., 2016) | Wuhan, China | Humid Subtropical (Cfa) | 1460 | May to November |
| 55 | (Jeong et al., 2016) | Seoul, Korea | Hot Summer Continental (Dwa) | 790 | Summer, autumn |
| 56 | (Kántor, 2016) | Szeged, Hungary | Warm Summer Continental (Dfb) | 5805 | Summer, autumn, winter |
| 57 | (Kariminia et al., 2016a) | Isfahan, Iran | Tropical and Subtropical Steppe (BSk) | 504 | July |
| 58 | (Kim and Macdonald, 2016) | San Francisco, CA, USA | Mediterranean (Csb) | 701 | From July to December |
| 59 | (Kovács et al., 2016) | Szeged, Hungary | Warm Summer Continental (Dfb) | 5128 | Summer, autumn, winter |
| 60 | (Li et al., 2016) | Guangzhou, China | Humid Subtropical (Cfa) | 1005 | From January to September |
| 61 | (Liu et al., 2016) | Changsha, China | Humid Subtropical (Cfa) | 7851 | Four seasons |
| 62 | (Lucchese et al., 2016) | Campo Grande, Brazil | Tropical Savanna (Aw) | 408 | July, November |
| 63 | (Maras et al., 2016) | Aachen, Germany | Marine West Coast (Cfb) | 138 | Summer, winter |
| 64 | (Middel et al., 2016) | Tempe, AZ, USA | Tropical and Subtropical Desert (Bwh) | 1284 | January, April, June and November |
| 65 | (Salata et al., 2016) | Rome, Italy | Mediterranean (Csa) | 941 | Four seasons |
| 66 | (Shooshtarian and Ridley, 2016b) | Melbourne, Australia | Marine West Coast (Cfb) | 1023 | From November to May |
| 67 | (Zhao et al., 2016) | Guangzhou, China | Humid Subtropical (Cfa) | 1582 | August, September and October |

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|---|---|---|---|---|---|
| 68 | (Amindeldar et al., 2017) | Teheran, Iran | Mediterranean (Csa) | 410 | winter |
| 69 | (Chan et al., 2017) | Hong Kong, China | Humid Subtropical (Cfa) | 1000 | Summer, winter |
| 70 | (Heidari and Azizi, 2017) | Kashan, Iran | Tropical and Subtropical Steppe (BSk) | 295 | July, August |
| 71 | (Hou et al., 2017) | Harbin, China | Hot Summer Continental (Dwa) | 602 | Four seasons |
| 72 | (Huang et al., 2017) | Hong Kong, China | Humid Subtropical (Cfa) | 1107 | Summer, autumn, winter |
| 73 | (Kruger and Drach, 2017) | Rio de Janeiro, Brazil | Tropical Savanna (Aw) | 985 | Summer |
| 74 | (Louafi et al., 2017) | Constantine, Algeria | Mediterranean (Csa) | 2220 | July |
| 75 | (Lucchese and Andreasi, 2017) | Campo Grande, Brazil | Tropical Savanna (Aw) | 524 | Winter, spring, summer |
| 76 | (Nasrollahi et al., 2017) | Isfahan, Iran | Tropical and Subtropical Steppe (BSk) | 281 | July |
| 77 | (Ndetto and Matzarakis, 2017) | Dar es Salaam, Tanzania | Tropical Savanna (Aw) | 606 | January, August and September |
| 78 | (Nouri and Costa, 2017) | Lisbon, Portugal | Mediterranean (Csa) | 110 | July |
| 79 | (Shih et al., 2017) | Anping District, Taiwan | Humid Subtropical (Cfa) | 164 | Summer, winter |
| 80 | (Shooshtarian and Rajagopalan, 2017) | Melbourne, Australia | Marine West Coast (Cfb) | 1059 | February, May and November |
| 81 | (Shooshtarian and Ridley, 2017) | Melbourne, Australia | Marine West Coast (Cfb) | 1023 | Spring, summer, autumn |
| 82 | (Tseliou et al., 2017) | Athens, Greece | Mediterranean (Csa) | 2313 | March to July, September to November |
| 83 | (Wang et al., 2017) | Groningen, Netherlands | Marine West Coast (Cfb) | 389 | Spring, summer |
| 84 | (Yang et al., 2017) | Umea, Sweden | Continental Subarctic (Dfc) | 525 | July, August |
| 85 | (Ali and Patnaik, 2018) | Bhopal, India | Mediterranean (Csa) | 640 | March, April |
| 86 | (Aljawabra and Nikolopoulou, 2018) | Marakech, Morocco | Mediterranean (Csa) | 303 | Summer, winter |
| | | Phoenix, AR, USA | Tropical and Subtropical Desert (BWh) | 126 | Summer, winter |
| 87 | (Cheung and Jim, 2018b) | Hong Kong, China | Humid Subtropical (Cfa) | 427 | From May to October |
| 88 | (Fang et al., 2018) | Guangzhou, China | Humid Subtropical (Cfa) | 2007 | Summer, autumn |
| 89 | (Golasi et al., 2018) | Rome, Italy | Mediterranean (Csa) | 869 | From June to April |
| 90 | (Hadianpour et al., 2018) | Tehran, Iran | Mediterranean (Csa) | 1008 | Four seasons |
| 91 | (Lam et al., 2018a) | Melbourne, Australia | Marine West Coast (Cfb) | 3320 | January, February |

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|---|---|---|---|---|---|
| 92 | (Lamarca et al., 2018) | Concepción, Chile | Mediterranean (Csb) | 301 | January |
| 93 | (Lindner-Cendrowska and Blazejczyk, 2018) | Warsaw, Poland | Marine West Coast (Cfb) | 662 | Four seasons |
| 94 | (Johansson et al., 2018) | Guayaquil, Ecuador | Tropical Savanna (Aw) | 544 | March, April and June |
| 95 | (Wang et al., 2018) | Guangzhou, China | Humid Subtropical (Cfa) | 1006 | January, September and December |
| 96 | (Xie et al., 2018) | Hong Kong, China | Humid Subtropical (Cfa) | 1107 | From March to December |
| 97 | (Yao et al., 2018) | Shanghai, China | Humid Subtropical (Cfa) | 1014 | January, February and December |
| 98 | (Canan et al., 2019) | Konya, Turkey | Mediterranean (Csa) | 296 | July, August |
| 99 | (Cohen et al., 2019) | Beer Sheva, Israel | Mid-Latitude Steppe and Desert (Bsh) | 996 | Summer, winter |
| 100 | (Fang et al., 2019) | Guangzhou, China | Humid Subtropical (Cfa) | 674 | From June to July |
| 101 | (Heng and Chow, 2019) | Singapore | Tropical Rainforest (Af) | 1573 | Summer, winter |
| 102 | (Huang et al., 2019) | Mianyang, China | Humid Subtropical (Cfa) | 523 | Summer, winter |
| 103 | (Lau et al., 2019a) | Hong Kong, China | Humid Subtropical (Cfa) | 1917 | From June to September |
| 104 | (Leng et al., 2020) | Harbin, China | Hot Summer Continental (Dwa） | 301 | April |
| 105 | (Manavvi and Rajasekar, 2020) | New Delhi, India | Mid-Latitude Steppe and Desert (Bsh) | 353 | June |
| 106 | (Sharmin et al., 2019) | Dhaka, Bangladesh | Tropical Savanna (Aw) | 1286 | May, June, September |
| 107 | (Xie et al., 2019) | Hong Kong, China | Humid Subtropical (Cfa) | 1600 | Four seasons |
| 108 | (de Area Leao Borges et al., 2020) | Cuiabá, Brazil | Tropical Savanna (Aw) | 685 | Four seasons |
| 109 | (Li et al., 2020) | Hong Kong, China | Humid Subtropical (Cfa) | 1638 | Four seasons |
| 110 | (Mi et al., 2020) | Xi'an, China | Humid Subtropical (Cfa) | 1146 | Winter, spring, summer |
| 111 | (Xi et al., 2020) | Harbin, China | Hot Summer Continental (Dwa） | 1740 | Winter, summer |

Table 2. Summary of longitudinal studies from the reviewed literature.

| No | Author, Year | City | Climatic Zone (Koppen Classification) | No. of Subjects | No. of Votes | Periods Investigated |
|---|---|---|---|---|---|---|
| 1 | (Givoni et al., 2003) | Tokyo, Japan | Humid Subtropical (Cfa) | 6 | N/a | N/a |
| | | Tel Aviv, Israel | Mediterranean (Csa) | 10 | N/a | May, June |
| | | Mash'abei-Sadeh, Israel | Mid-Latitude Steppe and Desert (Bsh) | 14 | N/a | July, August |
| 2 | (Shimazaki et al., 2011) | Osaka, Japan | Humid Subtropical (Cfa) | 57 | N/a | Summer |
| 3 | (Cheng et al., 2012) | Hong Kong, China | Humid Subtropical (Cfa) | 8 | 286 | Summer, winter |
| 4 | (Schnell et al., 2012) | Tel Aviv, Israel | Mediterranean (Csa) | 36 | 1457 | Four seasons |
| 5 | (Xi et al., 2012) | Guangzhou, China | Humid Subtropical (Cfa) | 21 | 114 | July |
| 6 | (Yin et al., 2012) | Nanjing, China | Humid Subtropical (Cfa) | 205 | N/a | August |
| 7 | (Zhou et al., 2013) | Wuhan, China | Humid Subtropical (Cfa) | N/a | 386 | June, July |
| 8 | (Pantavou et al., 2014) | Athens, Greece | Mediterranean (Csa) | 5 | 200 | July |
| 9 | (Sangkertadi and Syafriny, 2014) | Manado, Indonesia | Tropical Rainforest (Af) | 300 | N/a | From May to September |
| 10 | (Watanabe et al., 2014) | Nagoya, Japan | Humid Subtropical (Cfa) | 42 | N/a | August, September |
| 11 | (Yoshida et al., 2015) | Osaka, Japan | Humid Subtropical (Cfa) | 6 | N/a | Summer |
| 12 | (Jeong et al., 2016) | Seoul, Korea | Hot Summer Continental (Dwa) | 12 | N/a | August, October |
| 13 | (Kurazumi et al., 2016) | Bangkok, Thailand | Tropical Savanna (Aw) | 17 | N/a | September |
| 14 | (Schnell et al., 2016) | Tel Aviv, Israel | Mediterranean (Csa) | 26 | N/a | Spring |
| 15 | (Song and Jeong, 2016) | Bucheon, Korea | Hot Summer Continental (Dwa) | 11 | 29 | August |
| 16 | (Lai et al., 2017a) | West Lafayette, IN, USA | Hot Summer Continental (Dfa) | 10 | 40 | March to September |
| | | Tianjin, China | Hot Summer Continental (Dwa) | 16 | 54 | From May to December |
| 17 | (Vanos et al., 2017) | Lubbock, TX, USA | Tropical and Subtropical Steppe (Bsk) | 14 | 261 | Spring |
| 18 | (Chen et al., 2018) | Harbin, China | Hot Summer Continental (Dwa) | 31 | 4131 | Four seasons |
| 19 | (Xu et al., 2018) | Xi'an, China | Humid Subtropical (Cfa) | 37 | 1008 | January |
| 20 | (Cohen et al., 2019) | Beer Sheva, Israel | Mid-Latitude Steppe and Desert (Bsh) | 112 | 1792 | Summer, winter |
| 21 | (Lau et al., 2019b) | Hong Kong, China | Humid Subtropical (Cfa) | 14 | N/a | August, September |

| | | | | | | |
|---|---|---|---|---|---|---|
| 22 | (Xu et al., 2019) | Xi’an, China | Humid Subtropical (Cfa) | 70 | 2510 | Summer, winter |
| 23 | (He et al., 2020) | Xi’an, China | Humid Subtropical (Cfa) | 58 | 1691 | Winter, spring, summer |

## 2.4 Models for outdoor thermal comfort

Various models can be employed to evaluate the thermal comfort level in an environment, and they can provide researchers with a wealth of information and a deep understanding of this topic. Selecting a suitable model is crucial in outdoor thermal comfort research. Potchter et al. (2018) summarized the models used in 117 studies from 2001 to 2017 and found that the physiologically equivalent temperature (PET) (Höppe, 1999), predicted mean vote (PMV) (Fanger, 1970), universal thermal climate index (UTCI) (Jendritzky et al., 2012), and standard effective temperature (SET*) (Gagge et al., 1986) are four most commonly used models, and they were employed in 53.3% of the studies. PET alone accounts for 30.2% of usage. Coccolo et al. (2016) reviewed thermal comfort models commonly used for outdoor environments and presented the physical equations of these models. Outdoor thermal comfort models can be categorized into two types according to the ways in which they were defined and developed: mechanism models and empirical models.

Mechanism models are based on the human thermal balance and can be further divided into equivalent temperature and thermal load models. Equivalent temperature is the most widely used type of model in outdoor thermal comfort research. Many popular models, including PET, UTCI, SET*, and OUT_SET* (outdoor version of SET*) (Pickup and de Dear, 2000), are equivalent temperatures. Equivalent temperature is defined as the air temperature of a typical indoor room that generates the same physiological responses (e.g., skin and core temperatures, skin wetness) as would the actual complex conditions. The main difference among various equivalent temperatures is the human heat transfer model used to calculate the physiological responses. For example, PET is based on the two-node Munich Energy-balance Model for Individuals (MEMI, (Höppe, 1993)). SET* and OUT_SET* use the two-node model developed by Gagge et al(1971). UTCI is based on Fiala's (Fiala et al., 2012) multi-node model. Besides using an advanced multi-node human heat transfer model, UTCI has made other improvements, such as employing a self-adaptive clothing model (Brode et al., 2012b) and using integrated physiological response (Brode et al., 2012a) as a criterion when comparing typical indoor and actual environments. The equivalent temperature is easy to interpret, and at the same time it has significant theoretical meaning. However, equivalent temperature is not directly related to thermal sensation. Therefore, researchers need to further associate the equivalent temperature with the thermal sensation data obtained from a field survey or subject test.

Similar to equivalent temperature, thermal load models, such as PMV (Fanger, 1970), COMFA (also called COMfort formulA) (Brown and Gillespie, 1986; Kenny et al., 2009a; Kenny et al., 2009b), and the index of thermal stress (ITS, (Givoni, 1963; Givoni, 1976)), are also based on the human energy balance. In thermal load models, the final output of the human energy balance equation is thermal load, and different levels of thermal load are associated with various categories of thermal sensation. Thermal load models differ in the way in which they calculate heat exchange terms such as convection, radiation, and evaporation. In the PMV model, the correlation between thermal load and thermal sensation was based on data from an indoor human subject test (Fanger, 1970). Several studies (Lai et al., 2014a; Nikolopoulou et al., 2001; Thorsson et al., 2007) have demonstrated that PMV overestimates the thermal sensation when directly applied to outdoor spaces. As for the COMFA and ITS models, little effort has been made to demonstrate their validity.

The thermal perception of subjects in outdoor spaces cannot be fully explained by the thermal balance of the human body. It is also affected by psychological, behavioral and other factors (Lin, 2009). Because of the complexity of outdoor thermal comfort, some studies have used a "black box" method and directly regressed the thermal sensation by environmental and personal variables. The empirical regressed models were assigned various names, such as the actual sensation vote (ASV) model by Nikolopoulou (2004), the thermal sensation (TS) model by Givoni et al. (2003) and Cheng et al. (2012), the thermal comfort index for cities of arid zones (IZA) model by Ruiz and Correa (2015), the Mediterranean outdoor comfort index (MOCI) model by Salata et al. (2016), and the Turkish outdoor comfort index (TOCI) by Canan et al. (2019). Golasi et al. (2018) further developed a global outdoor comfort index (GOCI) by summarizing the regressed models from worldwide studies. Usually, regressed models are multivariate linear regression models. Lai et al. (2018a) and Lai and Chen (2019) proposed the use of an ordered probability model and multinomial logit model, and demonstrated that the prediction accuracies of these two kinds of models were higher than that of a multivariate linear model. The regressed models are simple and easy to use. However, they cannot be applied outside the climate regions in which the data was obtained. In addition to linear, probit, and logit regression models, an increasing number of machining learning models were proposed (Jovic et al., 2016; Kariminia et al., 2015; Kariminia et al., 2016a; Kariminia et al., 2016b; Liu et al., 2020), and authors usually claim the machining learning approaches provided good prediction accuracy.

The equivalent temperatures, thermal load models, and regression models apply only for steady state, and thus cannot take into account the dynamic influences that widely exist in outdoor thermal comfort. Lai et al. (2017b) developed a dynamic thermal sensation model for outdoor environments by using thermal load, mean skin temperature, and the change rate of skin temperature as input variables. Lai's model can address transient situations because it includes the dynamic response of skin temperature to the changing outdoor thermal environment. However, it is not easy to measure skin temperature in practice. Human skin temperature can also be calculated with the use of a human heat transfer model, and can then be used as an input to predict dynamic thermal sensation outdoors. Lai and Chen (2016) and Lai et al. (2017a) developed a multi-segment human heat transfer model applicable in outdoor thermal environments. Melnikov et al. (2018) developed a dynamic human thermal regulation model by extending Gagge's two-node model (Gagge et al., 1986).

In the above discussion, it can be seen that there is no versatile model for studying outdoor thermal comfort. Greater effort should be devoted to the development of an accurate, simple and universally applicable outdoor thermal comfort model.

## 3 Direct and indirect influences on outdoor thermal comfort

Many factors can influence outdoor thermal comfort, and they can be classified as either direct or indirect, as shown in Figure 2. Factors with a direct influence on outdoor thermal comfort include physical, physiological and psychological aspects. Other factors have an indirect effect on outdoor thermal comfort through the physiological and psychological factors. In this paper, seven indirect factors, namely, behavioral, personal, social and cultural factors, thermal history, site, and alliesthesia, are reviewed. Direct and indirect factors can be further decomposed into various aspects. For example, air temperature, thermal radiation, wind, and humidity are the four parameters that constitute the physical factor of outdoor thermal comfort. The following two sections provide a detailed review of the direct and indirect influencing factors.

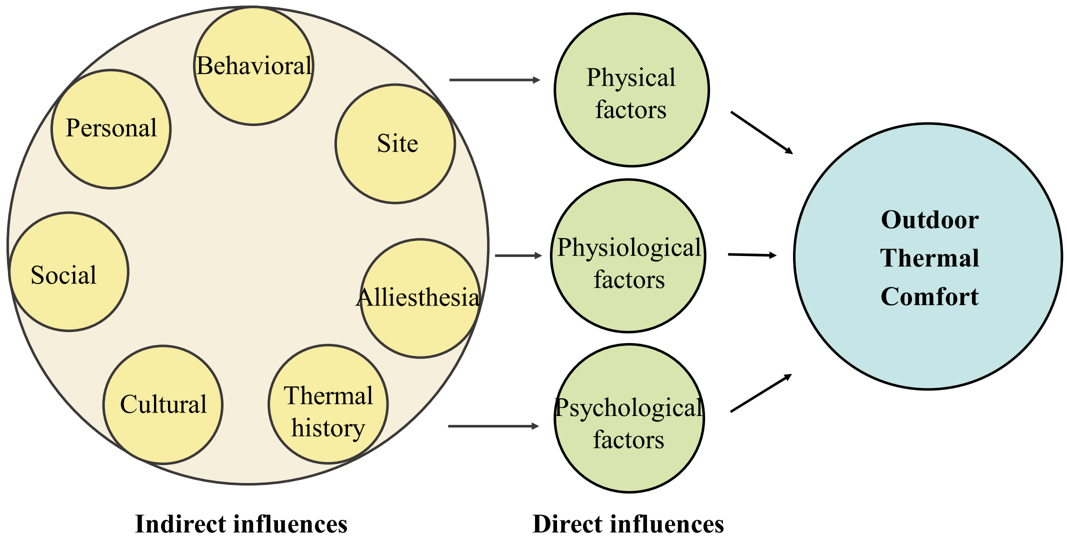


Fig. 2. Direct and indirect influences on outdoor thermal comfort

### 3.1 Direct influences

#### 3.1.1 Physical factors

This section reviews the influence of physical factors such as air temperature, thermal radiation, wind, and relative humidity on outdoor thermal comfort. Table 3 provides a summary of obtained information from the review of physical factor.

Table 3. Summary of the influence of physical factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Physical | Air temperature | Air temperature had the greatest impact on or highest association with outdoor thermal comfort among the four climatic parameters. | (Chen et al., 2018; Lai et al., 2014a; Liu et al., 2016; Tsitoura et al., 2014) |
| | Radiation and wind | Radiation had a greater influence or higher association than wind. | (Hwang and Lin, 2007; Lin et al., 2011; Liu et al., 2016; Shih et al., 2017; Tseliou et al., 2015; Xu et al., 2018; Yang et al., 2013b; Yin et al., 2012) |
| | | Wind had a greater influence than radiation. | (Krüger and Rossi, 2011; Metje et al., 2008; Walton et al., 2007) |
| | | Wind and radiation changes dynamically in outdoor space. | (Lai et al., 2017a; Lau et al., 2019b; Nakayoshi et al., 2015; Vasilikou and Nikolopoulou, 2019) |

| | | | |
|---|---|---|---|
| | | The impact of wind and radiation on human have directions. | (Hadianpour et al., 2019; Kubaha et al., 2004) |
| | Humidity | Humidity had a negligible influence. | (Chen et al., 2018; Cheng et al., 2012; Kantor et al., 2012; Lai et al., 2014a) |
| | | Humidity was perceived as the most unpleasant parameter under high air temperature. | (Chow et al., 2016) |

#### 3.1.1.1 Air temperature, radiation, wind, and humidity

The physical environment largely determines the convective, radiative, evaporative, and respiratory heat exchange between the human body and its surroundings. Air temperature directly determines the convective heat exchange between the human body and the surrounding outdoor space, and indirectly affects the radiative, evaporative, and respiratory heat exchange. A number of studies have identified air temperature as the most vital parameter in outdoor thermal comfort, among the four microclimatic variables. For example, based on a multifactor analysis of variance of 7851 samples collected in Changsha, China, Liu et al. (2016) showed that the relative contribution of air temperature to outdoor human thermal sensation was close to 65% among four climatic parameters on a yearly basis. In a study by Chen et al. (2018) in Harbin, China, interviewed subjects selected air temperature as the microclimate parameter with the greatest effect on outdoor thermal comfort. Moreover, researchers (Lai et al., 2014a; Tsitoura et al., 2014) found that air temperature exhibited the highest level of association with outdoor thermal sensation among the four microclimatic parameters.

Although air temperature plays a vital role in outdoor thermal comfort, it is hard to modify the temperature in outdoor spaces. Lai et al. (2019b) summarized the effects of four different passive strategies—changing geometry, adding vegetation, using reflective pavement, and incorporating water bodies—on air temperature. The mean reductions in the hottest time period in summer for the four strategies were only around 2 K. Meanwhile, Niu et al. (2015) pointed out that wind speed and radiant temperature differences have a significant influence on thermal comfort. When creating thermally comfortable urban open spaces, the general practice is to control the levels of thermal radiation or wind. Thus, in order to reasonably choose between the two strategies, one must compare the relative importance of thermal radiation and wind. Current studies have offered various answers to this question.

Most studies have found that the influence of radiation is greater than that of wind. For example, by using logistic regression, Tseliou et al. (2015) observed that solar radiation caused a large change in thermal sensation, while wind speed caused only small-scale differences. Liu et al. (2016) determined that the relative contributions of thermal radiation and wind speed were 22% and 8%, respectively, over a one-year period. Hwang and Lin (2007) analyzed the subjective votes for thermal, sun, and wind sensations, and concluded that solar radiation had greater capacity to change a subject's thermal sensation than did air movement. Shih et al. (2017) demonstrated that in summer months in Taiwan, dissatisfaction with the thermal environment was associated more closely with solar radiation than with wind. In addition, Yin et al. (2012), Lin et al. (2011), Yang et al. (2013b), and Xu et al. (2018) demonstrated that radiation had a greater impact than wind on outdoor thermal comfort, or that there was a greater association between outdoor thermal sensation and solar radiation than between outdoor thermal sensation and wind.

In contrast, studies by Walton et al. (2007) in Wellington, New Zealand, Krüger and Rossi (2011) in Curitiba, Brazil, and Metje et al. (2008) in Birmingham, UK, have found that wind had a greater influence than radiation. The temperate climate (Cfb, or maritime temperate climate, according to the Koppen climate classification) of the above studied cities may be the reason for the conflicting results, since wind speed was perceived as stronger under lower air temperatures (Lin et al., 2013a; Trindade da Silva and Engel de Alvarez, 2015; Wang et al., 2018). This perception may have been due to the greater convective heat loss under lower air temperature. Studies have found that preferred wind speed (Yang et al., 2013b) and acceptable wind speed (Kim et al., 2018; Kim and Macdonald, 2016) decreased with a reduction in air temperature. Similarly, in a study by Oliveira and Andrade (2007) in Lisbon in winter and spring (air temperature < 24 ºC), interviewees perceived wind speed as the most unpleasant microclimate variable.

Humidity has usually been considered the least important climatic variable affecting outdoor thermal comfort, as can be seen in the results of Chen et al. (2018), Kantor et al. (2012), and Lai et al. (2014a). Cheng et al. (2012) regressed the outdoor thermal sensation by means of two linear equations, with and without relative humidity, in Hong Kong and found that the difference between the two regressed lines was negligible. However, as the air temperature rises, the air can hold more water vapor, and the influence of humidity on outdoor thermal comfort might increase. For example, in high-temperature, high-humidity Singapore, subjects voted humidity as the most uncomfortable microclimatic variable (Chow et al., 2016).

#### 3.1.1.2 Dynamic features of radiation and wind speed

An important feature of the outdoor physical environment is its dynamic nature. In other words, outdoor microclimatic parameters are constantly fluctuating. Lai et al. (2017a) defined a fluctuation index (FI) for outdoor thermal environment parameters by dividing the standard deviation of a parameter over its mean value. The authors (Lai et al., 2017a) found that the FI for air temperature and relative humidity was less than 0.05, while the FI for global solar radiation was close to 0.2, and wind speed had the largest fluctuation with FI close to 0.5. Possibly because of the fast-changing nature of outdoor wind, the correlation between wind and thermal sensation was usually observed to be weaker than the correlations for air temperature and radiation (Lin et al., 2011; Liu et al., 2016; Xu et al., 2018; Yang et al., 2013a; Yin et al., 2012). On a longer time scale, the thermal environment and thermal comfort condition in a place can change within one day, and dynamic thermal conditions may be preferred by visitors. Perkins and Debbage (2016) found that in zoos in Atlanta and Phoenix, the peak attendance was accompanied by dynamic changes in thermal environment, while a stagnant thermal environment corresponded to lower attendance.

In addition to the fluctuating nature of wind speed and thermal radiation, the dynamic nature of the outdoor thermal environment also arises from changes encountered by the occupant as he/she moves from place to place. Nakayoshi et al. (2015) conducted a test in which the subjects walked through different urban spaces in Tajimi, Japan. The subjects wore a set of sensors to measure various parameters of the thermal environment along the way, and large variations in radiation flux and wind speed were observed. Lau et al. (2019b) and Vasilikou and Nikolopoulou (2019) conducted similar research in Hong Kong, Rome, and London. Overall, the impact of the changing outdoor thermal environment on thermal comfort has not been sufficiently studied.

#### 3.1.1.3 Directionality of radiation and wind speed

Besides the dynamic nature of the outdoor thermal environment, the directionality of wind and solar radiation may play a significant role in outdoor thermal comfort. The research of Hadianpour et al. (2019) in Tehran, Iran, shows that under the same PET value, the thermal sensation of windward-facing subjects was 0.5 unit lower than that of leeward-facing subjects. Non-uniform solar radiation may also cause a large deviation in thermal sensation, because different segments of the human body absorb significantly different amounts of solar radiation (Kubaha et al., 2004). However, no research has been conducted on the influence of non-uniform solar radiation on outdoor thermal comfort.

### 3.1.2 Physiological factors

Physiological indicators have direct connections with outdoor thermal comfort and thus is reviewed in this section. Table 4 is a summary of the conclusions drawn from the review of physiological factors.

Table 4. Summary of the influence of physiological factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Physiological | Skin temperature | Skin temperature was a good indicator of outdoor thermal comfort. | (Jeong et al., 2016; Kurazumi et al., 2014; Lai et al., 2017a; Song and Jeong, 2016) |
| | | Skin temperature of occupants fluctuated in outdoor spaces. | (Lai et al., 2017a; Pantavou et al., 2014; Song and Jeong, 2016) |
| | Rectal temperature | Rectal temperature responded slowly to outdoor thermal environment. | (Song and Jeong, 2016) |
| | Sweat rate | Sweat rate had gender dependence. | (Nakayoshi et al., 2015) |

The connection between physiological factors and outdoor thermal comfort starts with the heat exchange between the human body and the surrounding environment, which leads to changes in the human body temperature. Thermoreceptors in human skin and organs detect the temperature and send signals to the brain, which integrates and interprets the signals as thermal sensation (Zhang et al., 2010). If the human body temperature deviates from the "set point," the thermoregulation system of the body then works to maintain the core temperature by sweating, shivering, and changing the peripheral blood flow. Physiological signals such as heart rate, pulse, and sweat rate may change along with the thermoregulation process, and may thus be useful indicators of thermal comfort.

In outdoor spaces, researchers have started to make connections between physiological signals and thermal comfort. The physiological factors that have been studied include skin temperature (Lai et al., 2017a), rectal temperature (Song and Jeong, 2016), sweat rate (Nakayoshi et al., 2015), heart rate (Vanos et al., 2017), and pulse (Nakayoshi et al., 2015).

**3.1.2.1 Skin temperature**

Of the many physiological parameters of outdoor thermal comfort, skin temperature is the most studied, since it is a direct indicator of thermal comfort and is relatively easy to measure. The comfortable mean skin temperature for indoor spaces has been reported at around 33.5 $^{o}$C (ASHRAE, 2017b; Fanger, 1970; Parsons, 2003), while in the outdoor environment, Lai et al. (2017b) found that the mean skin temperature corresponding to neutral thermal sensation was 32.7 $^{o}$C. Song and Jeong (2016) found that in summer, the mean skin temperature of subjects in places with a high sky-view factor (SVF) was as high as 36.0 $^{o}$C, while the mean skin temperature of subjects in low-SVF spaces was 33.9 $^{o}$C. Jeong et al. (2016) conducted similar research and found that in an urban forest, the mean skin temperature of tested subjects was lower than that of subjects in a central building district. Lai et al. (2017a) and Kurazumi et al. (2014) investigated the association between mean skin temperature and outdoor thermal sensation and found that the correlation coefficients were 0.85 and 0.66, respectively. Lai et al. (2017b) further studied associations between outdoor thermal sensation and the skin temperature of different local segments. The strengths of association of exposed segments such as the head, face, and hands, were much higher than those of central segments such as the abdomen and thorax. Metje et al. (2008) took advantage of the high correlation between hand skin temperature and outdoor thermal comfort and developed a regression model to predict comfort value from hand skin temperature. These examples demonstrate that skin temperature is a reasonable indicator of thermal comfort in outdoor spaces.

Skin temperature is also a useful parameter for studying the dynamic characteristics of outdoor thermal comfort. Because of the difference between the indoor and outdoor thermal environment, when a subject enters an outdoor space from indoors, the subject's skin temperature changes. Hoppe (2002) used the two-node Instationary Munich Energy-balance Model (IMEM) to simulate changes in the skin and core temperatures of a typical subject when he or she moves from a neutral indoor space to an outdoor space under winter and summer scenarios. Under the winter scenario, the skin temperature did not reach equilibrium even after three hours of exposure, while under the summer scenario, the skin temperature stabilized within half an hour. Lai et al. (2017a), meanwhile, reported a trend in measured skin temperature in an actual situation. The difference was that in the actual situation, dynamic changes in the wind and solar radiation led to fluctuations in skin temperature. Tests by Pantavou et al. (2014), Lai et al. (2017a) and Song and Jeong (2016) have all demonstrated fluctuations in skin temperature. Lai et al. (2017a) also revealed higher fluctuations in skin temperature in summer than in winter, because more of the subjects' body segments were directly exposed to the outdoor environment during the summer.

**3.1.2.2 Other physiological factors**

Physiological parameters other than skin temperature have not been measured and analyzed very often in outdoor thermal comfort studies. Song and Jeong (2016) compared the rectal temperature of subjects in spaces affected by buildings and tree coverage. Because the measurement point of rectal temperature is at the core of the human body, the impact of thermal environment on its value is delayed. After 44 minutes of exposure, the rectal temperature of subjects in a building-surrounded area became statistically significantly higher than that of subjects in a tree-covered area. In addition to core temperature, sweat rate is a potential indicator of human thermal comfort (ASHRAE, 2017b). A study by Nakayoshi et al. (2015) revealed the dependence of sweat rate in an outdoor thermal environment on gender and body weight. Nakayoshi et al. (2015) also measured pulse rate in their subject test, but the results were not further analyzed. Meanwhile, Vanos et al. (2017) recorded heart rate, but the authors did not present the results.

### 3.1.3 Psychological factor

Since thermal comfort is defined as a "condition of mind," the subjective psychological condition of occupants is a fundamental factor in thermal comfort. Table 5 provides an overview of the review of psychological factor.

Table 5. Summary of the influence of psychological factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Psychological | Experience | The comfortable temperature of occupants was close to what they have experienced. | (Cheung and Jim, 2018a; Potchter et al., 2018) |
| | | Thermal perception of one season was affected by the proceeding season. | (Nikolopoulou and Lykoudis, 2006) |
| | Expectation | Expectation affected subjects' thermal sensation. | (Chen et al., 2018; Lam et al., 2018b; Li et al., 2018; Rutty and Scott, 2015; Tseliou et al., 2015) |
| | Perceived control/ autonomy | If people had a high degree of control, they had high tolerance toward the environment. | (Elnabawi et al., 2016; Johansson et al., 2018; Lam et al., 2018b; Lin et al., 2013b; Lindner-Cendrowska and Blazejczyk, 2018) |
| | | "Purpose of visit" did not have a statistically significant influence on outdoor thermal sensation. | (Shooshtarian and Ridley, 2017; Yang et al., 2013a) |
| | Naturalness, environmental stimulation, and time of exposure | Proposed by Nikolopoulou and Steemers (2003), but have not been addressed frequently in other studies. | (Nikolopoulou and Steemers, 2003) |
| | Checking weather forecast, emotion, security | Had statistically insignificant influences on outdoor thermal sensation. | (Galindo and Hermida, 2018; Shooshtarian and Ridley, 2017) |

Experience, expectation, and perceived control (Nikolopoulou and Steemers, 2003) are the most commonly discussed psychological parameters in outdoor thermal comfort studies, and these three factors are reviewed below.

#### 3.1.3.1 Experience

People's past experiences affect their perception of the outdoor thermal environment. The temperature at which people feel comfortable will be close to what they have previously experienced. This hypothesis has been verified by numerous studies. For example, the synthesized analyses of global outdoor thermal comfort pattern by Potchter et al. (2018) and Cheung and Jim (2018a) indicate that the neutral PET in different cities is strongly associated with the local background air temperature. The examination of an outdoor thermal comfort database of 14 cities in Europe by Nikolopoulou and Lykoudis (2006) concluded that the neutral air temperature in autumn was higher than that in spring. This finding shows that occupants' perception of a given season was affected by their experience of the preceding season. For example, an occupant's perception of autumn is affected by his/her experience of summer, and the perception of spring by his/her experience of winter.

#### 3.1.3.2 Expectation

People's past experience, rather than the current thermal environment, determines their expectation of what it should be. Thus, experience directly affects expectation (Nikolopoulou and Steemers, 2003). Such expectation influences the subjective thermal sensation. In Greece, for example, where hot summers are expected, people have learned to cope with and are not seriously affected by the hot weather, and thus the percentage of hot discomfort vote was found to be low in summer (Tseliou et al., 2015). In cold winters in Harbin, China, when people are routinely exposed to the cold outdoor thermal environment, their thermal sensation in late winter was one unit higher than that in early winter, even under the same PET (Chen et al., 2018). Lam et al. (2018b) suggested that the thermal expectation of visitors affected their perception during a heat wave; under the same PET value, their thermal sensation during the heat wave was higher than that during a non-heat wave period.

The expectation of subjects about particular environmental parameters may also affect their overall thermal sensation. A study by Li et al. (2018) in Hong Kong found that subjects who expected higher wind and weaker solar radiation had significantly higher thermal sensation than those who desired lower wind and stronger solar radiation. Tourists may have a particular expectation about the thermal environment of their destinations. As a result, the comfort perception of tourists may be fundamentally different than that of local citizens. For example, the preferred air temperature identified for Caribbean beach tourists (Rutty and Scott, 2015) was 18 $^{o}$C higher than that in urban parks of Lisbon (Andrade et al., 2011). Meanwhile, the investigation by Rutty and Scott (2015) found that when UTCI was as high as 39.2 $^{o}$C, 62% of interviewed beach tourists still preferred that the thermal environment remain unchanged, and 10% desired an even warmer thermal environment.

#### 3.1.3.3 Perceived control/autonomy

Perceived control is the phenomenon in which, if people have a high degree of control over a source of discomfort, then they have high tolerance toward their environment (Nikolopoulou and Steemers, 2003). In some studies, perceived control is referred to as "autonomy." Different types of activity in outdoor spaces correspond to different degrees of autonomy, and may lead to different levels of thermal comfort. People engaged in activities such as recreation, relaxation, exercise, etc., have a high degree of autonomy because they can move to another location or simply leave the space at any time. In contrast, people who enter a space in order to attend to children, work, or simply pass through, have a low degree of autonomy. It has been found that high-autonomy groups have a higher thermal comfort level or a more neutral thermal sensation than do low-autonomy groups (Elnabawi et al., 2016; Johansson et al., 2018; Lam et al., 2018b; Lin et al., 2013b; Lindner-Cendrowska and Blazejczyk, 2018). However, according to tests conducted by Shooshtarian and Ridley (2017) and Yang et al. (2013a), "purpose of visit" did not have a statistically significant influence on outdoor thermal sensation.

#### 3.1.3.4 Other factors

In addition to experience, expectation, and perceived control, Nikolopoulou and Steemers (2003) included naturalness, environmental stimulation, and time of exposure in their framework of psychological adaptation. However, these factors have not been addressed frequently in studies. Shooshtarian and Ridley (2017) examined the impact of the weather forecast, and Galindo and Hermida (2018) evaluated the influence of emotion (pleasant/unpleasant) and security (safe/unsafe). According to the results, all of the above factors had a statistically insignificant influence on outdoor thermal sensation.

## 3.2. Indirect influences

This section provides reviews seven indirect influence factors, namely, behavioral, personal, social and cultural factors, thermal history, site, and alliesthesia.

### 3.2.1 Behavioral factors

Occupants often adapt to the outdoor thermal environment by changing their surroundings (such as seeking shade) or adjusting their own thermal state (such as removing a layer of clothing). In addition to particular adaptive behaviors, attendance in spaces is a frequently studied phenomenon. This section reviews the behavioral factors and the main findings are summarized in Table 6.

Table 6. Summary of the influence of behavioral factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Behavioral | Attendance | Attendance increased with thermal indices in cool season, while in the hot season, attendance decreased with thermal indices. | (Chen et al., 2015; Lai et al., 2019a; Lai et al., 2014b; Li et al., 2016; Lin et al., 2013a; Lin et al., 2012; Lin et al., 2013b; Zeng and Dong, 2015) |
| | | Number of people continued to increase as weather became warmer in temperate climate. | (Eliasson et al., 2007; Nikolopoulou et al., 2001; Thorsson et al., 2004) |
| | | Intense activity was sensitive to hot, and less sensitive to cold. | (Huang et al., 2016; Lai et al., 2019a) |
| | | Attending children is sensitive to both hot and cold. | (Lai et al., 2019a; Lin et al., 2013b) |
| | | Optional activity sensitive to thermal | (Sharifi et al., 2015) |

| | | | |
|---|---|---|---|
| | | environment, necessary activity resilient to heat stress, social activity more affected by time and organizational adjustment. | |
| | | Attendance of a space was related to life pattern. | (Chow et al., 2017; Lai et al., 2019a; Li et al., 2016; Zacharias et al., 2001) |
| | Seeking shade | Seeking shade was the most selected adaptive behavior in outdoor spaces. | (Elnabawi et al., 2016; Lin, 2009; Lin et al., 2013b; Wang et al., 2017; Yang et al., 2013a) |
| | | Quantitative description of occupants interactions with shading as the thermal environment changes. | (Lai et al., 2019a; Li et al., 2016; Martinelli et al., 2015; Watanabe and Ishii, 2016; Zacharias et al., 2001) |
| | Changing clothes | Wide regional difference in clothing. | (Aljawabra and Nikolopoulou, 2018; Chen et al., 2018; Elnabawi et al., 2016; Fang et al., 2018; Lai et al., 2014a; Lam et al., 2018b; Li et al., 2016; Lin et al., 2011; Lin et al., 2013b; Lindner-Cendrowska, 2013; Metje et al., 2008; Pantavou et al., 2013; Salata et al., 2018; Thorsson et al., 2004; Yahia and Johansson, 2013) |

#### 3.2.1.1 Attendance

Attendance is an external indicator of people's satisfaction with the outdoor thermal environment. Microclimatic parameters such as air temperature, thermal radiation, wind speed, and humidity can influence the number of people in an urban open space. Among these four microclimatic parameters, air temperature and solar radiation have exhibited a stronger association with attendance than have wind speed and humidity (Nikolopoulou and Lykoudis, 2007; Watanabe and Ishii, 2016). Chueng and Jim (2018b) found that integrated thermal indices such as PET and UTCI were more closely associated with attendance than air temperature alone.

Usually, the largest number of people are present in an outdoor under optimum thermal comfort. According to studies (Lai et al., 2019a; Lai et al., 2014b) in a housing community in Wuhan, China, and in a park in Tianjin, China, attendance reached a maximum when the thermal sensation of occupants was neutral. Moreover, an investigation by Lin et al. (2012) in Taiwan found that largest number of people were present in the park during periods of 26–30 $^{o}$C PET, which corresponds to the comfortable range in Taiwan (Lin and Matzarakis, 2008). When the outdoor thermal environment deviated from the comfortable range, people "voted with their feet" by moving to shady/sunny locations, or simply left the space. Typically, in the cool season, the number of people in outdoor spaces has been found to be positively correlated with thermal indices, while in the hot season, the correlation has been negative. This phenomenon was demonstrated repeatedly in studies in Guanghzou, China (Li et al., 2016), Taiwan (Lin et al., 2013a; Lin et al., 2012; Lin et al., 2013b), Chengdu, China (Zeng and Dong, 2015), and Shanghai, China (Chen et al., 2015). However, in temperate regions, such as in Cambridge, UK (Nikolopoulou et al., 2001), and Gothenburg, Sweden (Eliasson et al., 2007; Thorsson et al., 2004), as the weather became warmer, the number of people continued to increase.

Cool and warm thermal environments may have different effects on attendance in outdoor spaces. According to a study in Taiwan (Lin et al., 2013a), a warmer environment led to a faster decrease in attendance than did a cooler environment. However, a study in Wuhan (Lai et al., 2014b) reached the opposite conclusion. Meanwhile, analyses by Huang et al. (2016) and Lai et al. (2019a) indicated that different degrees of sensitivity to warm and cool environments were associated with different types of activity. The additional metabolic heat generated by intense activity, such as exercise, made occupants less sensitive to cold than to heat. In contrast, occupants who were engaged in moderate activities experienced a faster decrease in sensitivity when the thermal environment became cold than when it became hot. Certain types of activity, such as attending to children, were sensitive to both cold and heat (Lai et al., 2019a). This may have been due to the high expectation of the children's parents or grandparents in regard to the thermal environment; i.e., concern that the children might suffer from adverse environmental conditions. Lin et al. (2013b) made a similar observation in Taiwan, where they found that the number of people in a children's playground was more sensitive to the microclimate than in other places.

Gehl (2011) classified outdoor activities into necessary, optional, and social activities. According to observational data collected in Adelaide, Australia, by Sharifi et al. (2015), optional activity was greatly affected by the outdoor thermal environment, while necessary activity was more resilient to heat stress. For social activity, although outdoor thermal comfort was one of its influencing factors, it was found to be more sensitive to time and organizational adjustment than to heat stress. Similarly, some researchers have shown that outdoor activities are significantly impacted by the time of day. This may be related to people's tendency to conduct certain activities at certain times. Similar temporal usage patterns have been revealed in many studies. For example, in a housing community in Guangzhou, China (Li et al., 2016), a park in Taiwan (Chow et al., 2017), and a park in Tianjin, China (Lai et al., 2019a), the attendance exhibited two peaks, in the morning and afternoon, and the number of people was lower at noon. The occupants of these sites were mainly residents from the nearby housing communities, and they may have been in the habit of going home for lunch and taking a nap afterward. However, in a study in downtown Montreal, Canada, by Zacharias et al. (2001), the maximum number of people in an urban open space appeared at noon on work days. The reason may have been that the users in Zacharias's study (2001) were primarily workers from adjacent buildings, and on work days, they had free time only during the noon break.

#### 3.2.1.2 Seeking shade

To adapt to the outdoor thermal environment, people adopt behaviors that change the surrounding microclimate or their own thermal state. A number of researchers (Elnabawi et al., 2016; Lin, 2009; Lin et al., 2013b; Wang et al., 2017; Yang et al., 2013a) have directly asked respondents to select the actions they would take to adapt to the outdoor environment, including seeking shade, using shading devices such as a hat or umbrella, consuming drinks, changing clothing, or leaving the outdoor space. Among all the choices, seeking shade was the most frequently selected behavior. The percentage for seeking shade was almost twice the percentage for any of the other choices. In hot-climate Taiwan (Lin et al., 2013a; Lin, 2009) or Singapore (Yang et al., 2013a), the percentage for seeking shade was as high as 80%. Chueng and Jim (2018b) demonstrated that attendance in shaded spaces in Hong Kong was twice that in unshaded spaces.

Because of the importance of shade, researchers also investigated people's interactions with shade in outdoor spaces. Lai et al. (2019a) observed that from the cool season to the hot season, people gradually moved from sunny spaces to shaded spaces. Li et al. (2016) determined the percentages of people in sunny and shaded spaces under different air temperature ranges in Guangzhou, China. When the air temperature was between 14 and 18 ºC, 80% of occupants were in sunny locations. This percentage decreased to 50% when the air temperature increased to 22 to 26 ºC, and almost no occupants were in the sun when the air temperature was between 30 and 34 ºC. In downtown Montreal, Zacharias et al. (2001) noted people's tendency to move into the shade when the air temperature was over 20 ºC. However, Watanabe and Ishii (2016) found that at 32 ºC, 50% of occupants were still in the sun while waiting for a traffic light. Because this waiting time was relatively short, people may have been able to endure greater solar radiation. In a square in Rome, Italy, in summer, Martinelli et al. (2015) discovered that occupants' location changed with the daily shade pattern. The above examples illustrate the need to take shade into account in the design of comfortable outdoor spaces.

#### 3.2.1.3 Changing clothes

The amount of clothing worn by a person affects the heat balance of his/her body and has a considerable impact on thermal comfort. The adjustment of clothing insulation in response to the outdoor thermal environment has been documented in studies in various cities. Most of these studies determined the relationship between clothing insulation and air temperature. Several studies analyzed the clothing insulation trend with respect to PET (Elnabawi et al., 2016; Yahia and Johansson, 2013), wet bulb globe temperature (WBGT) (Lin et al., 2013b), or mean radiant temperature ($T_{mrt}$) (Thorsson et al., 2004). Tables 3 and 4 summarize the associations between air temperature and clothing. Table 3 shows regressed equations, while the studies in Table 4 only provided scatter points of averaged clothing insulation for certain air temperatures.

Figure 3 is a summary of the regressed equations and scatter points from Tables 7 and 8. It is obvious that clothing insulation decreased with an increase in air temperature. However, the decrease was slower when the air temperature exceeded 25 ºC, probably because the clothing level had been reduced to socially acceptable limits. It can also be seen that when the air temperature was lower than 10 ºC, the increase in clothing insulation again reached a limit. In addition to the general trend, Figure 3 shows distinctive differences in the amount of clothing worn among regions, even under the same air temperature. These differences can be attributed in part to cultural factors. For example, due to cultural norms, Marrakech residents would wear clothing that covers most of the body even in summer, while Phoenix residents do not generally have such a restriction (Aljawabra and Nikolopoulou, 2018). As a result, the clothing insulation value for Marrakech residents was almost two times that for Phoenix residents. Furthermore, the regional difference in clothing insulation changed with the air temperature. The difference was small under high air temperature but became large when the air temperature decreased. For example, when the air temperature exceeded 30 °C, the regional difference in clothing insulation was less than 0.25 clo. However, at 10 °C, the largest difference was close to 1.0 clo.

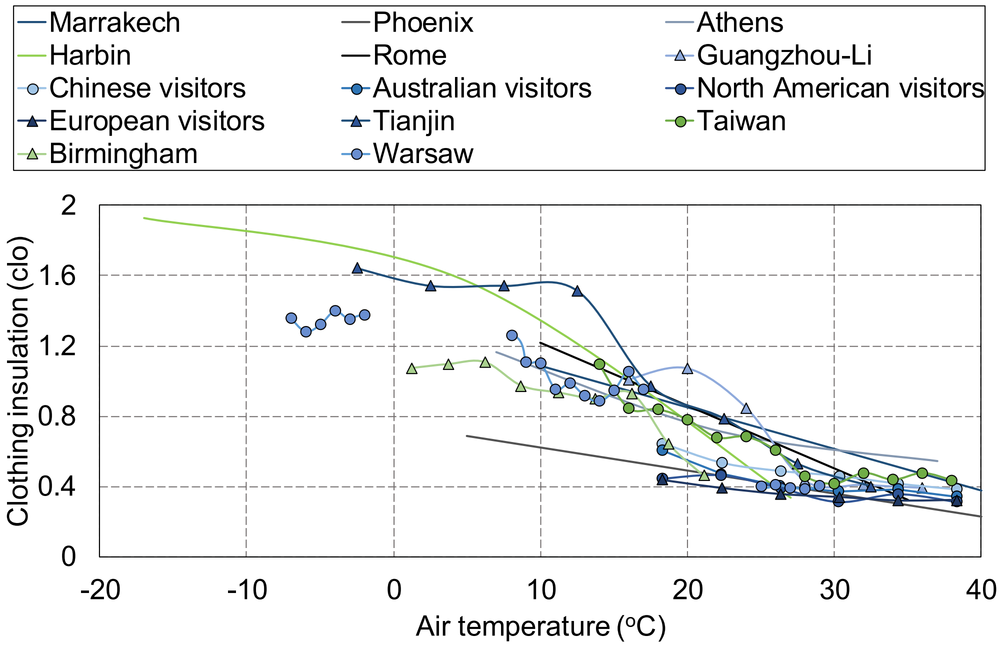


Figure 3. Change in clothing insulation in relation to air temperature.

Table 7. Regressed equations for clothing insulation in relation to air temperature, from the literature

| **Author, Date** | **Cities** | **Regressed Equations** |
|---|---|---|
| (Pantavou et al., 2013) | Athens, Greece | $y = 1.15 + 0.02\ T_a - 0.003\ T_a^2 + 0.00005453\ T_a^3$ |
| (Aljawabra and Nikolopoulou, 2018) | Marrakech, Morocco | $y = -0.0238\ T_a + 1.3265$ |
| (Aljawabra and Nikolopoulou, 2018) | Phoenix, US | $y = -0.0131\ T_a + 0.7537$ |
| (Chen et al., 2018) * | Harbin, China | $y = -0.0009\ T_a^2 - 0.0272\ T_a + 1.7248$ |
| (Fang et al., 2018) | Guangzhou, China | $y = -0.0326 T_a + 1.4054$ |
| (Salata et al., 2018) | Rome, Italy | $y = -0.0357\ T_a + 1.5743$ |

* Regressed by the authors

Table 8. Studies providing scatter-point associations between clothing and air temperature

| **Author, Date** | **Cities** |
|---|---|
| (Metje et al., 2008) | Birmingham, UK |
| (Lin et al., 2011) | Taichung, Yunlin, and Chiayi, Taiwan |
| (Lindner-Cendrowska, 2013) | Warsaw, Poland |
| (Lai et al., 2014a) | Tianjin, China |

| | |
|---|---|
| (Li et al., 2016) | Guangzhou, China |
| (Lam et al., 2018b) | Melbourne, Australia<br>(For visitors from Australia, China, Europe, and North America) |

### 3.2.2 Personal factors

Because of individual differences, subjects may have different thermal perception, even if they are exposed to the same thermal environment. In outdoor thermal comfort studies, researches have documented and analyzed personal differences in outdoor thermal comfort due to gender, age, skin color, and body weight. The research efforts of personal difference on outdoor thermal comfort is reviewed in this section and the summary is provided in Table 9.

Table 9. Summary of the influence of personal factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Personal | Gender | Descriptively, females were more sensitive than males, but the difference was small. But no statistical significance had been detected. | (Ali and Patnaik, 2018; Amindeldar et al., 2017; Brode et al., 2012b; Galindo and Hermida, 2018; Knez and Thorsson, 2006; Kruger and Drach, 2017; Krüger and Rossi, 2011; Lai et al., 2017b; Lam and Lau, 2018; Lindner-Cendrowska and Blazejczyk, 2018; Pantavou et al., 2013; Shooshtarian and Ridley, 2016b; Villadiego and Velay-Dabat, 2014; Yang et al., 2017) |
| | | Females showed higher tolerance to cold than males. | (Cohen et al., 2019) |
| | | Females preferred weaker sunshine, cooler environment, and had stronger negative reaction to wind than males. | (Huang et al., 2016; Oliveira and Andrade, 2007; Rutty and Scott, 2015; Tung et al., 2014) |
| | Age | The elderly was the least sensitive and had the greatest acceptance to thermal environment among all groups. | (Amindeldar et al., 2017; Andrade et al., 2011; Kruger and Drach, 2017; Krüger and Rossi, 2011; Lai et al., 2014a; Lindner-Cendrowska and Blazejczyk, 2018; Yang et al., 2017) |
| | | Observed increased sensitivity for persons aged over 55. | (Pantavou et al., 2013) |

#### 3.2.2.1 Gender

After data collection, some researchers divided the data by gender and compared the outdoor thermal comfort for males and females. Although different methods were applied in the analyses, most studies found that females were more sensitive to outdoor thermal environment than males. Several researchers simply compared the distribution of thermal sensation vote for male and female groups (Lindner-Cendrowska and Blazejczyk, 2018; Pantavou et al., 2013; Villadiego and Velay-Dabat, 2014), and found that males had higher percentages of “neutral” votes than females. Other researchers compared the mean thermal sensation for both genders under different ranges of air temperature. In Umea, Sweden, Yang et al. (2017) found that females felt warmer than males when the air temperature was high, and colder than males under low air temperature. Lam and Lau (2018) demonstrated that when the air temperature was above 24 $^{o}$C, the thermal sensation for females under 65 was constantly higher than that for males. A number of researchers obtained regressed equations of thermal sensation against thermal indices such as PET and UTCI for both genders. For all the developed regressed equations, the slopes of the female lines were greater than those of the male lines (Amindeldar et al., 2017; Galindo and Hermida, 2018; Kruger and Drach, 2017; Krüger and Rossi, 2011; Lai et al., 2017b; Shooshtarian and Ridley, 2016b). Only Cohen et al. (2019) reported that in Beer Sheva, Israel, females had shown higher tolerance to cold than did males. Overall, the differences between females and males as found in the studies were very small. Therefore, some researchers have claimed that the gender difference is negligible (Lai et al., 2017b). In numerous cases, statistical tests have been applied to further examine the gender difference (Ali and Patnaik, 2018; Brode et al., 2012b; Galindo and Hermida, 2018; Knez and Thorsson, 2006; Kruger and Drach, 2017; Shooshtarian and Ridley, 2016b; Villadiego and Velay-Dabat, 2014). However, no statistical significance has been detected in any of these studies.

Differences in preference of microclimate parameters between males and females have been examined in multiple studies. For example, Tung et al. (2014) found that females in Taiwan preferred weaker sunshine than did males. Oliveira and Andrade (2007) showed that females in Lisbon had a stronger negative reaction toward wind than did males. According to a study of tourists on a Caribbean beach by Rutty and Scott (2015), women preferred a cooler thermal environment than men. Huang et al. (2016) also confirmed females' preference for a cool environment. These studies all indicated that women had a lower tolerance to the outdoor thermal environment than men. In addition to psychological perception, gender differences in physiological and behavioral aspects have been investigated. In an outdoor walking test, Nakayoshi et al. (2015) found a higher sweat rate in males than females. Watanabe and Ishii (2016) found that in Japan, females were more careful in protecting themselves from solar radiation than males, through the use of hats and parasols.

#### 3.2.2.2 Age

In addition to gender, age is an important personal factor in outdoor thermal perception. Following a similar approach to that used for gender influence, researchers separated the data according to the age of respondents and compared the thermal sensation distributions (Lai et al., 2014a; Yang et al., 2017) or regressed equations (Amindeldar et al., 2017; Kruger and Drach, 2017; Krüger and Rossi, 2011) of the different age groups. The above studies found that senior citizens as a group were the least sensitive to the outdoor thermal environment. Only Pantavou et al. (Pantavou et al., 2013) observed increased sensitivity for persons aged over 55. Furthermore, statistical tests have been performed to examine the effect of age on outdoor thermal sensation. Among seven studies (Brode et al., 2012b; Galindo and Hermida, 2018; Knez and Thorsson, 2006; Kruger and Drach, 2017; Lindner-Cendrowska and Blazejczyk, 2018; Pantavou et al., 2013; Shooshtarian and Ridley, 2016b), only one investigation found that age had a statistically significant influence on thermal sensation. Besides being less sensitive to the thermal environment, older subjects exhibited greater acceptance of the environment (Andrade et al., 2011; Lindner-Cendrowska and Blazejczyk, 2018). One reason may have been the more highly insulated clothing worn by the elderly, as observed by Lai et al. (2014a) and Andrade et al. (2011).

### 3.2.2.3 Skin color and body weight

Meanwhile, skin color may influence outdoor thermal comfort by affecting the amount of solar radiation absorbed by the body. Only three studies (Galindo and Hermida, 2018; Kruger and Drach, 2017; Shooshtarian and Ridley, 2016b) examined the influence of skin color, and they reported different results. Although all three studies performed statistical tests, only Kruger and Drach (2017) determined that skin color had a statistically significant influence on outdoor thermal sensation. In addition to statistical tests, Shooshtarian and Ridley (2016b) and Kruger and Drach (2017) plotted the mean thermal sensation against the changing outdoor thermal environment for groups with different skin color. Shooshtarian and Ridley (2016b) observed higher sensitivity for subjects with dark skin than those with light skin. Within the research scope of Kruger and Drach (2017), although the thermal sensitivity for dark-skinned respondents was lower than for light-skinned subjects, the absolute thermal sensation for the dark-skinned group was consistently higher than for the light-skinned group.

Kruger and Drach (2017) categorized interviewees by weight—normal, overweight, and obese—and found that those of normal weight had the highest thermal sensation, followed by those who were overweight. Obese people had the lowest thermal sensation. The differences in thermal sensation among normal-weight, overweight, and obese people were found to be statistically significant. Body weight has also been found to influence physiological aspects. Nakayoshi et al. (2015) demonstrated that overweight subjects sweated more than normal-weight and underweight subjects.

### 3.2.3 Social factors

Urban open spaces are created and used by people. Therefore, it is important to consider human and social factors in research on outdoor thermal comfort. Nevertheless, few researchers have studied the impact of social factors on outdoor thermal perception, and according to the current studies, no consistent conclusion has been reached, as shown in Table 10.

Table 10. Summary of the influence of social factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Social | Position | No consistent conclusion, Shooshtarian and Ridley (2016b) found statistically significant difference, while Galindo and Hermida (2018) didn't. | (Galindo and Hermida, 2018; Shooshtarian and Ridley, 2016b) |
| | Companion | No consistent conclusion, Shooshtarian and Ridley (2016b) found statistically significant difference, while Galindo and Hermida (2018) didn't. | (Galindo and Hermida, 2018; Shooshtarian and Rajagopalan, 2017; Shooshtarian and Ridley, 2016b) |
| | Socio-economical level | No consistent conclusion, Aljawabra and Nikolopoulou (2018) showed greater sensitivity of higher socio-economical level, while Ali and Patnaik (2018) didn't find statistically significant impact. | (Ali and Patnaik, 2018; Aljawabra and Nikolopoulou, 2018) |

Shooshtarian and Ridley (2016b) defined social factors as position (academic and non-academic) and companion (with and without company), and showed that both factors had a statistically significant impact on outdoor thermal sensation. Shooshtarian and Rajagopalan (2017) further found that people with company had lower sensitivity to the outdoor thermal environment than people without company. In a similar analysis to that of Shooshtarian and Ridley (2016b) in regard to the impact of social factors, Galindo and Hermida (2018) subdivided the position factor into student and non-student categories. However, neither the position factor nor the companion factor had a statistically significant impact on outdoor thermal comfort in Galindo and Hermida (2018). Meanwhile, some researchers have analyzed the influence of socio-economic level on outdoor thermal comfort. While Ali and Patnaik (2018) did not observe a statistically significant impact, Aljawabra and Nikolopoulou (2018) showed that people with higher socio-economic level were more sensitive to the outdoor thermal environment.

### 3.2.4 Cultural factors

This section reviews the rich implication of cultural factor has on outdoor thermal comfort, and the main findings is summarized in Table 11.

Table 11. Summary of the influence of cultural factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Cultural | Ideal of beauty/ sun preference | Scandinavian residents long for the sun, they consider suntanned skin as beauty, while east Asians considers fair skin tone as beauty. | (Gehl, 2011; Thorsson et al., 2007; Tung et al., 2014) |
| | National characteristics | Japanese might evaluate outdoor spaces more modestly than Swedes. | (Knez and Thorsson, 2006; Knez and Thorsson, 2008) |
| | Cultural norms | Cultural norms lead to different clothing behavior between Marrakech and Phoenix (Aljawabra and Nikolopoulou, 2018) residents and shading behavior between females and males in Cairo (Elnabawi et al., 2016). | (Aljawabra and Nikolopoulou, 2018; Elnabawi et al., 2016) |

To analyze the influence of socio-economic level, Aljawabra and Nikolopoulou (2018) pooled data from Marrakech and Phoenix, cities with different cultural traditions. Uncertainty may have been introduced into this pooling process by the complex behavioral, physiological, psychological, and economic aspects of culture. For example, Shooshtarian and Ridley (2016b) and Galindo and Hermida (2018) both found that different cultural backgrounds gave rise to statistically significantly different thermal comfort levels. However, since occupants from different backgrounds may also have lived in different climates, it is possible that the thermal sensation differences between subjects with different cultural backgrounds were largely due to physiological acclimatization and psychological adaptation. Culture may also influence people's clothing-related behavior. The influence of culture on clothing was discussed in Sections 3.2.1 and 4.1. People's psychological attitudes toward certain microclimate parameters, such as sun exposure, may also be influenced by culture. Thorsson et al. (2007) identified a difference in attitude toward the sun between Japanese and Swedish people. In Scandinavian countries, where the winters are dark, residents long for the sun (Gehl, 2011). Furthermore, suntanned skin is considered beautiful in Scandinavia, and sunbathing is a frequent activity. In Japan, by contrast, the ideal of beauty is fair skin; people tend to avoid sun exposure. Knez and Thorsson (2006; 2008) pointed out that national characteristics can influence people's choices. For example, the Japanese might evaluate outdoor spaces more modestly than Swedes.

### 3.2.5 Thermal history

The thermal environment experienced by subjects in the past can influence their current thermal perception, and the influence of thermal history can be categorized into long-term and short-term. The use of air conditioners is an example of subjects' thermal history. Table 12 is a summary of thermal history factor from the literature.

Table 12. Summary of the influence of thermal history factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Thermal history | Long-term | Longer residence time led to higher acceptance to the environment. | (Chen et al., 2015; Gosling et al., 2014; Lindner-Cendrowska and Blazejczyk, 2018; Makaremi et al., 2012; Yang et al., 2017) |
| | | Climate of former residence of residents affects their thermal sensation. | (Wang et al., 2017; Wang et al., 2018; Yao et al., 2018) |
| | Short-term | Longer exposure in the outdoor space led to more neutral perception and reduced prediction error of steady state models. | (Chen et al., 2015; Krüger et al., 2017; Thorsson et al., 2004; Yang et al., 2013a) |
| | Use of air conditioner | (Long-term) Air conditioner usage increased people's sensitivity to outdoor thermal environment. | (Krüger et al., 2015; Yahia and Johansson, 2013) |
| | | (Short-term) Using air conditioner just before exposing in outdoor environments in summer lowered thermal sensation. | (Johansson et al., 2018; Middel et al., 2016; Ng and Cheng, 2012) |

#### 3.2.5.1 Long-term thermal history

When people expose themselves to a particular climate for a long period of time, they become adapted to that climate (Gosling et al., 2014). Many researchers have discovered that compared to foreign visitors, local residents have a higher percentage of neutral votes. For example, Lindner-Cendrowska and Blażejczyk (2018) classified interviewees into local, domestic, and foreign groups, and demonstrated that local respondents had the highest percentage of neutral thermal sensation vote, followed by domestic and foreign respondents. In a study conducted during cool months in Shanghai, China, by Chen et al. (2015), respondents who had resided longer in Shanghai had a higher proportion of neutral sensation votes. In Umeå, Sweden, Yang et al. (2017) found that within the surveyed thermal environment (10 $^{o}$C < PET < 40 $^{o}$C), the thermal sensation of a local person was about 0.8 unit higher than that of a non-local person, which demonstrated that the local person was more acclimatized to the cold climate of Sweden than the non-local person. In hot, humid Malaysia, Makaremi et al. (2012) showed that while local students considered the outdoor thermal environment acceptable, international students felt thermally uncomfortable. However, a study by Wang et al. (2017) in the Netherlands did not detect statistical significance in the relationship between length of residence and thermal sensation.

In addition to the length of residence, the climate of an occupant's former residential location affects his/her outdoor thermal sensation. For example, Yao et al. (2018) found that when respondents had lived in Shanghai for less than six months, they perceived the environment as cold if they were from warm regions, and warm or neutral if they were from cold regions. Studies by Wang et al. (2017; 2018) in Guangzhou, China, and Groningen, the Netherlands, have found similar results.

#### 3.2.5.2 Short-term thermal history

When people spend time in outdoor spaces, their exposure time is usually in the range of minutes, and this duration is not sufficient for the human body to reach a steady state. Kruger et al. (2017) and Thorsson et al. (2004) found that longer exposure time reduced the predictive error of dynamic thermal sensation (DTS) and PMV models. Field studies in Shanghai, China, by Chen et al. (2015) and in Singapore by Yang et al. (2013a) reported that with longer exposure time, people's thermal sensation became closer to neutral. After analyzing subject test data from 16 volunteers, Kruger et al. (2017) suggested a minimum of 30 minutes of exposure time for interviewees in outdoor field studies.

#### 3.2.5.3 Use of air conditioner

The use of air conditioning in a building can be considered part of the thermal history of subjects. Researchers have studied the impact of air conditioner (AC) usage on outdoor thermal comfort. The influence of AC usage can be categorized into long-term and short-term. From a long-term perspective, the use of air conditioners may increase occupants' sensitivity to the outdoor thermal environment, and thus they become less tolerant to heat stress. Yahia and Johansson (Yahia and Johansson (2013) found that people who did not have air conditioners at home or at work had a wider acceptable PET range than those who had air conditioners. Kruger et al. (2015) divided respondents into AC users, partial AC users, and non-users, and found that within the studied thermal environment (27 $^{o}$C < UTCI < 43 $^{o}$C), AC users had the highest thermal sensation, followed by partial AC users, and non-users.

However, from a short-term standpoint, people coming from air-conditioned rooms may have low skin and core temperatures, and thus are less affected by a hot environment. In Guayaquil, Ecuador, Johansson et al. (2018) found that subjects who had been in air-conditioned rooms 30 minutes before the interview accepted a higher SET* than those who were in the sun 30 minutes beforehand. Middel et al. (2016) divided surveyed subjects into two groups according to their exposure to AC five minutes before the survey. The authors (Middel et al., 2016) demonstrated that the thermal sensation of the exposed group was lower than that of the non-exposed group, and the difference was statistically significant. Ng and Cheng's study (2012) in Hong Kong found that the neutral PET of an AC group was higher than a non-AC group. In contrast, Yang et al. (2013a) found that in Singapore, the neutral operative temperature for an AC group (28.3 $^{o}$C) was slightly lower than for a natural ventilation group (28.8 $^{o}$C). The above studies were all conducted under hot climates. Chen et al. (2015) conducted a similar comparison study during the cool season in Shanghai, China, and no statistically significant difference was observed between AC and non-AC groups in terms of outdoor thermal sensation.

### 3.2.6 Site

This section reviews the impact of different sites on outdoor thermal comfort, and Table 13 is a summary of major findings.

Table 13. Summary of the influence of site factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Site | Microclimatic factors | Different sites had different levels of thermal sensation. | (Ali and Patnaik, 2018; Canan et al., 2019; Cohen et al., 2013; Givoni et al., 2003; Jeong et al., 2016; Lamarca et al., 2018; Mahmoud, 2011; Xu et al., 2018) |
| | Other factors | Microclimatic difference along cannot explain the site difference in TSV. | (Kruger et al., 2017) (Huang et al., 2017) |

Distinct thermal comfort levels have been found at different outdoor sites (Ali and Patnaik, 2018; Canan et al., 2019; Cohen et al., 2013; Lamarca et al., 2018; Mahmoud, 2011; Xu et al., 2018), mainly due to the variations in microclimate in outdoor spaces with different sky-view factor (SVF), height-to-width ratio (H/W), vegetation cover, and albedo (Sharmin et al., 2015). For example, Shih et al. (2017) found that the SVF level was associated with PET frequency, and, consequently, a high-SVF site had a statistically significantly higher TSV than did a low-SVF site (Shooshtarian and Ridley, 2017). According to Givoni et al. (2003), the largest difference in TSV among different spaces could be as high as 3 units.

Jeong et al. (2016) compared human thermal responses between an urban forest area and a central building district in Seoul, Korea. They found that in summer, the urban forest had lower OUT_SET*, lower human body skin temperature, cooler thermal sensation, and wider acceptable air temperature range than did the CBD. Other researchers (Huang et al., 2015; Lam et al., 2018b) have attributed differences in outdoor thermal comfort to air temperature differences. In contrast, based on a comprehensive analysis, Niu et al. (2015) concluded that differences in thermal comfort were caused mainly by wind speed and radiant temperature differences among various outdoor spaces.

Some studies have compared the thermal comfort level in shaded and unshaded spaces. Givoni et al. (2003) identified a TSV difference of around 1 unit between sunny and shaded areas. Middel et al. (2016) found that shade reduced TSV by 1 unit in summer. Kantor et al. (2016) identified a seasonal variation in shade-induced TSV difference. Watanabe et al. (2014) found that shade provided a greater reduction in heat stress on sunny days than on cloudy days. Several researchers have further compared the effects of different types of shade. For example, Middel et al. (2016) showed that the effects of artificial shade (photovoltaic canopy) and natural shade (tree canopy) were similar, while Watanabe et al. (2014) found that building shade provided slightly better performance than pergola shade.

Nevertheless, some studies have found that differences in microclimate in various spaces cannot fully explain differences in thermal sensation. For example, Krüger et al. (2017) demonstrated different thermal sensation levels in spaces with low, medium, and high SVF, even under the same PET value. The authors found that under moderate heat stress, subjects in a high-SVF place had greater TSV than medium- or low-SVF places, but the relationship was reversed under strong heat stress. Huang et al. (2017) compared the thermal sensation in areas underneath elevated buildings (UEB) and in open spaces. UEB areas were perceived as significantly cooler than open spaces under the same PET or UTCI range. According to Huang et al. (2017), the thermal comfort difference between UEB and open areas were likely caused by the underestimation of certain microclimate parameters' effects on people’s thermal sensation due to expectation, individual preference, or other physical factors.

### 3.2.7 Alliesthesia

Some researchers have employed “alliesthesia” to explain phenomena found in outdoor thermal comfort surveys. This section reviews the alliesthesia factor and a summary is shown in Table 14.

Table 14. Summary of the influence of alliesthesia factor on outdoor thermal comfort.

| Factor | Sub-factors | Summary | Reference |
|---|---|---|---|
| Alliesthesia | Temporal Alliesthesia | Dynamic outdoor thermal environment caused fluctuations in skin temperature, and changed thermal sensation. | (Lai et al., 2017b) |
| | Seasonal Alliesthesia | A slightly warm thermal sensation considered the most comfortable in cool season, vice versa in the warm season. | (Lai et al., 2014a; Yao et al., 2018) |
| | | Preferred temperature much lower than the neutral temperature in warm, humid climate. | (Johansson et al., 2018) |
| | | Winter neutral temperatures were higher than summer ones. | (Spagnolo and de Dear, 2003; Yahia and Johansson, 2013) |

Alliesthesia is a term put forward by Cabanac (1971) to describe the pleasant or unpleasant feeling caused by an increase or decrease in the deviation from the set point of certain regulated variables. In the field of the built environment, if the thermal state of a person is displaced from its set point, then external stimuli from the thermal environment that reduce this displacement are perceived as pleasant. de Dear (2011) and Parkinson (2016) have proposed alliesthesia as a systematic theoretical framework to explain the phenomenon of thermal pleasure in an indoor built environment. The outdoor thermal environment changes in both the short and long term, and this dynamic environment can increase or decrease the displacement from the set point, thus also leading to the alliesthesia effect. Researchers have adopted the theory of alliesthesia to explain various phenomena observed in outdoor thermal comfort studies.

#### 3.2.7.1 Temporal alliesthesia

In the short term, the dynamic nature of the outdoor thermal environment, especially changes in wind speed and solar radiation, cause fluctuations in skin temperature, and the difference between actual skin temperature and the "setpoint" skin temperature fluctuates as well. Lai et al. (2017b) have provided examples of alliesthesia during subject tests. In a case conducted in a cold environment, the mean skin temperature of a tested subject fell to 28.5 $^{o}$C at the end of the first half hour of exposure, and the thermal sensation decreased to -3 (cold). During the second half of the test, a reduction in wind speed caused the mean skin temperature of the subject to increase slightly, by 0.5 $^{o}$C, but the thermal sensation increased significantly, from -3 to 1 (slightly warm). Becker et al. (2003) found that after a certain period of exposure under heat stress, even slight cooling could induce feelings of comfort, although the authors (Becker et al., 2003) attributed this phenomenon to expectation. In addition to short-term temporal alliesthesia, spatial alliesthesia may exist outdoors. The non-uniform, dynamic outdoor thermal environment may cause the skin temperature of various local body segments to change in opposite directions, and thus create positive comfort sensation (Parkinson and de Dear, 2015). For example, while wind cools most parts of the body, the non-uniform solar radiation may warm other segments. Parkinson and de Dear (2015; 2016) demonstrated the existence of spatial alliesthesia caused by contact heating and air movement in an indoor climate chamber. However, no studies have addressed spatial alliesthesia in outdoor spaces.

#### 3.2.7.1 Seasonal alliesthesia

Meanwhile, in outdoor spaces, "seasonal alliesthesia" has been observed by Lai et al. (2014a) and Yao et al. (2018). In the cool season, a slightly warm thermal sensation was considered as the most comfortable, while in the warm season, a slightly cool thermal sensation was perceived as the most comfortable. Johansson et al. (2018) found that in warm, humid Guayaquil, Ecuador, the preferred temperature was much lower than the neutral temperature, demonstrating that local people expected a cooler environment. This phenomenon was also attributed to alliesthesia by Johansson et al. (2018). Spagnolo and de Dear (2003) and Yahia and Johansson (2013) found in their field surveys that winter neutral temperatures were higher than summer ones, and they identified alliesthesia as the reason for this phenomenon. However, in other studies, the winter neutral temperatures were lower than the summer values, and researchers attributed this to adaptation factors such as experience and expectation. Such a difference in results and explanations suggests that further analysis is warranted.

## 4. Discussion

### 4.1 Interactions among influencing factors

As outlined before, indirect factors influence outdoor thermal comfort through direct factors. For example, the phenomenon of temporal alliesthesia arises from dynamic changes in skin temperature and alters the general relationship between physiological response and psychological perception. In addition to temporal alliesthesia, thermal history can serve as an example of how indirect factors are based on direct factors. In the short term, thermal history influences outdoor thermal comfort because the skin temperature of the human body does not become balanced within a short period of time, due to the difference between the indoor thermal environment and outdoor microclimate. Whereas the effect of short-term thermal history is determined mainly by physiological factors, the effect of long-term thermal history is greatly impacted by experience, a psychological factor.

Indirect factors may interact with one another. Taking the interactions between personal and behavioral factors as an example, it is often observed that the elderly wear more clothing than other age groups to compensate for their lower metabolic rate (Schofield, 1985). Culture-influenced behavior has also been shown to impact outdoor thermal comfort. In the Royal Botanic Garden in Melbourne, Australia, during the summer, Chinese visitors' clothing insulation was approximately 0.1 clo greater than that of western visitors (Lam et al., 2018b). The explanation offered by the authors was that East Asians, including Chinese, consider a light skin tone to be an important component of beauty. As result, Chinese visitors, especially females, covered more of their body with clothing than western visitors (Tung et al., 2014). In Cairo, Egypt, because of conservative culture traditions, only 2% of the interviewed women chose to adapt to the hot outdoor thermal environment by reducing clothing. In contrast, 14% of surveyed men selected clothing reduction as an adaptive strategy. Culture may also influence other behavior such as seeking shade. Elnabawi et al. (2016) identified different behavioral adaptation strategies between genders in Cairo, Egypt. For example, while as many as 48% of males chose moving to shade as an adaptive behavior, only 8% females selected this choice. The authors (Elnabawi et al., 2016) have attributed this difference to the conservative culture in the studied area, where separation of men and women is common.

Other examples of interactions between influencing factors are available, in addition to the cases described above. For instances, people at different socio-economic levels may have different degrees of access to air conditioners, and thus different thermal histories. The purpose of this section is not to discuss all possible interactions. Studies may be designed and conducted to examine further connections among the influencing factors.

### 4.2 Adaptation

Adaptation is defined as the gradual decrease in an organism's response to repeated environmental stimulation, allowing the organism to survive in a given environment (Brager and de Dear, 1998). Adaptation is often used to explain the high level of acceptance of the outdoor thermal environment by occupants, and the climatic patterns of outdoor thermal comfort.

In an outdoor space, occupants usually have a high acceptance level, even though they are exposed to wide ranges of climatic parameters. For example, Nikolopoulou and Lykoudis (2006) determined that the overall comfort levels for outdoor spaces were over 75% according to a dataset of nearly 10,000 questionnaires collected in 14 cities across five European countries. In a field campaign in Tianjin, China (Lai et al., 2014a), 83.3% of interviewed people considered the outdoor thermal conditions to be acceptable. Besides the high acceptance level, outdoor thermal comfort has an obvious seasonal pattern. A large number of studies have calculated seasonal neutral thermal indices. Most of these studies have shown that the neutral temperature followed a seasonal pattern. For example, in the studies of Lindner and Błażejczyk (2018), Hadianpour et al. (2018), Aljawabra and Nikolopoulou (2018), Salata et al. (2016), Liu et al. (2016), Li et al. (2016), and Lin et al. (2011), the neutral thermal indices of the hot season were always greater than those of the cold season. Ng and Cheng (2012) and Hwang et al. (2010) reported a close positive correlation between neutral thermal indices and outdoor air temperature in Hong Kong ($R^2$ = 0.68) and Taiwan ($R^2$ = 0.88). In addition to the seasonal pattern, it has been found that the thermal environment in which people feel comfortable is close to the local climate (Cheung and Jim, 2018a; Potchter et al., 2018).

The above-mentioned phenomena—the wide acceptance level and the seasonal and regional patterns—are usually attributed to adaptation. Nikolopoulou and Steemers (2003) characterized types of adaptation as physical, psychological, or physical. Physical adaptation includes the changes one makes in order to adjust oneself to the environment or to alter the environment to one's needs. Since physical adaption always involve specific behavior, some researchers have referred physical adaptation as behavioral adaptation (Lin, 2009; Lin et al., 2013b) or adaptive behavior (Yang et al., 2013a). Examples of behavioral adaptation, such as changing clothing or seeking sun or shade, were discussed in Section 3.2.1.

Physiological adaptation refers to changes in physiological responses resulting from repeated exposure to a stimulus, leading to a gradually decreased strain from such exposure. Nikolopoulou and Steemers (2003) referred to physiological adaptation as physiological acclimatization and asserted that it is important only under extreme environmental conditions. Lin (2009) argued that physiological adaptation to a climate is generally slow. This type of adaptation has not generally been the focus of thermal comfort studies, and no specific examples were provided in the available studies. To explain psychological adaptation, researchers have usually employed experience and expectation factors, which are discussed in Section 3.1.3.

Although adaptation provides a reasonable framework for the distinctive features, such as the wide comfortable range, found in outdoor thermal comfort studies, no attempt has yet been made to quantify the relative weights of these factors. Such an effort would extend our understanding of outdoor thermal comfort.

**4.3 Practical implications**

Understanding thermal comfort is beneficial to the creation of various satisfactory built environments(He et al., 2019; Lai et al., 2018b; Lan et al., 2018; Lan et al., 2017; Lan et al., 2011; Shen et al., 2020; Wu et al., 2020; Xia et al., 2020; Xiong et al., 2019), including outdoor thermal environment. An increased understanding of outdoor thermal comfort would contribute to the quality of outdoor spaces. Before designing, creating, or retrofitting thermally comfortable outdoor spaces in certain cities, it would be beneficial to evaluate the existing conditions by calculating hourly thermal indices such as PET, UTCI, OUT_SET* using data from weather stations. For example, Unger et al. (2018), Algeciras and Matzarakis et al. (2016), Lin and Matzarakis (2008), and Eludoyin and Adelekan (2013) used weather data to assess the local thermal comfort conditions in Szeged (Hungary), Barcelona (Spain), Taiwan, and Nigeria, respectively. Results of outdoor thermal comfort evaluations can also guide people as they decide which activities to perform and when to do so. For example, in their evaluation of outdoor thermal comfort by OUT_SET*, Spagnolo and de Dear (2003) found that in Sydney, mid-summer was more suitable for sedentary activities, while mid-winter was more suitable for light activities such as walking. Salata et al. (2018) calculated the seasonal thermal perception distribution for Mediterranean subjects as they traveled to other cities by using a local thermal index (the Mediterranean Outdoor Comfort Index, MOCI). This calculation would be useful to a Mediterranean person in planning travel to destinations with specific climates. In addition to the general assessment of thermal comfort in a city, weather data can be imported into microclimate models for evaluation of thermal comfort at specific sites. For example, Honjo et al. (2018) and Vanos et al. (2019) studied outdoor thermal comfort along the marathon course of the 2020 Tokyo Olympics. Al-Rabghi et al. (2017) assessed the thermal stress around three holy mosques.

After assessing thermal comfort, some researchers further investigated design strategies for improving comfort. As early as 1989, Arens and Bosselmann (1989) used wind tunnel tests and shading analysis to examine various design strategies for a public square in San Francisco. The test results suggested that in the San Francisco climate, shade provided a greater improvement in thermal comfort than did wind acceleration. Meanwhile, Algeciras and Matzarakis (2016) assessed the strategies of shading, ventilation, and a combination of the two in Barcelona. The authors concluded that shading was the most effective means of alleviating heat stress, while modifying the wind speed was more effective in reducing cold stress.

Because of global warming, thermal comfort changes over time. Thorsson et al. (2011), Cheung and Hart (2014) and Huang et al. (2018) assessed changes in thermal comfort in Gothenburg (Sweden), Hong Kong, and Taiwan as a result of climate change. Because of differences in the background climate, these regions exhibited different changes in thermal comfort. For cold-climate Gothenburg, the reduction in cold stress exceeded the increase in heat stress. As a result, the number of hours with no thermal stress increased by 40 to 200 hours. However, in hot-climate Hong Kong and Taiwan, the reduction in cold stress was smaller than the increase in heat stress. As a result, there was a decrease in the total time with no thermal stress. Meanwhile, Huang et al. (2018) studied shading at different orientations as a means of mitigating the negative impact of climate change.

**4.4 Future studies**

Current studies have provided valuable knowledge about outdoor thermal comfort. However, the topic is complex, and more effort is required to gain further understanding. On the basis of the above review, the following studies are recommended:

Making changes to solar radiation and wind speed is the most feasible way to create thermally comfortable outdoor spaces. Existing studies have addressed the relative influence of these two parameters. It is possible that their effects are coupled with that of air temperature. Therefore, to guide the choice of design strategies in different climates, it necessary to comprehensively compare the impact of wind speed and solar radiation under different air temperature ranges. In addition, the dynamic, non-uniform nature of outdoor wind and solar radiation may lead to fluctuations and inhomogeneity in human skin temperature. It would be interesting to investigate the temporal and spatial thermal alliesthesia caused by the transient and non-uniform outdoor thermal environment.

The global indoor thermal comfort databases (de Dear, 1998; Földváry Ličina et al., 2018) developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have provided valuable open-source research data to the heating, ventilation, and air conditioning (HVAC) research community. As summarized in Table 1, current outdoor thermal comfort studies have accumulated over 130,000 sets of observations from around the world. The development of a standardized outdoor thermal comfort database would provide a useful resource for the diverse research efforts in this sphere.

According to Section 3.2.3 (social factors), only five studies have addressed the impact of social factors, and no consistent conclusions have been reached. In these studies, only a few unrelated social parameters were tested, such as companion, position, and economic level. In the future, researchers could use a systematic framework to investigate the influence of social factors.

Behavior is an external measurement of people's satisfaction with the outdoor environment. Behavioral studies have been far fewer than studies of subjective thermal perception. Additional studies of attendance and behavior would elucidate people's diverse requirements for the thermal environment and facilitate the creation of high-quality urban open spaces.

Further efforts are required to improve the accuracy of existing outdoor thermal comfort models, since the current models consider only some of the influencing factors. For example, the definition and calculation process for equivalent temperatures only account for physical, physiological, and a small number of behavioral influencing factors, and do not consider other very important aspects, such as psychological, cultural, and social factors. Moreover, some of the factors may be inaccurately represented in the models. For example, although indices such as UTCI can account for clothing in the model calculations, the clothing model used to determine UTCI was based on data from European subjects. Since clothing behavior varies greatly among regions, errors may arise when UTCI is applied to regions other than Europe. Another example is the calculation of PET, for which clothing is an input variable. According to a study by Fang et al. (2018), a change in clothing insulation from 0.3 to 1.2 caused only a negligible change in PET. For PET and UTCI, the influence of clothing on outdoor thermal comfort should be determined with greater accuracy. In addition to clothing behavior, many other factors influence thermal comfort. The effects of some factors are major, while other factors exert minor, negligible, or unclear influences. Higher priority should be given to factors with greater impact when researchers develop or refine the models.

## 5. Conclusions

Urban open spaces with good outdoor thermal comfort conditions attract citizens and improve the vitality of a city. Therefore, outdoor thermal comfort is an important research issue and the topic of a growing number of studies. This paper reviewed the benchmarks, the data collection method, and the models used in these studies. A framework of influencing factors was proposed, with physical, physiological and psychological factors as direct influences, and behavioral, personal, social, and cultural factors, thermal history, site, and alliesthesia as indirect influences. The effects of these factors on outdoor thermal comfort were then reviewed, and the interactions among these factors were discussed. The main findings of each influencing factor are provided in Tables 3 to Table 6, and Table 9 to Table 14, and the novel findings is summarized below:

1) Most studies have found that radiation is a more important parameter than wind speed, but three studies in a temperate climate determined that wind speed had a greater effect than radiation.

2) Microclimate parameters such as radiation and wind have dynamic and directional features, but their dynamic and directional impact on thermal comfort has not been well investigated.

3) Skin temperature has been found to be a good indicator of outdoor thermal comfort. It also provides a useful mean of recording the dynamic influence of the outdoor thermal environment.

4) Culture has rich implications, it impacts residents' behavior and subjective evaluation in outdoor spaces through cultural norms, national characteristics.

5) Alliesthesia is a notable phenomenon. When the human body or the thermal environment is at cool condition, a slight warm feeling can lead to high level of comfort, and vice versa.

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**References**

Ahmed KS. Comfort in urban spaces defining the boundaries of outdoor thermal comfort for the tropical urban environments. Energy and Buildings 2003; 35: 103-110.

Al-Rabghi OM, Al-Ghamdi AS, Kalantan MM. Thermal Comfort Around the Holy Mosques. Arabian Journal for Science and Engineering 2017; 42: 2125-2139.

Ali SB, Patnaik S. Thermal comfort in urban open spaces: Objective assessment and subjective perception study in tropical city of Bhopal, India. Urban Climate 2018; 24: 954-967.

Aljawabra F, Nikolopoulou M. Thermal comfort in urban spaces: a cross-cultural study in the hot arid climate. Int J Biometeorol 2018; 62: 1901-1909.

Amindeldar S, Heidari S, Khalili M. The effect of personal and microclimatic variables on outdoor thermal comfort: A field study in Tehran in cold season. Sustainable Cities and Society 2017; 32: 153-159.

Andrade H, Alcoforado MJ, Oliveira S. Perception of temperature and wind by users of public outdoor spaces: relationships with weather parameters and personal characteristics. Int J Biometeorol 2011; 55: 665-80.

Arens E, Bosselmann P. Wind, sun and temperature—Predicting the thermal comforf of

people in outdoor spaces. Building and Environment 1989; 24: 315-320.
ASHRAE. ANSI/ASHRAE Standard 55 - Thermal Envrionmental Conditions for Human Occupancy, 2017a.
ASHRAE. ASHRAE Handbook (SI), Fundamentals. Atlanta: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc., 2017b.
Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific data 2018; 5: 180214-180214.
Becker S, Potchter O, Yaakov Y. Calculated and observed human thermal sensation in an extremely hot and dry climate. Energy and Buildings 2003; 35: 747-756.
Brager GS, de Dear R. Thermal adaptation in the built environment: a literature review. Energy and Buildings 1998; 27: 83-96.
Brode P, Fiala D, Blazejczyk K, Holmer I, Jendritzky G, Kampmann B, et al. Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). Int J Biometeorol 2012a; 56: 481-94.
Brode P, Kruger EL, Rossi FA, Fiala D. Predicting urban outdoor thermal comfort by the Universal Thermal Climate Index UTCI--a case study in Southern Brazil. Int J Biometeorol 2012b; 56: 471-80.
Brown RD, Gillespie TJ. Estimating outdoor thermal comfort using a cylindrical radiation thermometer and an energy budget model. International Journal of Biometeorology 1986; 30: 43-52.
Cabanac M. Physiological role of pleasure. Science 1971; 173: 1103-7.
Canan F, Golasi I, Ciancio V, Coppi M, Salata F. Outdoor thermal comfort conditions during summer in a cold semi-arid climate. A transversal field survey in Central Anatolia (Turkey). Building and Environment 2019; 148: 212-224.
Chan SY, Chau CK, Leung TM. On the study of thermal comfort and perceptions of environmental features in urban parks: A structural equation modeling approach. Building and Environment 2017; 122: 171-183.
Chen L, Wen Y, Zhang L, Xiang W-N. Studies of thermal comfort and space use in an urban park square in cool and cold seasons in Shanghai. Building and Environment 2015; 94: 644-653.
Chen X, Xue P, Liu L, Gao L, Liu J. Outdoor thermal comfort and adaptation in severe cold area: A longitudinal survey in Harbin, China. Building and Environment 2018; 143: 548-560.
Cheng V, Ng E, Chan C, Givoni B. Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong. Int J Biometeorol 2012; 56: 43-56.
Cheung CS, Hart MA. Climate change and thermal comfort in Hong Kong. Int J Biometeorol 2014; 58: 137-48.
Cheung PK, Jim CY. Determination and application of outdoor thermal benchmarks. Building and Environment 2017; 123: 333-350.
Cheung PK, Jim CY. Global pattern of human thermal adaptation and limit of thermal neutrality: Systematic analysis of outdoor neutral temperature. International Journal of Climatology 2018a; 38: 5037-5049.
Cheung PK, Jim CY. Subjective outdoor thermal comfort and urban green space usage in

humid-subtropical Hong Kong. Energy and Buildings 2018b; 173: 150-162.
Chow HW, Mowen AJ, Wu Gl. Who is using outdoor fitness equipment and how? The case of Xihu Park. International Journal of Environmental Research and Public Health 2017; 14: 448.
Chow WTL, Akbar SNABA, Heng SL, Roth M. Assessment of measured and perceived microclimates within a tropical urban forest. Urban Forestry & Urban Greening 2016; 16: 62-75.
Coccolo S, Kämpf J, Scartezzini J-L, Pearlmutter D. Outdoor human comfort and thermal stress: A comprehensive review on models and standards. Urban Climate 2016; 18: 33-57.
Cohen P, Potchter O, Matzarakis A. Human thermal perception of Coastal Mediterranean outdoor urban environments. Applied Geography 2013; 37: 1-10.
Cohen P, Shashua-Bar L, Keller R, Gil-Ad R, Yaakov Y, Lukyanov V, et al. Urban outdoor thermal perception in hot arid Beer Sheva, Israel: Methodological and gender aspects. Building and Environment 2019; 160: 106169.
de Area Leao Borges VC, Callejas IJA, Durante LC. Thermal sensation in outdoor urban spaces: a study in a Tropical Savannah climate, Brazil. Int J Biometeorol 2020; 64: 533-545.
de Dear R. A global database of thermal comfort field experiments. ASHRAE Transactions 1998; 104: 1141-1152.
de Dear R. Revisiting an old hypothesis of human thermal perception: alliesthesia. Building Research & Information 2011; 39: 108-117.
Eliasson I, Knez I, Westerberg U, Thorsson S, Lindberg F. Climate and behaviour in a Nordic city. Landscape and Urban Planning 2007; 82: 72-84.
Elnabawi MH, Hamza N, Dudek S. Thermal perception of outdoor urban spaces in the hot arid region of Cairo, Egypt. Sustainable Cities and Society 2016; 22: 136-145.
Eludoyin OM, Adelekan IO. The physiologic climate of Nigeria. Int J Biometeorol 2013; 57: 241-64.
Fang Z, Lin Z, Mak CM, Niu J, Tse K-T. Investigation into sensitivities of factors in outdoor thermal comfort indices. Building and Environment 2018; 128: 129-142.
Fang Z, Xu X, Zhou X, Deng S, Wu H, Liu J, et al. Investigation into the thermal comfort of university students conducting outdoor training. Building and Environment 2019; 149: 26-38.
Fanger PO. Thermal Comfort. New York: McGraw Hill, 1970.
Fiala D, Havenith G, Brode P, Kampmann B, Jendritzky G. UTCI-Fiala multi-node model of human heat transfer and temperature regulation. Int J Biometeorol 2012; 56: 429-41.
Földváry Ličina V, Cheung T, Zhang H, de Dear R, Parkinson T, Arens E, et al. Development of the ASHRAE Global Thermal Comfort Database II. Building and Environment 2018; 142: 502-512.
Gagge AP, Fobelets AP, Berglund LG. A standard predictive index of human response to the thermal environment. ASHRAE Transactions 1986; 92.
Gagge AP, Stolwijk AJA, Nishi Y. An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Transactions 1971; 77: 247-262.
Galindo T, Hermida MA. Effects of thermophysiological and non-thermal factors on outdoor

thermal perceptions: The Tomebamba Riverbanks case. Building and Environment 2018; 138: 235-249.
Gehl J. Life between buildings: using public space. Washington DC: Island press, 2011.
Giannakis E, Bruggeman A, Poulou D, Zoumides C, Eliades M. Linear Parks along Urban Rivers: Perceptions of Thermal Comfort and Climate Change Adaptation in Cyprus. Sustainability 2016; 8: 1023.
Givoni B. Estimation of the effect of climate on man: development of a new thermal index. Technion-Israel Institute of Technology, Haifa, 1963.
Givoni B. Man, Climate and Architecture. New York: Van Nostrand Reinhold, 1976.
Givoni B, Noguchi M, Saaroni H, Pochter O, Yaacov Y, Feller N, et al. Givoni-Outdoor comfort research issues. Energy and Buildings 2003; 35: 77-86.
Golasi I, Salata F, de Lieto Vollaro E, Coppi M. Complying with the demand of standardization in outdoor thermal comfort: a first approach to the Global Outdoor Comfort Index (GOCI). Building and Environment 2018; 130: 104-119.
Gómez F, Luisa G, José J. Experimental investigation on the thermal comfort in the city: relationship with the green areas, interaction with the urban microclimate. Building and Environment 2004; 39: 1077-1086.
Gosling SN, Bryce EK, Dixon PG, Gabriel KM, Gosling EY, Hanes JM, et al. A glossary for biometeorology. Int J Biometeorol 2014; 58: 277-308.
Hadianpour M, Mahdavinejad M, Bemanian M, Haghshenas M, Kordjamshidi M. Effects of windward and leeward wind directions on outdoor thermal and wind sensation in Tehran. Building and Environment 2019; 150: 164-180.
Hadianpour M, Mahdavinejad M, Bemanian M, Nasrollahi F. Seasonal differences of subjective thermal sensation and neutral temperature in an outdoor shaded space in Tehran, Iran. Sustainable Cities and Society 2018; 39: 751-764.
He M, Lian Z, Chen P. Evaluation on the performance of quilts based on young people's sleep quality and thermal comfort in winter. Energy and Buildings 2019; 183: 174-183.
He X, An L, Hong B, Huang B, Cui X. Cross-cultural differences in thermal comfort in campus open spaces: A longitudinal field survey in China's cold region. Building and Environment 2020; 172: 106739.
Heidari S, Azizi M. Evaluation of thermal comfort in urban areas. International Journal of Urban Management and Energy Sustainability 2017; 1: 49-58.
Heng SL, Chow WTL. How 'hot' is too hot? Evaluating acceptable outdoor thermal comfort ranges in an equatorial urban park. Int J Biometeorol 2019; 63: 801-816.
Hirashima SQdS, Assis ESd, Nikolopoulou M. Daytime thermal comfort in urban spaces: A field study in Brazil. Building and Environment 2016; 107: 245-253.
Honjo T, Seo Y, Yamasaki Y, Tsunematsu N, Yokoyama H, Yamato H, et al. Thermal comfort along the marathon course of the 2020 Tokyo Olympics. Int J Biometeorol 2018; 62: 1407-1419.
Hoppe P. Different aspects of assessing indoor and outdoor thermal comfort. Energy and Buildings 2002; 34: 661-665.
Höppe P. Heat balance modelling. Experientia 1993; 49: 741-746.
Höppe P. The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. International Journal of

Biometeorology 1999; 43: 71-75.
Hou T, Lu M, Fua J. Microclimate perception features of commercial street in severe cold cities. Energy Procedia 2017; 134: 528-535.
Huang J, Zhou C, Zhuo Y, Xu L, Jiang Y. Outdoor thermal environments and activities in open space: An experiment study in humid subtropical climates. Building and Environment 2016; 103: 238-249.
Huang K-T, Lin T-P, Lien H-C. Investigating Thermal Comfort and User Behaviors in Outdoor Spaces: A Seasonal and Spatial Perspective. Advances in Meteorology 2015; 2015: 1-11.
Huang KT, Yang SR, Matzarakis A, Lin TP. Identifying outdoor thermal risk areas and evaluation of future thermal comfort concerning shading orientation in a traditional settlement. Sci Total Environ 2018; 626: 567-580.
Huang T, Li J, Xie Y, Niu J, Mak CM. Simultaneous environmental parameter monitoring and human subject survey regarding outdoor thermal comfort and its modelling. Building and Environment 2017; 125: 502-514.
Huang Z, Cheng B, Gou Z, Zhang F. Outdoor thermal comfort and adaptive behaviors in a university campus in China's hot summer-cold winter climate region. Building and Environment 2019; 165: 106414.
Hwang R-L, Lin T-P. Thermal Comfort Requirements for Occupants of Semi-Outdoor and Outdoor Environments in Hot-Humid Regions. Architectural Science Review 2007; 50: 357-364.
Hwang R-L, Lin T-P, Cheng M-J, Lo J-H. Adaptive comfort model for tree-shaded outdoors in Taiwan. Building and Environment 2010; 45: 1873-1879.
Jendritzky G, de Dear R, Havenith G. UTCI--why another thermal index? Int J Biometeorol 2012; 56: 421-8.
Jeong M-A, Park S, Song G-S. Comparison of human thermal responses between the urban forest area and the central building district in Seoul, Korea. Urban Forestry & Urban Greening 2016; 15: 133-148.
Johansson E, Thorsson S, Emmanuel R, Krüger E. Instruments and methods in outdoor thermal comfort studies – The need for standardization. Urban Climate 2014; 10: 346-366.
Johansson E, Yahia MW, Arroyo I, Bengs C. Outdoor thermal comfort in public space in warm-humid Guayaquil, Ecuador. Int J Biometeorol 2018; 62: 387-399.
Jovic S, Arsic N, Vilimonovic J, Petkovic D. Thermal sensation prediction by soft computing methodology. J Therm Biol 2016; 62: 106-108.
Kántor N. Differences between the evaluation of thermal environment in shaded and sunny position. Hungarian Geographical Bulletin 2016; 65: 139-153.
Kantor N, Egerhazi L, Unger J. Subjective estimation of thermal environment in recreational urban spaces--part 1: investigations in Szeged, Hungary. Int J Biometeorol 2012; 56: 1075-88.
Kantor N, Unger J, Gulyas A. Human bioclimatology evaluation with objective and subjective approaches on the thermal conditions of a square. Acta Climatologica et Chorologica 2007; 40: 47-58.
Kariminia S, Motamedi S, Shamshirband S, Petković D, Roy C, Hashim R. Adaptation of

ANFIS model to assess thermal comfort of an urban square in moderate and dry climate. Stochastic Environmental Research and Risk Assessment 2015; 30: 1189-1203.
Kariminia S, Motamedi S, Shamshirband S, Piri J, Mohammadi K, Hashim R, et al. Modelling thermal comfort of visitors at urban squares in hot and arid climate using NN-ARX soft computing method. Theoretical and Applied Climatology 2016a; 124: 991-1004.
Kariminia S, Shamshirband S, Hashim R, Saberi A, Petković D, Roy C, et al. A simulation model for visitors' thermal comfort at urban public squares using non-probabilistic binary-linear classifier through soft-computing methodologies. Energy 2016b; 101: 568-580.
Katavoutas G, Flocas HA, Matzarakis A. Dynamic modeling of human thermal comfort after the transition from an indoor to an outdoor hot environment. Int J Biometeorol 2015; 59: 205-16.
Kenny NA, Warland JS, Brown RD, Gillespie TG. Part A: Assessing the performance of the COMFA outdoor thermal comfort model on subjects performing physical activity. Int J Biometeorol 2009a; 53: 415-28.
Kenny NA, Warland JS, Brown RD, Gillespie TG. Part B: Revisions to the COMFA outdoor thermal comfort model for application to subjects performing physical activity. Int J Biometeorol 2009b; 53: 429-41.
Kim H, Lee K, Kim T. Investigation of Pedestrian Comfort with Wind Chill during Winter. Sustainability 2018; 10: 274.
Kim H, Macdonald E. Measuring the effectiveness of San Francisco's planning standard for pedestrian wind comfort. International Journal of Sustainable Development & World Ecology 2016; 24: 502-511.
Klemm W, Heusinkveld BG, Lenzholzer S, Jacobs MH, Van Hove B. Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in The Netherlands. Building and Environment 2015; 83: 120-128.
Knez I, Thorsson S. Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square. Int J Biometeorol 2006; 50: 258-68.
Knez I, Thorsson S. Thermal, emotional and perceptual evaluations of a park: Cross-cultural and environmental attitude comparisons. Building and Environment 2008; 43: 1483-1490.
Kovács A, Unger J, Gál CV, Kántor N. Adjustment of the thermal component of two tourism climatological assessment tools using thermal perception and preference surveys from Hungary. Theoretical and Applied Climatology 2016; 125: 113-130.
Krüger E, Drach P, Bröde P. Implications of air-conditioning use on thermal perception in open spaces: A field study in downtown Rio de Janeiro. Building and Environment 2015; 94: 417-425.
Kruger E, Drach P, Broede P. Outdoor comfort study in Rio de Janeiro: site-related context effects on reported thermal sensation. Int J Biometeorol 2017; 61: 463-475.
Krüger E, Drach P, Emmanuel R, Corbella O. Urban heat island and differences in outdoor comfort levels in Glasgow, UK. Theoretical and Applied Climatology 2012; 112: 127-141.

Kruger EL, Drach P. Identifying potential effects from anthropometric variables on outdoor thermal comfort. Building and Environment 2017; 117: 230-237.
Krüger EL, Rossi FA. Effect of personal and microclimatic variables on observed thermal sensation from a field study in southern Brazil. Building and Environment 2011; 46: 690-697.
Krüger EL, Tamura CA, Bröde P, Schweiker M, Wagner A. Short- and long-term acclimatization in outdoor spaces: Exposure time, seasonal and heatwave adaptation effects. Building and Environment 2017; 116: 17-29.
Kubaha K, Fiala D, Toftum J, Taki AH. Human projected area factors for detailed direct and diffuse solar radiation analysis. International Journal of Biometeorology 2004; 49: 113-129.
Kurazumi Y, Ishii J, Fukagawa K, Kondo E, Aruninta A. Ethnic Differences in Thermal Responses between Thai and Japanese Females in Tropical Urban Climate. American Journal of Climate Change 2016; 05: 52-68.
Kurazumi Y, Ishii J, Kondo E, Fukagawa K, Bolashikov ZD, Sakoi T, et al. The influence of outdoor thermal environment on young Japanese females. Int J Biometeorol 2014; 58: 963-74.
Lai D, Chen B, Liu K. Quantification of the influence of thermal comfort and life patterns on outdoor space activities. Building Simulation 2019a; 10.1007/s12273–019–0565–x.
Lai D, Chen C. Comparison of the linear regression, multinomial logit, and ordered probability models for predicting the distribution of thermal sensation. Energy and Buildings 2019; 188-189: 269-277.
Lai D, Chen C, Liu W, Shi Y, Chen C. An ordered probability model for predicting outdoor thermal comfort. Energy and Buildings 2018a; 168: 261-271.
Lai D, Chen Q. A two-dimensional model for calculating heat transfer in the human body in a transient and non-uniform thermal environment. Energy and Buildings 2016; 118: 114-122.
Lai D, Guo D, Hou Y, Lin C, Chen Q. Studies of outdoor thermal comfort in northern China. Building and Environment 2014a; 77: 110-118.
Lai D, Jia S, Qi Y, Liu J. Window-opening behavior in Chinese residential buildings across different climate zones. Building and Environment 2018b; 142: 234-243.
Lai D, Liu W, Gan T, Liu K, Chen Q. A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. Science of The Total Environment 2019b; 661: 337-353.
Lai D, Zhou C, Huang J, Jiang Y, Long Z, Chen Q. Outdoor space quality: A field study in an urban residential community in central China. Energy and Buildings 2014b; 68: 713-720.
Lai D, Zhou X, Chen Q. Measurements and predictions of the skin temperature of human subjects on outdoor environment. Energy and Buildings 2017a; 151: 476-486.
Lai D, Zhou X, Chen Q. Modelling dynamic thermal sensation of human subjects in outdoor environments. Energy and Buildings 2017b; 149: 16-25.
Lam CKC, Gallant AJE, Tapper NJ. Perceptions of thermal comfort in heatwave and non-heatwave conditions in Melbourne, Australia. Urban Climate 2018a; 23: 204-218.
Lam CKC, Lau KK. Effect of long-term acclimatization on summer thermal comfort in

outdoor spaces: a comparative study between Melbourne and Hong Kong. Int J Biometeorol 2018; 62: 1311-1324.
Lam CKC, Loughnan M, Tapper N. Visitors' perception of thermal comfort during extreme heat events at the Royal Botanic Garden Melbourne. Int J Biometeorol 2018b; 62: 97-112.
Lamarca C, Qüense J, Henríquez C. Thermal comfort and urban canyons morphology in coastal temperate climate, Concepción, Chile. Urban Climate 2018; 23: 159-172.
Lan L, Qian XL, Lian ZW, Lin YB. Local body cooling to improve sleep quality and thermal comfort in a hot environment. Indoor Air 2018; 28: 135-145.
Lan L, Tsuzuki K, Liu YF, Lian ZW. Thermal environment and sleep quality: A review. Energy and Buildings 2017; 149: 101-113.
Lan L, Wargocki P, Lian Z. Quantitative measurement of productivity loss due to thermal discomfort. Energy and Buildings 2011; 43: 1057-1062.
Lau KK-L, Chung SC, Ren C. Outdoor thermal comfort in different urban settings of sub-tropical high-density cities: An approach of adopting local climate zone (LCZ) classification. Building and Environment 2019a; 154: 227-238.
Lau KK, Shi Y, Ng EY. Dynamic response of pedestrian thermal comfort under outdoor transient conditions. Int J Biometeorol 2019b; 63: 979-989.
Leng H, Liang S, Yuan Q. Outdoor thermal comfort and adaptive behaviors in the residential public open spaces of winter cities during the marginal season. Int J Biometeorol 2020; 64: 217-229.
Li J, Niu J, Mak CM, Huang T, Xie Y. Assessment of outdoor thermal comfort in Hong Kong based on the individual desirability and acceptability of sun and wind conditions. Building and Environment 2018; 145: 50-61.
Li J, Niu J, Mak CM, Huang T, Xie Y. Exploration of applicability of UTCI and thermally comfortable sun and wind conditions outdoors in a subtropical city of Hong Kong. Sustainable Cities and Society 2020; 52: 101793.
Li K, Zhang Y, Zhao L. Outdoor thermal comfort and activities in the urban residential community in a humid subtropical area of China. Energy and Buildings 2016; 133: 498-511.
Lin C-H, Lin T-P, Hwang R-L. Thermal Comfort for Urban Parks in Subtropics: Understanding Visitor’s Perceptions, Behavior and Attendance. Advances in Meteorology 2013a; 2013: 1-8.
Lin T-P. Thermal perception, adaptation and attendance in a public square in hot and humid regions. Building and Environment 2009; 44: 2017-2026.
Lin T-P, de Dear R, Hwang R-L. Effect of thermal adaptation on seasonal outdoor thermal comfort. International Journal of Climatology 2011; 31: 302-312.
Lin T-P, Tsai K-T, Hwang R-L, Matzarakis A. Quantification of the effect of thermal indices and sky view factor on park attendance. Landscape and Urban Planning 2012; 107: 137-146.
Lin T-P, Tsai K-T, Liao C-C, Huang Y-C. Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types. Building and Environment 2013b; 59: 599-611.
Lin TP, Matzarakis A. Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. Int J

Biometeorol 2008; 52: 281-90.
Lindner-Cendrowska K. Assessment of bioclimatic conditions in cities for tourism and recreational purposes (a Warsaw case study). Geographia Polonica 2013; 86: 55-66.
Lindner-Cendrowska K, Blazejczyk K. Impact of selected personal factors on seasonal variability of recreationist weather perceptions and preferences in Warsaw (Poland). Int J Biometeorol 2018; 62: 113-125.
Liu K, Nie T, Liu W, Liu Y, Lai D. A machine learning approach to predict outdoor thermal comfort using local skin temperatures. Sustainable Cities and Society 2020; 59: 102216.
Liu W, Zhang Y, Deng Q. The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate. Energy and Buildings 2016; 128: 190-197.
Louafi S, Abdou S, Reiter S. <2017-Louafi-Effect of vegetation cover on thermal and visual comfort of pedestrians in urban spaces in hot and dry climate.pdf>. Nature and Technology 2017; 17: 30-41.
Lucchese JR, Andreasi WA. Designing Thermally Pleasant Open Areas: The Influence of Microclimatic Conditions on Comfort and Adaptation in Midwest Brazil. Journal of Sustainable Development 2017; 10: 11.
Lucchese JR, Mikuri LP, de Freitas NV, Andreasi WA. Application of selected indices on outdoor thermal comfort assessment in Midwest Brazil. International Journal of Energy and Environment 2016; 7: 291-302.
Mahmoud AHA. Analysis of the microclimatic and human comfort conditions in an urban park in hot and arid regions. Building and Environment 2011; 46: 2641-2656.
Makaremi N, Salleh E, Jaafar MZ, GhaffarianHoseini A. Thermal comfort conditions of shaded outdoor spaces in hot and humid climate of Malaysia. Building and Environment 2012; 48: 7-14.
Manavvi S, Rajasekar E. Semantics of outdoor thermal comfort in religious squares of composite climate: New Delhi, India. Int J Biometeorol 2020; 64: 253-264.
Maras I, Schmidt T, Paas B, Ziefle M, Schneider C. The impact of human-biometeorological factors on perceived thermal comfort in urban public places. Meteorologische Zeitschrift 2016; 25: 407-420.
Martinelli L, Lin T-P, Matzarakis A. Assessment of the influence of daily shadings pattern on human thermal comfort and attendance in Rome during summer period. Building and Environment 2015; 92: 30-38.
Melnikov V, Krzhizhanovskaya VV, Lees MH, Sloot PMA. System dynamics of human body thermal regulation in outdoor environments. Building and Environment 2018; 143: 760-769.
Metje N, Sterling M, Baker CJ. Pedestrian comfort using clothing values and body temperatures. Journal of Wind Engineering and Industrial Aerodynamics 2008; 96: 412-435.
Mi J, Hong B, Zhang T, Huang B, Niu J. Outdoor thermal benchmarks and their application to climate–responsive designs of residential open spaces in a cold region of China. Building and Environment 2020; 169: 106592.
Middel A, Selover N, Hagen B, Chhetri N. Impact of shade on outdoor thermal comfort-a

seasonal field study in Tempe, Arizona. Int J Biometeorol 2016; 60: 1849-1861.

Nakayoshi M, Kanda M, Shi R, de Dear R. Outdoor thermal physiology along human pathways: a study using a wearable measurement system. Int J Biometeorol 2015; 59: 503-15.

Nasrollahi N, Hatami Z, Taleghani M. Development of outdoor thermal comfort model for tourists in urban historical areas; A case study in Isfahan. Building and Environment 2017; 125: 356-372.

Ndetto EL, Matzarakis A. Assessment of human thermal perception in the hot-humid climate of Dar es Salaam, Tanzania. Int J Biometeorol 2017; 61: 69-85.

Ng E, Cheng V. Urban human thermal comfort in hot and humid Hong Kong. Energy and Buildings 2012; 55: 51-65.

Nikolopoulou M, Baker N, Steemers K. Thermal comfort in outdoor urban spaces understanding the human parameter. Solar Energy 2001; 70: 227-235.

Nikolopoulou M, Lykoudis S. Thermal comfort in outdoor urban spaces: Analysis across different European countries. Building and Environment 2006; 41: 1455-1470.

Nikolopoulou M, Lykoudis S. Use of outdoor spaces and microclimate in a Mediterranean urban area. Building and Environment 2007; 42: 3691-3707.

Nikolopoulou M, Steemers K. Thermal comfort and psychological adaptation as a guide for designing urban spaces. Energy and Buildings 2003; 35: 95-101.

Nikolopoulou ME. Designing open spaces in the urban environment: A bioclimatic approach. Athens: Centre for Renewable Energy Sources, 2004.

Niu J, Liu J, Lee T-c, Lin Z, Mak C, Tse K-T, et al. A new method to assess spatial variations of outdoor thermal comfort: Onsite monitoring results and implications for precinct planning. Building and Environment 2015; 91: 263-270.

Nouri AS, Costa JP. Addressing thermophysiological thresholds and psychological aspects during hot and dry mediterranean summers through public space design: The case of Rossio. Building and Environment 2017; 118: 67-90.

Oliveira S, Andrade H. An initial assessment of the bioclimatic comfort in an outdoor public space in Lisbon. Int J Biometeorol 2007; 52: 69-84.

Pantavou K, Chatzi E, Theoharatos G. Case study of skin temperature and thermal perception in a hot outdoor environment. Int J Biometeorol 2014; 58: 1163-73.

Pantavou K, Theoharatos G, Santamouris M, Asimakopoulos D. Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI. Building and Environment 2013; 66: 82-95.

Parkinson T. Thermal Pleasure and Alliesthesia in the Built Environment. Ph.D. University of Sydney, 2016.

Parkinson T, de Dear R. Thermal pleasure in built environments: spatial alliesthesia from contact heating. Building Research & Information 2015; 44: 248-262.

Parkinson T, de Dear R. Thermal pleasure in built environments: spatial alliesthesia from air movement. Building Research & Information 2016; 45: 320-335.

Parsons KC. Human thermal environments: the effect of hot, moderate and cold environments on human health, comfort and performance. London: Taylor & Francis, 2003.

Pearlmutter D, Jiao D, Garb Y. The relationship between bioclimatic thermal stress and subjective thermal sensation in pedestrian spaces. Int J Biometeorol 2014; 58: 2111-

27.
Perkins D, Debbage K. Weather and Tourism: Thermal Comfort and Zoological Park Visitor Attendance. Atmosphere 2016; 7: 44.
Pickup J, de Dear R. An outdoor thermal comfort index (OUT_SET*)-part I-the model and its assumptions. Biometeorology and urban climatology at the turn of the millenium, Sydney, Australia, 2000.
Potchter O, Cohen P, Lin TP, Matzarakis A. Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification. Sci Total Environ 2018; 631-632: 390-406.
Rodriguez Algeciras JA, Matzarakis A. Quantification of thermal bioclimate for the management of urban design in Mediterranean climate of Barcelona, Spain. Int J Biometeorol 2016; 60: 1261-70.
Ruiz MA, Correa EN. Adaptive model for outdoor thermal comfort assessment in an Oasis city of arid climate. Building and Environment 2015; 85: 40-51.
Rutty M, Scott D. Bioclimatic comfort and the thermal perceptions and preferences of beach tourists. Int J Biometeorol 2015; 59: 37-45.
Saaroni H, Pearlmutter D, Hatuka T. Human-biometeorological conditions and thermal perception in a Mediterranean coastal park. Int J Biometeorol 2015; 59: 1347-62.
Salata F, Golasi I, Ciancio V, Rosso F. Dressed for the season: Clothing and outdoor thermal comfort in the Mediterranean population. Building and Environment 2018; 146: 50-63.
Salata F, Golasi I, de Lieto Vollaro R, de Lieto Vollaro A. Outdoor thermal comfort in the Mediterranean area. A transversal study in Rome, Italy. Building and Environment 2016; 96: 46-61.
Sangkertadi S, Syafriny R. New equation for estimating outdoor thermal comfort in humid tropical environment. European Journal of Sustainable Development 2014; 3: 43-52.
Schnell I, Dor L, Tirosh E. The effects of selected urban environments on the autonomic balance in the elderly. Journal of Multidisciplinary Engineering Science and Technology 2016; 3: 4903-4909.
Schnell I, Potchter O, Yaakov Y, Epstein Y, Brener S, Hermesh H. Urban daily life routines and human exposure to environmental discomfort. Environmental monitoring and assessment 2012; 184: 4575-90.
Schofield WN. Predicting basal metabolic rate, new standards and review of previous work. Human nutrition. Clinical nutrition 1985; 39 Suppl 1: 5-41.
Sharifi E, Sivam A, Boland J. Resilience to heat in public space: a case study of Adelaide, South Australia. Journal of Environmental Planning and Management 2015; 59: 1833-1854.
Sharmin T, Steemers K, Humphreys M. Outdoor thermal comfort and summer PET range: A field study in tropical city Dhaka. Energy and Buildings 2019; 198: 149-159.
Sharmin T, Steemers K, Matzarakis A. Analysis of microclimatic diversity and outdoor thermal comfort perceptions in the tropical megacity Dhaka, Bangladesh. Building and Environment 2015; 94: 734-750.
Shen J, Zhang X, Lian Z. Impact of wooden versus nonwooden interior designs on office workers' cognitive performance. Perceptual and Motor Skills 2020; 127: 36-51.
Shih WM, Lin TP, Tan NX, Liu MH. Long-term perceptions of outdoor thermal environments

in an elementary school in a hot-humid climate. Int J Biometeorol 2017; 61: 1657-1666.
Shimazaki Y, Yoshida A, Suzuki R, Kawabata T, Imai D, Kinoshita S. Application of human thermal load into unsteady condition for improvement of outdoor thermal comfort. Building and Environment 2011; 46: 1716-1724.
Shooshtarian S, Rajagopalan P. Study of thermal satisfaction in an Australian educational precinct. Building and Environment 2017; 123: 119-132.
Shooshtarian S, Ridley I. Determination of acceptable thermal range in outdoor built environments by various methods. Smart and Sustainable Built Environment 2016a; 5: 352-371.
Shooshtarian S, Ridley I. The effect of individual and social environments on the users thermal perceptions of educational urban precincts. Sustainable Cities and Society 2016b; 26: 119-133.
Shooshtarian S, Ridley I. The effect of physical and psychological environments on the users thermal perceptions of educational urban precincts. Building and Environment 2017; 115: 182-198.
Song GS, Jeong MA. Morphology of pedestrian roads and thermal responses during summer, in the urban area of Bucheon city, Korea. Int J Biometeorol 2016; 60: 999-1014.
Spagnolo J, de Dear R. A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. Building and Environment 2003; 38: 721-738.
Stathopoulos T, Wu H, Zacharias J. Outdoor human comfort in an urban climate. Building and Environment 2004; 39: 297-305.
Thorsson S, Honjo T, Lindberg F, Eliasson I, Lim E-M. Thermal Comfort and Outdoor Activity in Japanese Urban Public Places. Environment and Behavior 2007; 39: 660-684.
Thorsson S, Lindberg F, Björklund J, Holmer B, Rayner D. Potential changes in outdoor thermal comfort conditions in Gothenburg, Sweden due to climate change: the influence of urban geometry. International Journal of Climatology 2011; 31: 324-335.
Thorsson S, Lindqvist M, Lindqvist S. Thermal bioclimatic conditions and patterns of behaviour in an urban park in Goteborg, Sweden. Int J Biometeorol 2004; 48: 149-56.
Trindade da Silva F, Engel de Alvarez C. An integrated approach for ventilation's assessment on outdoor thermal comfort. Building and Environment 2015; 87: 59-71.
Tseliou A, Tsiros IX, Nikolopoulou M. Seasonal differences in thermal sensation in the outdoor urban environment of Mediterranean climates - the example of Athens, Greece. Int J Biometeorol 2017; 61: 1191-1208.
Tseliou A, Tsiros IX, Nikolopoulou M, Papadopoulos G. Outdoor thermal sensation in a Mediterranean climate (Athens): The effect of selected microclimatic parameters. Architectural Science Review 2015; 59: 190-202.
Tsitoura M, Tsoutsos T, Daras T. Evaluation of comfort conditions in urban open spaces. Application in the island of Crete. Energy Conversion and Management 2014; 86: 250-258.
Tung CH, Chen CP, Tsai KT, Kantor N, Hwang RL, Matzarakis A, et al. Outdoor thermal comfort characteristics in the hot and humid region from a gender perspective. Int J

Biometeorol 2014; 58: 1927-39.
Unger J, Skarbit N, Gal T. Evaluation of outdoor human thermal sensation of local climate zones based on long-term database. Int J Biometeorol 2018; 62: 183-193.
Vanos JK, Herdt AJ, Lochbaum MR. Effects of physical activity and shade on the heat balance and thermal perceptions of children in a playground microclimate. Building and Environment 2017; 126: 119-131.
Vanos JK, Kosaka E, Iida A, Yokohari M, Middel A, Scott-Fleming I, et al. Planning for spectator thermal comfort and health in the face of extreme heat: The Tokyo 2020 Olympic marathons. Sci Total Environ 2019; 657: 904-917.
Vasilikou C, Nikolopoulou M. Outdoor thermal comfort for pedestrians in movement: thermal walks in complex urban morphology. International Journal of Biometeorology 2019; 64: 277-291.
Villadiego K, Velay-Dabat MA. Outdoor thermal comfort in a hot and humid climate of Colombia: A field study in Barranquilla. Building and Environment 2014; 75: 142-152.
Walton D, Dravitzki V, Donn M. The relative influence of wind, sunlight and temperature on user comfort in urban outdoor spaces. Building and Environment 2007; 42: 3166-3175.
Wang Y, de Groot R, Bakker F, Wortche H, Leemans R. Thermal comfort in urban green spaces: a survey on a Dutch university campus. Int J Biometeorol 2017; 61: 87-101.
Wang Y, Ni Z, Peng Y, Xia B. Local variation of outdoor thermal comfort in different urban green spaces in Guangzhou, a subtropical city in South China. Urban Forestry & Urban Greening 2018; 32: 99-112.
Watanabe S, Ishii J. Effect of outdoor thermal environment on pedestrians' behavior selecting a shaded area in a humid subtropical region. Building and Environment 2016; 95: 32-41.
Watanabe S, Nagano K, Ishii J, Horikoshi T. Evaluation of outdoor thermal comfort in sunlight, building shade, and pergola shade during summer in a humid subtropical region. Building and Environment 2014; 82: 556-565.
Woolley H. Urban Open Spaces. Abingdon: Taylor and Francis, 2003.
World Population Bureau. World Population Data Sheet, 2018.
Wu CF, Hsieh YF, Ou SJ. Thermal Adaptation Methods of Urban Plaza Users in Asia's Hot-Humid Regions: A Taiwan Case Study. Int J Environ Res Public Health 2015; 12: 13560-86.
Wu J, Lian Z, Zheng Z, Zhang H. A method to evaluate building energy consumption based on energy use index of different functional sectors. Sustainable Cities and Society 2020; 53: 101893.
Xi T, Li Q, Mochida A, Meng Q. Study on the outdoor thermal environment and thermal comfort around campus clusters in subtropical urban areas. Building and Environment 2012; 52: 162-170.
Xi T, Wang Q, Qin H, Jin H. Influence of outdoor thermal environment on clothing and activity of tourists and local people in a severely cold climate city. Building and Environment 2020; 173: 106757.
Xia L, Lan L, Tang J, Wan Y, Lin Y, Wang Z. Bed heating improves the sleep quality and

health of the elderly who adapted to no heating in a cold environment. Energy and Buildings 2020; 210: 109687.

Xie Y, Huang T, Li J, Liu J, Niu J, Mak CM, et al. Evaluation of a multi-nodal thermal regulation model for assessment of outdoor thermal comfort: Sensitivity to wind speed and solar radiation. Building and Environment 2018; 132: 45-56.

Xie Y, Liu J, Huang T, Li J, Niu J, Mak CM, et al. Outdoor thermal sensation and logistic regression analysis of comfort range of meteorological parameters in Hong Kong. Building and Environment 2019; 155: 175-186.

Xiong J, Ma T, Lian Z, de Dear R. Perceptual and physiological responses of elderly subjects to moderate temperatures. Building and Environment 2019; 156: 117-122.

Xu M, Hong B, Jiang R, An L, Zhang T. Outdoor thermal comfort of shaded spaces in an urban park in the cold region of China. Building and Environment 2019; 155: 408-420.

Xu M, Hong B, Mi J, Yan S. Outdoor thermal comfort in an urban park during winter in cold regions of China. Sustainable Cities and Society 2018; 43: 208-220.

Yahia MW, Johansson E. Evaluating the behaviour of different thermal indices by investigating various outdoor urban environments in the hot dry city of Damascus, Syria. Int J Biometeorol 2013; 57: 615-30.

Yang B, Olofsson T, Nair G, Kabanshi A. Outdoor thermal comfort under subarctic climate of north Sweden – A pilot study in Umeå. Sustainable Cities and Society 2017; 28: 387-397.

Yang W, Wong NH, Jusuf SK. Thermal comfort in outdoor urban spaces in Singapore. Building and Environment 2013a; 59: 426-435.

Yang W, Wong NH, Zhang G. A comparative analysis of human thermal conditions in outdoor urban spaces in the summer season in Singapore and Changsha, China. Int J Biometeorol 2013b; 57: 895-907.

Yao J, Yang F, Zhuang Z, Shao Y, Yuan PF. The effect of personal and microclimatic variables on outdoor thermal comfort: A field study in a cold season in Lujiazui CBD, Shanghai. Sustainable Cities and Society 2018; 39: 181-188.

Yin J, Zheng Y, Wu R, Tan J, Ye D, Wang W. An analysis of influential factors on outdoor thermal comfort in summer. Int J Biometeorol 2012; 56: 941-8.

Yoshida A, Hisabayashi T, Kashihara K, Kinoshita S, Hashida S. Evaluation of effect of tree canopy on thermal environment, thermal sensation, and mental state. Urban Climate 2015; 14: 240-250.

Zacharias J, Stathopoulos T, Wu H. Microclimate and Downtown Open Space Activity. Environment and Behavior 2001; 33: 296-315.

Zeng Y, Dong L. Thermal human biometeorological conditions and subjective thermal sensation in pedestrian streets in Chengdu, China. Int J Biometeorol 2015; 59: 99-108.

Zhang H, Arens E, Huizenga C, Han T. Thermal sensation and comfort models for non-uniform and transient environments: part I: Local sensation of individual body parts. Building and Environment 2010; 45 380-388.

Zhao L, Zhou X, Li L, He S, Chen R. Study on outdoor thermal comfort on a campus in a subtropical urban area in summer. Sustainable Cities and Society 2016; 22: 164-170.

Zhou Z, Chen H, Deng Q, Mochida A. A field study of thermal comfort in outdoor and semi-outdoor environments in a humid subtropical climate city. Journal of Asian Architecture and Building Engineering 2013; 12: 73-79.