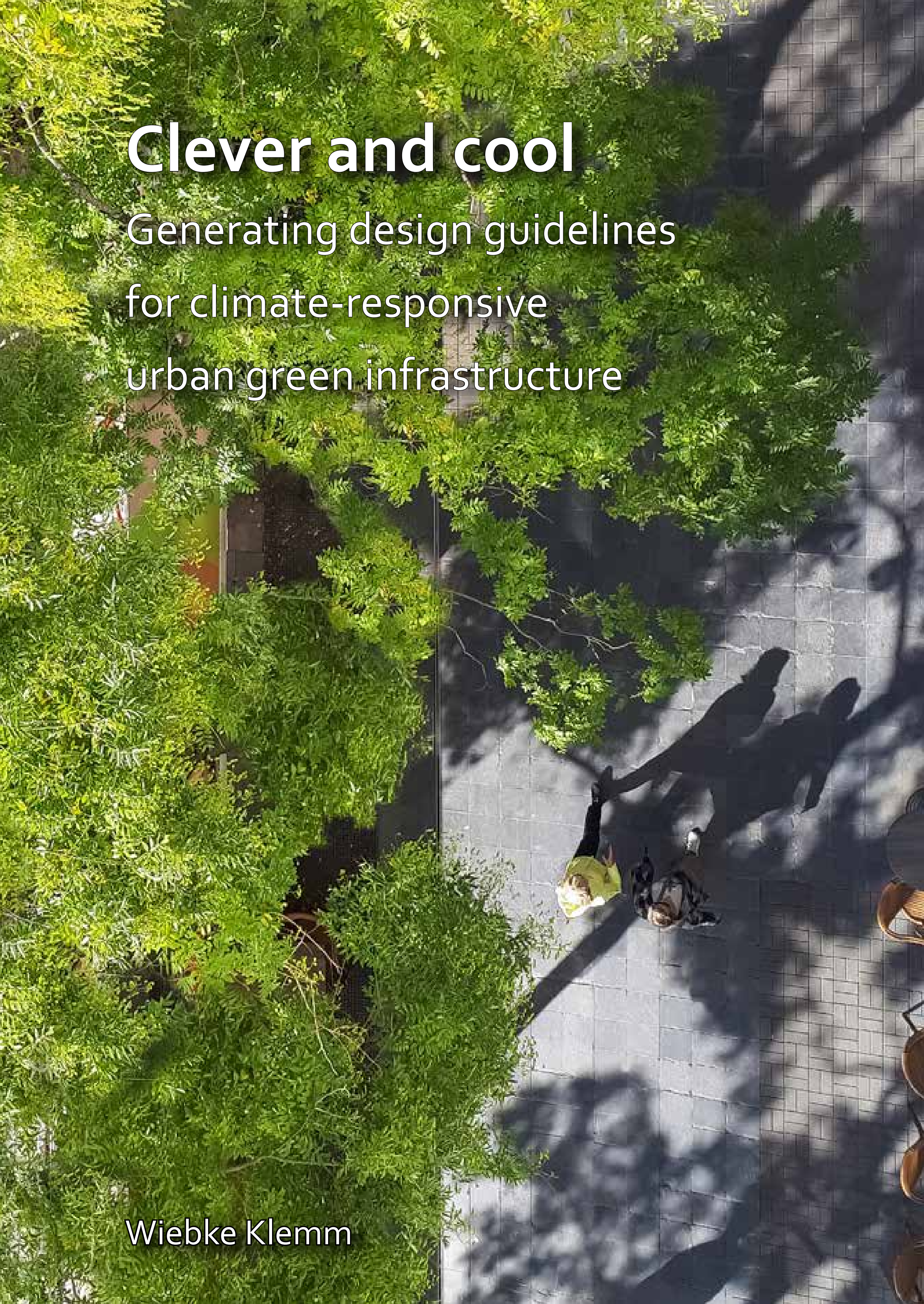

Clever and cool

Generating design guidelines for climate-responsive urban green infrastructure

Wiebke Klemm

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for climate responsive

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Generating design guidelines for climate responsive urban green infrastructure

Wiebke Klemm

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Voor Michiel, Lieke & Renske

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1 Introduction

1.1 Motivation

In 2010, I presented a design proposal for a climate-responsive neighbourhood at a symposium for environmental professionals. The design proposal was the result of the study 'Climate change adaptation in the city' that I had worked on with colleagues from the landscape and urban design office, Bosch Slabbers, in commission of the (former) Dutch Ministry of Housing, Spatial Planning and the Environment. The project's aim was to showcase integrating climate change adaptation in landscape architectural design as a response to the challenges of global warming and urbanization in the Netherlands.

At the time, climate change adaptation was a rather new topic in the Netherlands, both for policy makers and for landscape architects, and other urban planning and design professionals. It was difficult to find appropriate knowledge on or guidance for designing outdoor spaces that contributed to urban climate adaptation. Little was known, especially about heat-related climate-responsive urban design which means shaping outdoor spaces that are thermally comfortable and facilitate usage and activity all year around (Brown, 2010). Such thermally comfortable spaces address the adverse effects of global warming and urban heat stress, and take advantage of the positive microclimate effects, namely longer warm periods which make outdoor activities attractive. Climate-responsive design in terms of water storage, for example, was less critical as Dutch planners and designers have a long-standing tradition in designing with water (e.g., Teeuw et al., 2005, Pötz et al., 2010, Van de Ven, 2009). Designing thermally comfortable outdoor spaces, in contrast, was new in the Dutch context.

We collected available information on climate-responsive urban design mainly from Germany, where urban design has been related to urban climate issues for a longer period (Ministry of Transport and Infrastructure Baden-Wuerttemberg, 2008). The general positive effects of green became clear from our literature research. Urban vegetation, in particular tree canopies, provides shade and moderates solar heat gain through evapotranspiration. We then studied green design interventions, such as the decrease of hard, and the increase of preferably green, permeable surfaces (e.g., the increase of lawns and trees in outdoor spaces), and applied them in design proposals. One of them was the design proposal for a climate-responsive neighbourhood in Transvaal, The Hague, which I presented at the symposium.

At the end of the presentation, a policymaker asked: "This is a nice neighbourhood design. How much cooling will this design proposal provide after implementation?". With mostly general, qualitative information at hand, answering this question was not easy. Studies on the quantitative impacts of urban green on urban climate conditions were deficient, so providing the requested knowledge was impossible. However what followed was a lively discussion between attending policymakers, researchers, and urban designers on the essence of heat-related climate-responsive urban design, and in particular, the role of urban green spaces and elements. This discussion opened my eyes. I became interested in the actual cooling impact of urban green spaces and elements, and how this type of quantitative knowledge could help urban designers to shape thermally comfortable urban spaces. Eventually, to contribute to creating useful knowledge and advancing urban climate adaptation, I decided to exchange my work place at the design office for the position of a PhD researcher at Wageningen University within the Climate-Proof Cities project cluster of the Dutch 'Knowledge for Climate' programme.

Since the start of my PhD research, public and political awareness of urban heat and its negative impacts on health and well-being has significantly raised. This is partly due to more frequent heat waves in the Netherlands in the last couple of years (e.g., Boezeman and Kooij, 2015). The awareness of urban heat stress increased interest in adapting urban areas to changing thermal conditions. At all policy levels (e.g., European Environment Agency, 2015, City of Amsterdam, 2015, European Environment Agency, 2010), more and more attention has been given to the need to develop climate-responsive urban areas by means of urban greening.

What is still lacking is specialised knowledge on heat-related climate-responsive design of urban green elements and spaces: What is the actual cooling effect of urban parks or street trees? And, how should landscape architects and urban designers shape vegetation structures in urban parks, streets or residential gardens to be thermally comfortable, not only on hot summer days, but also all year round to enable outdoor activity? Currently it seems that the general belief of '*green is good*' appears to be sufficient to inform design. The adage seems to be: '*the greener, the better urban spaces are adapted to urban heat issues*'. Ubiquitous urban green solutions are presented as a panacea for all urban climate issues. However, it is obvious that such a generalist assertion is unrealistic and untenable. There is not only the financial issue of implementation and maintenance, but there are also possible detrimental effects of urban green if implemented incorrectly (Demuzere et al., 2014). Street trees, for example, can have adverse effects on traffic-related air pollution (e.g., Morakinyo and Lam, 2016, Jin et al., 2014). Therefore, to design urban green elements and spaces in a thermally comfortable and resourceful way, more spatially explicit knowledge on the cooling impacts of urban green elements and spaces is needed. Such evidence-based knowledge can inform urban and landscape architectural design and advance urban climate adaptation.

This thesis concerns the generation of spatially explicit knowledge regarding urban green (i.e., vegetated) spaces and elements, such as parks and street greenery, that informs climate-responsive urban and landscape architectural design as a response to global climate change and urban heat problems. For this purpose, the thesis studies the impact of urban green spaces and elements on objective thermal conditions, and on residents' subjective thermal perceptions during summer in the moderate climate of the Netherlands. Research findings are subsequently translated into useful knowledge for landscape architects and other urban design professionals. This knowledge supports the design of climate-responsive urban green; thus urban green that is '*clever and cool*'.

1.2 Global warming and urban heat stress

Global warming has induced an increase in heatwaves in the moderate climate of the Netherlands (KNMI, 2015). This has consequences for human thermal comfort and heat stress which are especially felt in urban areas because of the Urban Heat Island (UHI) effect. This effect is caused by artificial, built and paved surfaces that retain warmth longer than the surrounding. The UHI effect causes higher air temperatures (T_a) in urban areas than in the rural surrounding, reaching up to 8 K in Dutch cities (Steeneveld et al., 2011, Van Hove et al., 2015). Residents may be exposed to heat stress, which is expected to increase substantially in the next decades (Molenaar et al., 2016).

In addition to global warming impacts, rapid population growth and urbanization (Seto et al., 2011) cause more heat stress in cities. By

2050 the global population is expected to grow from 7.2 billion people in 2014 to 9.5 billion people, 66% of whom will live in urban areas (United Nations, 2015). In the Netherlands, too, particularly in the western and central parts of the country, the urban population is increasing and this growth is expected to continue in the next decades (Huisman et al., 2013). Urban expansion and densification will most likely lead to more built and paved surfaces and, as such, to higher temperatures in the urban environment.

Higher temperatures have direct implications for urban life. On one hand, higher temperatures in the Netherlands, for example, provide longer periods for outdoor recreation and activity, with possible positive health and economic effects (Klok and Kluck, 2016). On the other hand, heat stress involves risks for human health and well-being. The most vulnerable groups are young children, the elderly, and people with specific lung and cardiovascular diseases (Haines et al., 2006, Huynen and Van Vliet, 2009). Heat stress affects the ability to sleep and concentrate, as well as work productivity (Daanen et al., 2013). It may even cause premature death (Garssen et al., 2005). Exposure to heat in outdoor urban spaces causes thermal discomfort and affects the activity and behaviour of urban residents (Arnberger et al., 2017, Vanos, 2015, Van Hove et al., 2015). In order to solve existing urban climate problems and adapt to challenges induced by global warming and ongoing urbanization, careful climate-responsive design of outdoor urban spaces is needed.

1.3 Landscape architecture and climate-responsive design

The main purpose of the discipline of landscape architecture is the conscious shaping of the external environment (e.g., ECLAS, 2017). This external environment includes natural or cultural landscapes as well as outdoor spaces in urban environments (e.g., see definitions of landscape architecture by ECLAS, 2017, Evert et al., 2010). The latter, outdoor urban spaces, are the focus of this thesis. Following the definitions referred to above, outdoor urban spaces need to be planned, designed and maintained in a way that guarantees functional, beautiful, and sustainable spaces appropriate to the needs of residents, now and in the long-term. Landscape architectural design thus responds to two dimensions: the people's surroundings, that is the urban environment with its outdoor spaces, and people's perception of and behaviour in this environment (also see Deming and Swaffield, 2011, Van den Brink et al., 2017).

For this purpose the discipline of landscape architecture operates from two divisions, the academic and the professional division (Evert et al., 2010). The discipline has a long history of professional practice originating from park and garden design. Since the early 20th century, the increasing complexity of the landscape architect's assignments and activities has expanded the applied art and craft approach, and developed into a scholarly discipline (Van den Brink et al., 2017), able to respond to societal challenges such as global climate change and urban heat problems (Brown and Corry, 2011, Bruns et al., 2017), for instance through climate-responsive design.

'Climate-responsive' design has been conceptualized and used by scholars in different ways. Terms similar to 'climate-responsive' (e.g., Lenzholzer, 2010a, Lenzholzer and Brown, 2012) occur in literature to describe the conscious design of thermally comfortable outdoor places, for instance, 'climate-sensitive' design (Eliasson et al., 2007), 'microclimatic' design (Brown, 2011) or 'climate-conscious' design (Szkordilisz, 2016, Erell, 2008). The term 'climate-responsive' originates from energy-efficient architecture (e.g., De Schiller et al., 2006, Looman, 2017), and describes a specific interaction between a building and its thermal environment. A 'climate-responsive' building acts as an environmental filter: it excludes unwanted forces and admits the beneficial ones (Hastings, 1989 in: Looman, 2017). Likewise, in the context of landscape architecture, 'climate-responsive' outdoor spaces are designed in a way that ameliorates negative effects of the microclimate, and takes advantage of positive aspects to create thermally comfortable environments, in all seasons and in all possible future climates (Lenzholzer, 2010a, Lenzholzer and Brown, 2012, Brown, 2011, Eliasson et al., 2007).

Key for appropriate landscape architectural design in general (e.g., Brown and Corry, 2011, Nassauer and Opdam, 2008, Prominski, 2017, Bruns et al., 2017, Nassauer, 2012), and likewise for climate-responsive design (Brown, 2011, Eliasson et al., 2007, Lenzholzer and Brown, 2012), is the combination of two types of knowledge. On one hand, urban designers need situational knowledge of the respective location, and on the other hand, they need generic knowledge of a wide variety of background topics, for instance recreation, biodiversity or microclimate. This generic knowledge is needed to improve site-specific conditions, for instance to make places more recreational attractive, more diverse for flora and fauna, or – as is the subject of this thesis – more thermally comfortable.

In the context of climate-responsive design, it is important that the urban microclimate is characterised by strong spatial variability (e.g., Oke, 1989, Erell, 2008). Each urban space is unique in terms of thermal conditions. Without an understanding of the situational thermal conditions, designs can create inadvertent microclimate modifications that can make the situation worse. On the other hand, solely situational knowledge is insufficient to solve complex problems, such as climate change adaptation (Bruns et al., 2017). Therefore, next to situational knowledge, landscape architects need general knowledge on how to improve the urban microclimate and residents' thermal perception, for instance through implementing UGI. Here knowledge based on intuition or personal experience is not sufficient (Brown, 2011, Prominski, 2017). Solid, evidence-based information gathered through scholarly investigations, like micrometeorological measurements and observations, is needed to guide appropriate evidence-based, climate-responsive design (Brown, 2011, Brown and Gillespie, 2017).

Section 1.5 elucidates the available scientific microclimate knowledge on UGI; the following section describes the concept of UGI in more detail.

1.4 Urban green infrastructure

Green (i.e., vegetated) elements and spaces within urban environments are conceptualized in different ways. There is the concept of 'urban green spaces' (e.g., James et al., 2009, Fryd et al., 2011, Mathey et al., 2011) that distinguishes predominantly 'green' unsealed and permeable surfaces, from predominantly 'grey' hard and impermeable surfaces in urban environments. More widely used in policy (European Commission, 2013, European Environment Agency, 2010), academia (Tzoulas et al., 2007, Lovell and Taylor, 2013, Matthews et al., 2015) and planning and design professions (Landscape Institute, 2013, Rouse and Bunster-Ossa, 2013) is the concept of 'green infrastructure'. In literature, the concept of green infrastructure is theorized by a broad range of terms and definitions, that are used simultaneously (e.g., Lennon, 2014, Wright, 2011). Nonetheless, an often cited and, it seems, generally accepted definition is the one from the European Commission (2013): "Green Infrastructure can be broadly defined as a strategically planned network of high-quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and to protect biodiversity in both rural and urban settings."

Derived from the concept of 'green infrastructure', scholars who have focussed on the urban environment more recently have distinguished the concept of 'urban green infrastructure' or UGI (Young et al., 2014, Norton et al., 2015, Demuzere et al., 2014). Norton et al. (2015, p.128) define 'urban green infrastructure' as "the network of planned and unplanned green spaces, spanning both the public and private realms, and managed as an integrated system to provide a range of benefits. Urban green infrastructure can include remnant native vegetation, parks, private gardens, golf courses, street trees and more engineered options such as green roofs, green walls, biofilters and raingardens". Urban green infrastructure, more than green infrastructure, is seen as a hybrid of the green and the built environment (Demuzere et al., 2014, Rouse and Bunster-Ossa, 2013, Young et al., 2014).

Since this thesis focusses on urban climate-responsive design, I use the concept of urban green infrastructure (UGI) to describe a network of green (i.e., vegetated) urban elements and spaces in built environments at various spatial scales, spanning both the public and private realms, such as urban forests, parks, gardens, and street trees, all of which are designed and managed to provide ecosystem services, with a focus on microclimate regulation. From this perspective, the thesis focusses on vegetated green spaces, like urban parks and street greenery.

Urban green infrastructure provides ecosystem services in the built environment (e.g., Ahern, 2013, Tzoulas et al., 2007, Roy et al., 2012). One of these ecosystem services is the microclimate regulating capacity of UGI which has been increasingly recognized in recent years (e.g., Demuzere et al., 2014, Norton et al., 2015, Andersson et al., 2014, Fryd et al., 2011, Gill et al., 2007). To ensure the provision of ecosystem services, scholars point out the need for scientific knowledge that can inform appropriate UGI planning and design (Ahern, 2013, Nassauer and Opdam, 2008). Mathey et al. (2011, p.484) for example suggest, "At the city-district level and below, attention must be paid to the design, ensuring an optimal shape, structure of vegetation, function (use) and maintenance of individual green spaces to guarantee the provision of ecosystem services.". To know what 'optimal' shape, structure of vegetation, or function and maintenance of green spaces entails in the light of microclimate regulation, it is necessary to understand the actual microclimate functioning of UGI (Demuzere et al., 2014, Fryd et al., 2011, Oke, 1989). This functioning concerns UGI impacts on the urban microclimate and human thermal comfort at the various scale levels, from city to street level, according to scale levels used in planning and design.

1.5 Urban green infrastructure impacts on urban microclimate and human thermal comfort

1.5.1 Urban microclimate and human thermal comfort

Urban climate phenomena occur on various meteorological layers and scales (Oke, 1989, Oke, 2006), from mesoscale to microscale, and can be linked to UGI planning and design scale levels (Demuzere et al., 2014, Fryd et al., 2011, Norton et al., 2015) (Figure 1.1). Three vertical atmospheric layers and associated horizontal scales can be distinguished: the climate of a city at the mesoscale is affected by phenomena in the urban boundary layer. The urban boundary layer starts from the rooftop and treetop level and extends up to the point where cities no longer influence the atmosphere. The phenomena in the urban boundary layer are determined by the geographical location, the general configuration, and morphology of the city. An example is the atmospheric urban heat island (UHI), which encompasses that air temperatures in urban areas are normally higher than in rural areas (Howard, 1833, Oke, 1973). On the neighbourhood, or local scale, the topography and morphology of the urban environment, including surface cover, size and spacing of buildings, determines the mean climate of the neighbourhood. The associated atmospheric scales are the urban boundary layer and urban canopy layer. The latter is the atmospheric layer where people live, from the ground to below the tops of trees, roofs and other obstacles. On the street scale, the dimensions of individual buildings, trees, roads, streets, courtyards, gardens determine the urban microclimate in the urban canopy layer. This is the scale level at which people perceive outdoor microclimate phenomena, such as wind, sun, and shade. The microclimate is affected by the conditions and

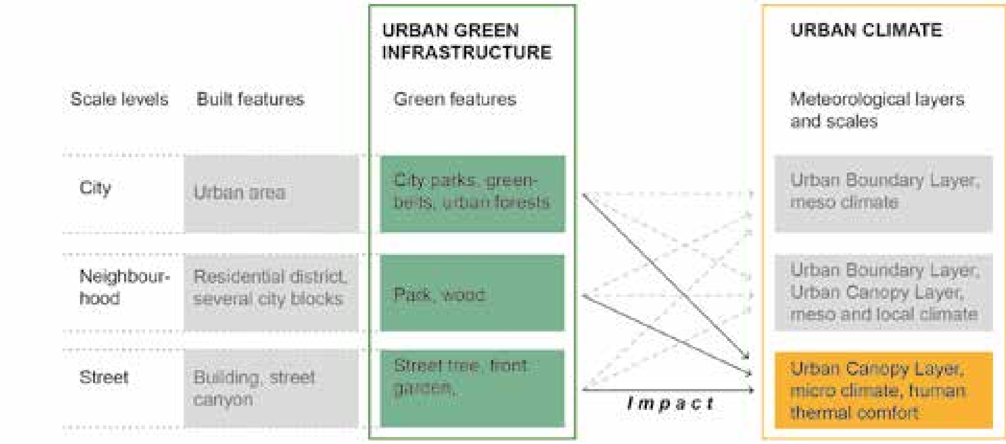


Figure 1.1: Scale levels of UGI and related meteorological layers, adapted from Oke (1989, 2006). The black arrows indicate the focus of this study

interactions at the mesoscale, and in turn, the microclimate can affect the mesoscale.

This thesis focuses on the microclimate scale and associated urban canopy layer (Figure 1.1). It is the atmospheric scale most relevant for urban design since thermal conditions and citizens' thermal perception are influenced (besides anthropogenic heat sources) by spatial characteristics of and interventions in built and green features (Brown and Gillespie, 1995, Eliasson et al., 2007, Oke, 1989, Oke, 2006, Brown, 2011). Built features include buildings and artificial, paved surfaces in street canyons or squares. Their spatial configuration determines the urban microclimate: the height to width ratio of street canyons and their orientation towards the sun regulates the amount of sunlight that is absorbed in street canyons (Ali-Toudert and Mayer, 2006, Herrmann and Matzarakis, 2012). The surface features, in particular the surface albedo, determines thermal emissions from buildings and other surfaces into the atmosphere, and the heat load within the street canyon (Lee et al., 2013, Shashua-Bar et al., 2012).

Green features, belonging to UGI, moderate microclimate conditions through shading and evapotranspiration (Bowler et al., 2010, Dimoudi and Nikolopoulou, 2003). Shading of tree canopies or other vertical vegetation reduces solar heat gains on buildings and surfaces and lowers surface temperatures, which in turn, reduces thermal emission from surfaces (Shashua-Bar and Hoffman, 2003). In addition, plant leaves use a part of the captured solar energy for the evaporation of water. This consumes energy that is no longer available to generate heat, leading to reductions in leaf canopy temperature and cooling or less warming of the surrounding air (Coutts et al., 2013, Dimoudi and Nikolopoulou, 2003). Therefore, this process is often referred to as 'latent cooling'. Similar to the way in which the spatial configuration of built features affects the urban microclimate, the level to which UGI moderates the microclimate is determined by spatial characteristics of UGI (e.g., size, dimension, distribution).

The microclimate scale is the scale of peoples' subjective perception and multisensory experiences. Perception here describes how a person consciously senses and experiences the urban environment, being the world 'out-there' (Jacobs, 2006). Besides views, noises or smells, people experience and sense thermal conditions in the urban environment (Lenzholzer, 2010a, Van Etteger, 2016) when they walk or spend time outdoors at any time of the day, in any season. Depending on individual aspects, such as age or gender, and on the specific location within the urban environment, people perceive thermal environments differently. For instance, one feels 'too hot' on a sunny site on a square with hard surfaces, whereas another person feels 'comfortable' at the same place. People's thermal experience thus depends on both objective and subjective components of the physical environment, which together have been conceptualized as 'thermal comfort'.

A classic definition of human 'thermal comfort' was established by Fanger (1970) for indoor environments. He defined 'thermal comfort' as the human satisfaction with its thermal environment, and developed the physiological index 'Predicted Mean Vote' or PMV (Fanger, 1972) to describe thermal comfort quantitatively. This concept was later adopted in outdoor thermal comfort studies, and other physiological indices followed, such as the 'Physiological Equivalent Temperature' or PET (Matzarakis et al., 1999). Studies that dealt with these indices included micrometeorological measurements of objective thermal conditions (air temperature or short- and long-wave radiation) related to human physiological responses.

Later, the concept 'thermal comfort' has been reviewed for its limited terminology and its narrowness concerning the subjective psychological and behavioural dimensions (e.g., Auliciems, 1981, Chen and Ng, 2012, Nikolopoulou, 2011, Nikolopoulou et al., 2001, Knez et al., 2009). Auliciems (1981) proposed a new term, 'thermal perception', which is a more neutral and inclusive term to describe the combined physiological and psychological influences. Additionally, the influence of behavioural aspects (physical adaptation) gained more importance. Adjustments to their own thermal conditions (clothing, location, level of activity) or in their thermal environment (creating shade by using a parasol) enable people to change their metabolic rate and improve their thermal perception (Nikolopoulou et al., 2001, Thorsson et al., 2004, Nikolopoulou, 2011).

Recent studies show a tendency towards a more holistic or comprehensive approach of thermal comfort, including objective components such as physical and physiological parameters and more subjective components such as psychological and behavioural parameters (e.g., Chen and Ng, 2012, Nikolopoulou, 2011, Vanos et al., 2010). This thesis applies such a comprehensive approach of thermal comfort (Figure 1.2). When subjective components, such as psychological or behavioural aspects, are considered, I use the term 'thermal perception' (that is, the perceived thermal comfort).

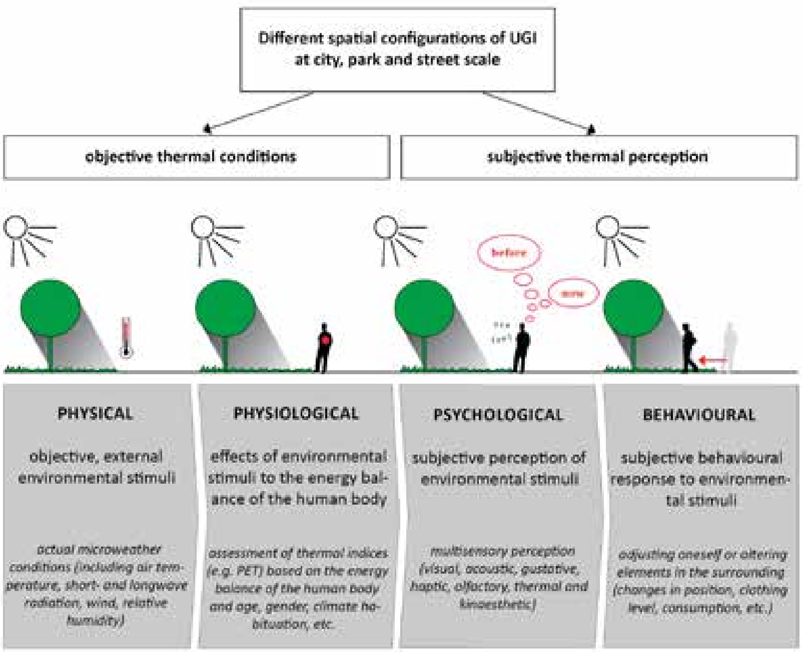


Figure 1.2: Components of thermal comfort in relation to UGI, adapted from Chen and Ng (2012) and Lenzholzer et al. (2018)

1.5.2 Urban green infrastructure impacts on objective thermal conditions

To date studies have focused on the objective impacts of UGI on thermal conditions. At city level, for instance, the green vegetation cover is considered an effective measure to mitigate urban heat islands (UHI) (Oke, 1987). In the Netherlands, Steeneveld et al. (2011) and Van Hove et al. (Van Hove et al., 2015) found a clear relationship between the UHI effect and the surface area covered by vegetation. Others demonstrated relationships between the vegetation fraction of cities and the surface UHI (Gill et al., 2007, Klok et al., 2012), and on nocturnal ambient urban temperature (Heusinkveld et al., 2014).

At the neighbourhood level, parks can be cooler than the built surrounding, and as such, provide thermally comfortable conditions for residents. This is shown in various studies (e.g., Bowler et al., 2010, Jamei et al., 2016), yet the number of field studies in moderate climates is limited. For parks, the daytime cooling effect on air temperature was, on average, 0.9 °C, at which the size of the park as well as the size of the tree canopy were determining factors (Bowler et al., 2010).

Urban green infrastructure impacts are increasingly recognised, especially at street level (e.g., Bowler et al., 2010, Jamei et al., 2016). Results of field measurements in moderate climates show air temperature (T_a) reductions of up to 1.7 °C under clustered, or large single tree canopies (Lee et al., 2013, Streiling and Matzarakis, 2003, Wang et al., 2015a, Gillner et al., 2015). In contrast, no significant reduction was found under smaller tree canopies (Armson et al., 2013). However, the physiological impact on pedestrians is greater because tree canopies reduce the radiation load on the body directly, and the radiation load of the surroundings through shade, and by lowering the mean radiant temperature (T_{mrt}). The reduction in T_{mrt} by large tree canopies can be substantial, up to 32.8 K (Lee et al., 2013, Streiling and Matzarakis, 2003), while smaller tree canopies still reduced T_{mrt} by 4 K (Armson et al., 2013).

1.5.3 Urban green infrastructure impacts on subjective thermal perception

While the physical benefits of UGI on thermal comfort are generally recognized, it is hard to predict how different UGI types influence subjective thermal perception. One psychological aspect that is related to the urban microclimate and that is believed to influence thermal perception is naturalness, which is referred to as 'the degree of artificiality of an environment' (Griffiths et al., 1987) or 'the degree of greening areas or vegetation views in landscapes' (Nikolopoulou and Steemers, 2003). Yet, there is limited scientific evidence that naturalness, or UGI in particular, relates to subjective thermal perception. At the neighbourhood level, Lenzholzer and van der Wulp (2010) suggest that green elements in squares are likely to improve thermal perception and aesthetic appreciation. Furthermore, Lafortezza et al. (2009) indicate that green urban spaces with shade and water are preferred urban outdoor spaces for recreation during warm summer periods. Other behavioural studies examine user preferences related to solar exposure in parks or squares (Kántor and Unger, 2010, Katzschner, 2004, Thorsson et al., 2004, Wang et al., 2017). No relevant studies on city or street level were found.

Independent of the thermal experience, naturalness and aesthetic appreciation are spatial characteristics of environments that influence people's perception and behavioural response (e.g., Hartig et al., 2014). People generally prefer natural (i.e., vegetated) to non-vegetated urban areas (Smardon, 1988, Ulrich, 1986). They visually appreciate vegetated environments for symbolic assigned values and sensory benefits. The latter include the experience of colours, or of the interplay of light and shadow, and the different layers of plants that enhance the sense of depth (Kaplan et al., 1998). Furthermore, aesthetic quality is also assigned to enhance outdoor activities in urban parks (Ward Thompson, 2013).

To summarise the overview above: UGI affects objective thermal conditions and subjective thermal perception. Most studies have focussed on physical impacts and were conducted outside the Netherlands. The impacts on thermal conditions and thermal perception were attributed to the spatial configuration of UGI: the aspects of street scale are spatially explicit, namely the size and shape (height and diameter) and the leaf density of tree crowns (Ali-Toudert and Mayer, 2007, Armson et al., 2013, Gillner et al., 2015). In contrast, the spatial aspects of city and neighbourhood scale are rather general: green fraction cover (Steeneveld et al., 2011, Van Hove et al., 2015), or size and tree canopy cover (Bowler et al., 2010), respectively. Regarding subjective thermal perception, the aspects of naturalness and aesthetic appreciation do have spatial connotations, but they are not distinct enough to guide design decisions. In their review, Bowler et al. (2010, p.147) conclude: "The current evidence base does not allow specific recommendations to be made on how best to incorporate greening into an urban area". To inform climate-responsive design of UGI, more spatially explicit knowledge of objective and subjective thermal impacts of UGI on the various scale levels is needed.

1.6 Need for useful design guidelines

Various scholars acknowledge that, to date, available scholarly knowledge on UGI microclimate functioning has hardly been incorporated in urban design practice (Norton et al., 2015, Fryd et al., 2011, James et al., 2009, Mathey et al., 2011). This is also true for more general scientific microclimate knowledge. Even though academics in the field of landscape architecture and other related fields widely acknowledge the need to incorporate scientific knowledge on microclimate functioning in design (e.g., Eliasson et al., 2007, Brown, 2011, Nikolopoulou and Steemers, 2003, Brown, 2010, Matthews et al., 2015, Erell, 2008, Lenzholzer, 2010a), climate-responsive design aspects are scarcely integrated into the practice of professional landscape architects.

Reasons for this shortcoming may differ: from the limited accessibility of scholarly evidence (Pijpers-van Esch, 2015, Prominski, 2017) to the limited prioritising on microclimate functioning in contrast to other functions that need to be integrated in design (De Schiller and Evans, 1996, Lenzholzer, 2010a, Mathey et al., 2011), or the limited understanding that practising designers have of the scientific knowledge of the microclimate (De Schiller and Evans, 1990). Clearly, there is an 'application gap' that hampers the translation of scientific urban climate knowledge related to UGI into useful knowledge for climate-responsive design in practice. The question arises: What type of knowledge of the microclimate regulating benefits of UGI can be useful, and contribute to enhancing climate-responsive design in the professional design practice?

The usefulness of scientific microclimate knowledge for design practice depends on three key criteria. Several authors emphasise that scientific knowledge of the microclimate should be presented in a way that is *comprehensible* for practising designers, ideally in a clear, graphic manner (Fryd et al., 2011, Eliasson, 2000, De Schiller and Evans, 1990). The knowledge should be *applicable*, easy to use in design processes (Brown and Corry, 2011, De Schiller and Evans, 1990, Eliasson, 2000, Lenzholzer, 2010a, Norton et al., 2015, Pijpers-van Esch, 2015). Also, the knowledge should be *feasible* in practice, since incorporating UGI spaces or elements into design often involves practical constraints. Those include implementation issues, such as the availability of land, space, property, or finances. Essentially, to be useful in design practice, scientific knowledge about UGI microclimate functioning should meet a set of criteria: be *comprehensible* to designers, be *applicable* to design processes, and be *feasible* to implement in practice. Assuming that scientific knowledge is useful in terms of comprehensibility, applicability and feasibility, the question remains: How should the 'informing' of urban design take place?

Various scholars consider design guidelines to be a possible tool with which to inform design practice. Design guidelines (Prominski, 2017), also referred to as (science) tools (Nassauer and Opdam, 2008) transfer key knowledge from science to design practice. Likewise, climate-responsive design guidelines (Lenzholzer, 2010a) or tools (Eliasson, 2000, Fryd et al., 2011) are needed to transfer microclimate knowledge of UGI into climate-responsive design practice. Even though the term 'design guidelines' (or related terms) frequently occurs in the professional and academic discipline, there are only a few scientific studies concerning definitions and methodology. Lenzholzer (2010a, p.120), for example, characterized guidelines as "easily applicable, 'pre-processed' scientific knowledge" that is "supposed to be applicable to many situations". Recently, Prominski (2017, p.194) stated that "a design guideline gives guidance for design action, meaning that it suggests a specific direction by excluding many other possible, and by implication, less suitable ones. A guideline also offers transferable knowledge because a principle is an abstraction (from a set of data or experiences) which works beyond a specific case to a more generalizable set of situations". Following these authors, and adding the criterion of usefulness in design practice, this thesis considers design guidelines to be a body of evidence-based, generally applicable knowledge that guides urban design actions in a variety of site-specific spatial and functional circumstances, and is considered useful by design professionals.

In the field of landscape architecture, little has been written about how to develop design guidelines based on scientific evidence. Prominski (2017) presents an approach to develop general design guidelines based on an analysis of multiple best-practice design projects, or based on a literature review of existing methods that respond to a certain problem. In Prominksi's approach, outcomes are subsequently abstracted into design guidelines which then are checked for their applicability in test-designs. In such an approach, the selection of best-practice projects/ studies is critical, and the established guidelines need regular updates in terms of new projects and theory.

Other than Prominski's approach, Nassauer and Opdam (2008), and similarly Brown and Corry (2011), present models where fundamental knowledge is the foundation for evidence-based design guidelines in landscape architecture. They suggest that scholarly evidence on underlying causes and impacts generated from methodically studied experiments or experiences in the field should be the basis for design guidelines in order to contribute to complex urban challenges. Both models integrate scientific knowledge from scientists, and practical knowledge from professionals to guarantee the usefulness of the design guidelines. Yet, studies that develop design guidelines based on fundamental knowledge are scarce. An early example is the research by Lenzholzer (2010a) who developed design guidelines for thermally comfortable squares based on micrometeorological measurements of squares, and interviews with pedestrians. She applied research outcomes in test designs using the microclimate model ENVI-met to generate general design guidelines for squares. Yet these guidelines were not tested for their usefulness for landscape architecture professionals in design practice. In the field of climate change adaptation, integrative processes between scientists and stakeholders are limited and remain at the academic margins (Groot et al., 2015).

The research framework of this thesis combines knowledge based on scientific research and knowledge of urban design practice to test and enhance the usefulness of evidence-based design guidelines in urban design practice. Similar to Lenzholzer's (2010a) approach, scientific evidence from site-specific investigations forms the basis for generally applicable design guidelines. The research framework of this thesis is extended: in order to enable the evidence-based guidelines to be applied in site-specific, climate-responsive urban design practice, the developed guidelines need to be tested and improved in terms of usefulness from the perspective of design practitioners. Therefore I involved potential end-users of the guidelines, for instance professional landscape architects, in the development process of the guidelines.

The challenges of developing evidence-based and useful design guidelines for climate-responsive UGI are posed by, first, the high spatial variability of the urban microclimate (e.g., Oke, 1989, Erell, 2008) and second, the knowledge gap between microclimate science and urban design practice (e.g., Eliasson, 2000, Lenzholzer, 2010a). Figure 1.3 illustrates the conceptual model for the development of generally applicable design guidelines for climate-responsive UGI in this thesis. The y-axis shows the range between site-specific knowledge in a particular real life context up to generally applicable knowledge, that in a later stage will be applied in various site-specific situations in real life contexts. The x-axis represents the different types of knowledge involved, ranging from scientific to practical design knowledge. The challenges in the development process of guidelines include (1) using site specific knowledge on UGI impacts gathered through fieldwork in real life urban environments to develop generally applicable knowledge, and (2) tuning this scientific knowledge with practical design knowledge to ensure its usefulness in design practice, and finally (3), implementing the evidence-based and useful guidelines, i.e., generally applicable knowledge, in site-specific real life contexts. The third challenge is

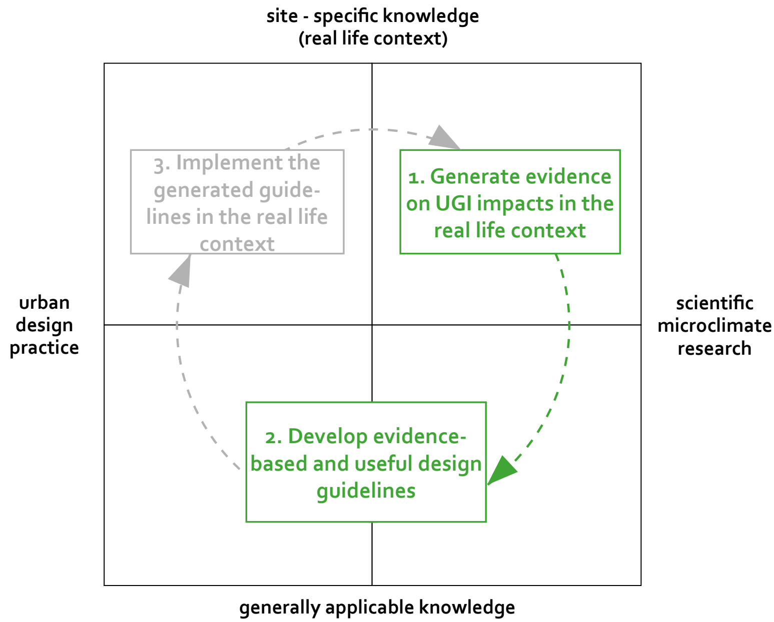


Figure 1.3: Conceptual model for the development of evidence-based and useful design guidelines for climate-responsive UGI (green features are part of this thesis; grey features are not included in this thesis)

not part of this thesis, but needs to be considered in order to ensure evidence-based climate-responsive design (Brown, 2011, Brown and Gillespie, 2017).

In order to link scientific research and design practice, this thesis involves both research inquiry and design activities. 'Research inquiry' here means conducting scholarly methodologies and methods and applying scholarly principles to gain new scientific evidence (Bruns et al., 2017). 'Designing' here refers to a creative, iterative and conscious/intentional process of giving form and meaning to elements and spaces at a range of scale levels to achieve desired outcomes (Lenzholzer et al., 2013, Motloch, 2001, Nassauer and Opdam, 2008, Nijhuis and Bobbink, 2012). The design activity needs to involve end-users of the guidelines from design practice, such as landscape architects and urban designers, to test the usefulness of the guidelines. 'Research through Designing' (RTD) (Lenzholzer et al., 2013) is a method that employs the activity of designing in research. It is a method used to generate and/or evaluate design guidelines and develop them further (Lenzholzer, 2010a, Prominski, 2017). To assess and ensure the usefulness of design guidelines for design practitioners especially, the 'participatory RTD' approach (Lenzholzer et al., 2013) might be valuable, because it is understood as a method to improve the ownership of knowledge and user commitment. However, the participatory RTD approach has not yet been used to test and enhance the practicality of scientific knowledge.

1.7 Knowledge gap and research questions

Urban green infrastructure (UGI) is generally acknowledged among scientists to moderate urban climate conditions on various scale levels, in particular on city, park, and street levels. To date, research has predominantly investigated objective impacts on thermal conditions: for example, at city level, the green fraction significantly influences air temperature (T_a). At park level, there is the park cooling island effect related to T_a. And at site or street level, tree canopies lower T_a and the mean radiant temperature (T_{mrt}), that impact the energy balance of the human body, expressed through the physiological equivalent temperature (PET). Those studies apply established scholarly methods, including in-situ micrometeorological measurements, and most have been conducted outside the Netherlands, in other countries with moderate climates.

Subjective aspects regarding thermo-spatial perception of UGI have been underrepresented in urban microclimate research. Few studies at the park level demonstrate that naturalness of the urban environment is a psychological factor that influences thermal perception and that people's behaviour is related to microclimatic conditions. Nevertheless, it is difficult to predict how different types of UGI influence people's subjective thermal perception, i.e., how a person senses and experiences physical thermal conditions in a vegetated as compared to a non-vegetated environment. This is particularly true for UGI on city and street levels and requires research on different scale levels.

The available scholarly knowledge on UGI has hardly had consequences for the current design practice. To date, landscape architects and other design professionals, who consciously shape urban environments, barely integrate the knowledge to enhance climate-responsive designing of UGI (Norton et al., 2015, Fryd et al., 2011, James et al., 2009, Mathey et al., 2011). What is missing in the available scientific body of knowledge is more spatially-explicit information relevant for the design of urban outdoor spaces (Bowler et al., 2010, Fryd et al., 2011). The spatial characteristics of UGI that determine its microclimate regulating functioning, for example green fraction, tree canopy cover, or naturalness, are too broad to inform site-specific design. To be more relevant for urban design practice, more spatially-explicit evidence regarding effects of UGI on thermal conditions and thermal perception are needed. Consequently, there is a demand for comprehensive approaches that focus on both objective and subjective aspects related to thermal perception (Chen and Ng, 2012), as well as for spatially and scale-explicit climate-regulating design aspects of UGI. In order to relate subjective thermal perception to objective microclimate conditions, UGI impacts on thermal conditions need to be explored more systematically.

In order to enhance the usefulness of such novel scientific evidence in urban design practice, integrated processes between scientists and stakeholders need to be established (Groot et al., 2015, Nassauer and Opdam, 2008). Microclimate knowledge needs to be tuned and melded with practical design knowledge so that the novel design guidelines are considered comprehensible, applicable in design and feasible in practice by urban design professionals. To this end research approaches have been described, that develop design guidelines based on fundamental research (Brown and Corry, 2011, Brown and Gillespie, 2017, Nassauer and Opdam, 2008) or that test this knowledge in participatory 'Research through Designing' (Lenzholzer et al., 2013). Yet, the practicality of these approaches needs to be confirmed.

This research set out to generate design guidelines for climate-responsive urban green infrastructure (UGI) at city, park and street level; guidelines that are based on scientific microclimate knowledge and are considered useful by urban design practitioners. It aims to answer the main research question: *What are useful, evidence-based design guidelines for climate-responsive urban green infrastructure (UGI)?* This research question is divided into the following sub-questions:

- *What is the impact of UGI on people's subjective thermal perception in relation to objective microclimate conditions?*
- *What is spatially explicit evidence regarding effects of UGI on thermal comfort?*
- *What are evidence-based and useful design guidelines for climate-responsive UGI and how can they be developed from the empirical evidence generated in this thesis?*

1.8 Research design

1.8.1 Epistemology

Bringing together knowledge from different scientific disciplines and design practice, I take a pragmatic perspective. Pragmatism, according to Creswell and Plano Clark (2011, p.41) is "pluralistic and oriented toward 'what works' in practice." It uses different worldviews and combines both objective and subjective knowledge to create a comprehensive understanding of a research problem and find solutions to this problem (Lenzholzer et al., 2013). I take a pragmatic perspective because this research is practice oriented; it aims to contribute to evidence-based solutions for designing climate-responsive UGI in design practice. For this purpose, this research links the scientific microclimate knowledge and design knowledge of practising landscape architects to advance the development of design guidelines. It is necessary to employ knowledge from multiple perspectives (Creswell, 2009), being different scientific disciplines, namely urban micrometeorology and landscape architecture, as well as knowledge from urban design practice. In linking science and practitioners' knowledge, researchers benefit from having expertise and experience in both research and practice (Van Kerkhoff, 2006). My expertise and experience in both the academic and professional field of landscape architecture, together with the newly gained microclimate knowledge enabled me to link different perspectives throughout this research.

The pragmatic worldview subsequently emphasises and / or combines different perspectives throughout this research (Figure 1.4). First, this research creates a broad understanding of thermal comfort related to UGI, encompassing objective, physical impacts of UGI on thermal conditions (post-positivistic knowledge) and subjective, thermo-spatial perception, including meanings, preferences, or behaviour of urban residents, related to UGI (social constructivist). Since this comprehensive knowledge is needed to inform future climate-responsive design, it is referred to as 'Research for Design' (Lenzholzer et al., 2013), an approach elaborated later in this section. Subsequently, the newly gathered scientific evidence of the first phase is linked to the perspective of practising landscape architects (the end-users). A participatory 'Research through Designing' (Lenzholzer et al., 2013) approach involved practical design settings in which participating landscape architects applied, tested, and evaluated the scientific evidence on its usefulness, which aimed at improving the ownership of the novel microclimate knowledge, and the user commitment of participants.

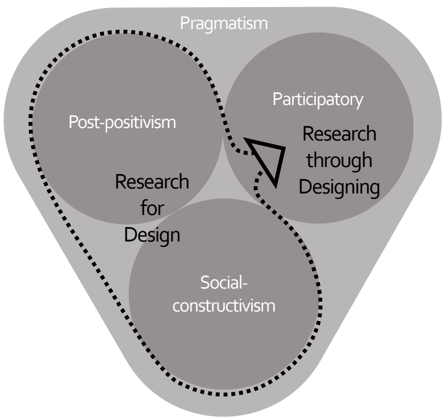


Figure 1.4: Linking worldviews in this research - based on Creswell (2009) and Creswell and Plano Clark (2011)

1.8.2 Methodology

In this thesis I applied a multiphase, mixed methods approach consisting of two independent, sequencing studies (Creswell and Plano Clark, 2011). First, a Research for Design study (Lenzholzer et al., 2013) encompassed a series of empirical studies conducted to answer the first two research sub-questions. Empirical research on the scale levels of city, park, and street, investigated the impacts of UGI on objective thermal conditions and subjective thermal perception. This Research for Design study resulted in novel scientific evidence on UGI related to thermal comfort that can inform urban design.

Subsequently, a participatory 'Research through Designing' (Lenzholzer et al., 2013) study was conducted to answer the third research sub-question. Here the novel scientific evidence was translated into preliminary design guidelines, and applied in practical design settings with landscape architects. An assessment of the usefulness of the preliminary guidelines in design practice made it possible to enhance the preliminary guidelines into revised design guidelines. Figure 1.5 illustrates the multiphase mixed methods approach of this thesis.

1.8.3 Research for Design

The Research for Design study was set up to gain novel scientific knowledge to substantiate climate-responsive designing in practice. The Research for Design approach allows knowledge to be gathered in order to improve the quality of objects and artefacts to be designed (Lenzholzer et al., 2013).

For this Research for Design micrometeorological and environmental psychological methods were chosen to study phenomena and perceptions in real life settings at three scales. The scale levels of field studies at city, park, and street level have been chosen to correspond with scales of urban meteorology (Oke, 1989, Oke, 2006) and urban planning and design (Demuzere et al., 2014, Fryd et al., 2011, Norton et al., 2015) (see Figure 1.1). The purpose is to match the scale of the new scientific knowledge with the scales in design practice. At each scale level, fieldwork was conducted in multiple cases to enhance the reliability of outcomes (Deming and Swaffield, 2011). The selected cases per scale level were based on criteria that allow for comparing and generalising outcomes for each scale level.

Common to all multi-scale cases is the mixed methods approach (Creswell and Plano Clark, 2011) which achieves a balanced overview

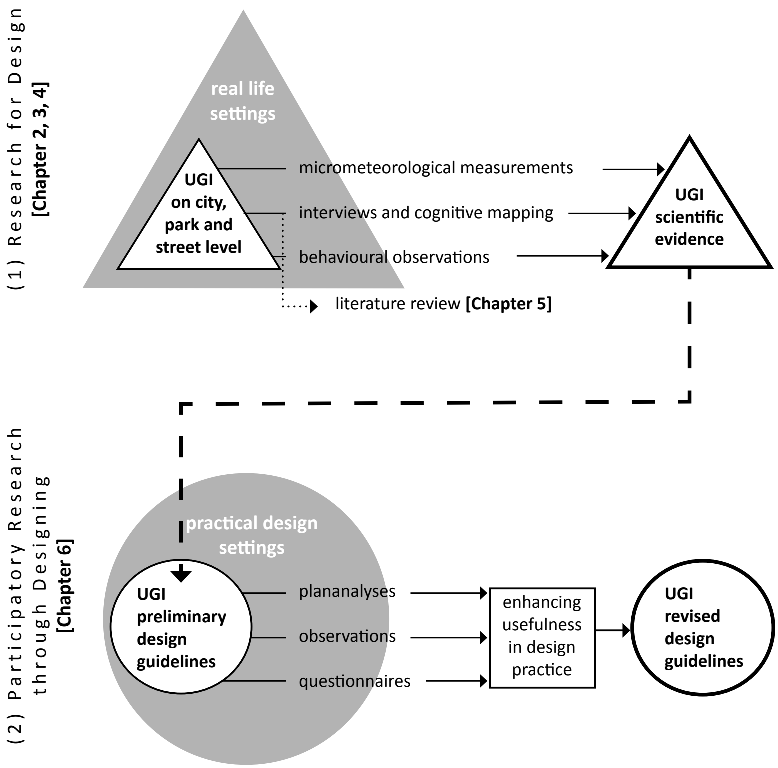


Figure 1.5: Overview multiphase mixed methods approach applied in this thesis

of both objective and subjective impacts of UGI on thermal comfort during warm summer periods. Quantitative methods predominantly deliver insights into objective thermal conditions, while qualitative methods bring about insights into subjective thermal perception and preferences (Lenzholzer et al., 2018). The quantitative methods applied in this thesis encompass mobile micrometeorological measurements (e.g., Heusinkveld et al., 2014) that collect data for various locations of interest, such as parks or street canyons, accompanied with the analyses of datasets gathered through nearby, rural meteorological reference stations. The qualitative methods used in this research include interviews with people in outdoor spaces on their subjective thermal perception (e.g., Eliasson et al., 2007, Thorsson et al., 2007a), including cognitive mapping techniques (Lenzholzer and Koh, 2010), and unobtrusive observations of park users on warm summer days (e.g., Nikolopoulou and Lykoudis, 2007, Kántor and Unger, 2010). Data collection and analysis in this mixed methods approach was conducted in a convergent parallel research design (Creswell and Plano Clark, 2011).

On each scale level two sets of data, a quantitative and a qualitative data set, were thoroughly collected and analysed. Afterwards the outcomes were related to each other in order to interpret the overall outcomes and get a balanced overview of the objective and subjective impacts of UGI on thermal perception on multiple scale levels. An overview of the Research for Design study is presented in Table 1.1, and briefly explained according to the scale levels below.

At city level (Chapter 2), two parallel studies examined residents' subjective thermal perception of various UGI types within a city, and the daytime cooling effects of large-scale UGI types, respectively. Finally, the results of both studies were compared. Interviews with randomly chosen pedestrians were conducted in three cities (Arnhem, Rotterdam, Utrecht) since subjective thermal perception might be sensitive to cities' spatial characteristics or cities' meteorological variances (e.g., maritime or continental). Mobile micrometeorological measurements were performed in the city of Utrecht for its spatial characteristics and for practical reasons. The compact city centre with a variety of different urban parks in the close vicinity allows for comparing measurements of thermal conditions in parks with those of the city centre and the open grassland outside the city in a short time period. Additionally, existing contacts with stakeholders who supported the fieldwork campaign (provision of data and facilities) were a practical reason.

At park level (Chapter 3), behavioural and psychological aspects of subjective thermal perception were investigated through unobtrusive observations of and interviews with resting park visitors, i.e., park visitors that were sitting or lying (as opposed to walking or moving). Results were related to datasets of meteorological reference stations. Two parks, one in the city of Utrecht and one in the city of Wageningen, were chosen as case studies for their similar spatial configurations, i.e., dimensions of open lawns, tree canopies and water surfaces, and the availability of data. In earlier studies, both parks appealed as cool spots in the cities during warm summer periods (Klemm et al., 2015a, Steeneveld et al., 2014), so it was interesting to find out how people use and value the spaces that were found thermally comfortable from the objective perspective of thermal comfort.

At street level (Chapter 4), the impact of street greenery on objective thermal conditions and subjective thermal perception as well as on aesthetic appreciation was studied. Interviews were conducted with randomly chosen pedestrians and mobile micrometeorological measurements were taken in nine streets in living environments. The streets chosen shared similar geometric configurations, namely: aspect ratio, materials, orientation, but had a varying amount of street greenery, including street trees and green front gardens. Representative sampling (Deming and Swaffield, 2011) resulted in three categories of cases: (1) streets without street greenery, (2) streets with street trees, and (3) streets with street trees and front gardens. This representative sampling helped to limit external factors of the built environment on thermal conditions and thermal perception, and focus on the impacts of street greenery in particular. The study was conducted in the city of Utrecht for the same practical reasons as the study on city level.

The Research for Design approach results in novel scientific evidence that can inform urban design: systematically collecting and analysing quantitative and qualitative data enabled me to relate subjective thermal perception to objective microclimate conditions, and subsequently answer the first research sub-question. Additionally, research results of both types of methods enabled me to comprehensively define spatially explicit characteristics of UGI that improve thermal comfort, and to answer the second research sub-question. Subsequently a literature review (Chapter 5) was conducted to reflect on and broaden the understanding of the applied qualitative research methods to study subjective thermal perception. This review focussed on studies that, similar to the mixed methods described above, investigated subjective and objective aspects of thermal perception in relation to the spatial perception of the environment.

1.8.4 Participatory 'Research through Designing'

To enhance the usefulness of the scientific evidence gathered in the Research for Design study, I conducted a participatory 'Research through Designing' (RTD) study (Chapter 6). This novel RTD approach that was described by Lenzholzer et al. (2013). There are no reports on the testing of this approach or on participatory approaches that combine fundamental knowledge and practical design knowledge to develop useful design guidelines. Because of the novelty of this approach, the participatory RTD study was explorative in character. This informed the choice of a qualitative in-depth study with a limited number of participants.

Table 1.1: Overview of the Research for Design field studies

Scale level	Research questions	Research methods	Study sites	Study period
CITY	**Objective impacts**: ▪ What are the physical thermal conditions in urban green spaces (T_a, T_{mrt}, PET) during warm summer days, and what are the dependences with spatial variables of specific sites?	Micrometeorological measurements using a cargo-bicycle equipped with meteorological sensors; Human thermal energy balance model Rayman	City of Utrecht,13 public parks with different spatial characteristics in close vicinity to city centre and rural surrounding	July/ August 2012
	Subjective impacts: ▪ How do people generally perceive green places in urban environments during warm summer days with respect to thermal conditions?	Surveys based on semi-structured questionnaires and cognitive maps with passers-by in outdoor urban spaces	Cities of Rotterdam, Utrecht and Arnhem	Summer 2011 and 2012
PARK	**Objective impacts**: ▪ How does extreme air temperature in summer influence daily park attendance? ▪ What are the user patterns related to solar exposure of resting park visitors on summer and tropical days? ▪ What are spatial typologies for optimal park use on summer and tropical days?	Unobtrusive observations of resting park visitors between 11:00 and 17:00, Analysis of meteorological data obtained from reference weather stations, GIS analysis	Two parks: Wilhelminapark (City of Utrecht) and Torckpark (City of Wageningen)	July/ August 2013
	Subjective impacts: ▪ What is the importance of microclimate on the spatial preferences of resting park visitors? ▪ What is the momentary thermal perception of resting park visitors on summer and tropical days?	Surveys based on semi-structured questionnaires among resting park visitors		

Scale level	Research questions	Research methods	Study sites	Study period
STREET	**Objective impacts**: ▪ What is the physical impact of street greenery (street trees and front gardens) on the parameters T_a and T_{mrt}?	Micrometeorological measurements using a cargo-bicycle equipped with meteorological sensors; Human thermal energy balance model Rayman	City of Utrecht, nine streets in close vicinity, three street types with similar spatial characteristics and varying amount of street greenery: (1) no greenery,	July/ August 2012
	Subjective impacts: ▪ What is the impact of street greenery (street trees and front gardens) on momentary and long-term thermal perception? ▪ How does momentary thermal perception relate to the evaluation of green street design (aesthetic appreciation)?	Surveys based on questionnaires with cognitive maps with passers-by in outdoor urban spaces	(2) street trees on both sides, (3) streets combined with street trees on both sides	June - September 2012

The newly gained microclimate knowledge, described in the chapters 2, 3 and 4, was used to formulate preliminary design guidelines. This step involved a translation of the scientific knowledge, which is communicated in technical language, into more practical knowledge, relevant for landscape architectural design. The preliminary design guidelines included more spatial and functional information than the previous scientific evidence. These preliminary design guidelines encompassed normative, generally applicable knowledge which – through applying the guidelines in real life design processes – should be transferable to various urban sites. Those preliminary design guidelines were tested in two case studies (Yin, 2009), being two design studios, one staffed with professional landscape architects, and the other with landscape architecture students. Both groups of participants represent the group of expected end-users of the design guidelines, and both had little to no experience in climate-responsive urban design. They applied the preliminary design guidelines in real-site design processes to test the usefulness of the evidenced-based guidelines in practice.

Typically, case study research is based on multiple methods and combinations of data sets to inform a phenomenon under study (Yin, 2009). This study used multiple methods to assess the usefulness, structured by the criteria of comprehensibility, applicability in design, and feasibility in practice of the preliminary design guidelines in the two case-studies. Observations of the design processes and plan analyses of the design results provide an understanding of how and to what extent the preliminary guidelines were implemented. Interviews with participants from the design studios provided additional in-depth insights into the participants' evaluation of the usefulness of the guidelines in terms of comprehensibility, applicability and feasibility. Those three datasets were analysed separately in a convergent parallel research design (Creswell and Plano Clark, 2011) in each case study. Afterwards results of both case studies were merged and interpreted to comprehensively assess and improve the usefulness of the preliminary design guidelines. This participatory RTD phase resulted in refined design guidelines for climate-responsive UGI that are considered to be useful by urban design practitioners and that can eventually be implemented in urban design practice.

1.9 Structure of the thesis

The general outline of this thesis is as follows: Chapters 2 to 5 represent the Research for Design study, encompassing the empirical field studies that comprehensively investigate impacts of UGI on subjective thermal perception and objective thermal conditions. Those chapters sequentially present the studies on the scale levels of city (Chapter 2), park (Chapter 3) and street (Chapter 4). Chapter 5 is a literature review that reflects on the qualitative methods used to study subjective thermo-spatial perception in outdoor urban spaces, such as applied in the previous chapters. Subsequently, Chapter 6 presents the participatory Research for Designing study in which the usefulness of the gathered evidence in Chapters 2 to 4 is tested and enhanced in practical design settings with future end-users. This chapter presents the evidence-based design guidelines for climate-responsive UGI developed in this thesis. The main body of this thesis – Chapters 2 to 6 – consists of five articles that were written as individual publications and that are all published in peer-reviewed journals. Some overlap between the chapters, in particular the introductions, therefore could not be avoided. Chapter 7, the final chapter, answers the research questions, discusses the contributions of this research to the academic and societal debate, and explores implications for future research and urban design practice. Table 1.2 presents an overview of chapters and articles.

Table 1.2 - Overview of chapters and articles

Chapter	Type of research/ scale levels	Title	Authors	Journal/ status
1	**Introduction**			
2	**'Research for Design' CITY LEVEL**	Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in The Netherlands.	Klemm, Heusinkveld Lenzholzer, Jakobs & Van Hove	*Building and Environment*, published 2015
3	**'Research for Design' PARK LEVEL**	Towards guidelines for designing parks of the future.	Klemm, Van Hove, Lenzholzer & Kramer	*Urban Forestry & Urban Greening*, published 2017
4	**'Research for Design' STREET LEVEL**	Street greenery and its physical and psychological impact on thermal comfort.	Klemm, Heusinkveld Lenzholzer & Van Hove	*Landscape and Urban Planning*, published 2015
5	**Methodological review**	Qualitative methods to explore thermal perception in outdoor urban spaces.	Lenzholzer, Klemm & Vasilikou	*Urban Climate*, published 2018
6	**Participatory 'Research through Designing'**	Development of green infrastructure design guidelines for urban climate adaptation.	Klemm, Lenzholzer & Van den Brink	*Journal of Landscape Architecture*, published 2017
7	**Conclusions and discussion**			

2 Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in the Netherlands

Klemm, W., Heusinkveld, B. G., Lenzholzer, S., Jacobs, M. H., Van Hove, B. (2015a). "Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in the Netherlands." *Building and Environment* 83: 120-128.

Abstract

Green infrastructure can improve thermal comfort in outdoor urban spaces in moderate climates. The impact of green spaces on thermal comfort is often exclusively investigated through meteorological variables and human-biometeorological indices. Yet, studies on perceived thermal comfort are scarce. As thermal comfort is a property of human perception of the thermal environment, this knowledge is crucial for understanding the relationship between green spaces and thermal comfort.

We investigated inhabitants' long-term perception of thermal comfort on warm summer days in three Dutch cities by means of questionnaires. Additionally, we examined the daytime cooling effect of green spaces in Utrecht, in order to find physical evidence to verify thermal comfort perception. To this end we used bicycles equipped with micrometeorological sensors. We compared thermal conditions of 13 parks with thermal conditions in the city centre and in the open grassland outside the city. And we analysed dependences between thermal conditions and spatial variables of parks (size, tree canopy, upwind vegetation cover).

Our results demonstrate that green infrastructure improves generally perceived thermal comfort. People evaluated green urban spaces as the most thermally comfortable spaces which was in line with the physical thermal investigations. Physiological equivalent temperature (PET) in parks on average was 1.9 K lower than in the city centre and 5 K lower than in the surrounding grasslands during the hottest period of the day. Thermal variance between parks was significantly influenced by tree canopy cover (mean radiant temperature $p = 0.00005$) and upwind vegetation cover (air temperature $p = 0.013$), not significantly for park size.

2.1 Introduction

The Netherlands has a temperate climate influenced by the North Sea, with moderate temperatures throughout the year. However, hot summer days in which temperatures rise above 30 °C, do occur and will occur more frequently in future due to climate change (Van den Hurk, 2006). Particularly in urban areas, this may have adverse consequences for human health and outdoor thermal comfort. In addition, future densification and extension of urban areas may further increase thermal discomfort and negative health impacts. The most vulnerable groups are elderly, young children and people with cardiovascular diseases (Haines et al., 2006, Huynen and Van Vliet, 2009). But also amongst other citizens sleep, the ability to concentrate and work productivity are affected (Daanen et al., 2013).

It has been demonstrated that green infrastructure within cities has the ability to effectively reduce heat and improve outdoor thermal comfort (Bowler et al., 2010, Dimoudi and Nikolopoulou, 2003, Gill et al., 2007, Heusinkveld et al., 2014, Steeneveld et al., 2011) besides other ecosystem services (Wang et al., 2014, Wolch et al., 2014). Urban green infrastructure is an accumulation of green elements and green spaces within the built environment (Gill et al., 2007, Heusinkveld et al., 2014, Steeneveld et al., 2011) which can be differentiated into various vegetation types (e.g., grass, trees, green facades, parks, urban forests) (Bowler et al., 2010, Dimoudi and Nikolopoulou, 2003). This study focusses on urban green spaces such as parks.

The impact of urban green spaces on thermal comfort during warm summer periods up to now was predominately studied from a physical perspective. Thermal comfort studies focused on meteorological variables and human-biometeorological indices that represent objective thermal conditions within the urban environment. Meteorological variables include air temperature (T_a), humidity, wind speed and short- and long-wave radiation, and the measurement or modelling of the mean radiant temperature (T_{mrt}). An often applied human-biometeorological index is the physiological equivalent temperature (PET), which is a measure of thermal comfort based on the energy balance of the human body (Matzarakis et al., 1999). T_{mrt} and PET are considered key human-biometeorological variables for outdoor thermal comfort during Central European weather conditions (Lee et al., 2013, Holst and Mayer, 2011).

Thermal performances of urban green spaces depend on certain spatial characteristics of the park itself and its built surrounding. Studies demonstrated an decrease of T_a along with an increase of size of parks (Bowler et al., 2010, Ren et al., 2013). Thermal comfort conditions were also improved through an increase of tree canopy cover within green spaces (Bowler et al., 2010) or within built environments (Ali-Toudert and Mayer, 2007, Klemm et al., 2013). Furthermore, the nocturnal urban temperature is affected by upwind land-use characteristics, most notably by vegetation cover within the upwind direction (Heusinkveld et al., 2014).

How people perceive thermal comfort related to urban green spaces depends on complex interactions of physical, physiological, behavioural and psychological factors (Chen and Ng, 2012). Particularly, the psychological impact of urban green spaces on people's perceived thermal comfort is yet a relatively unexplored domain of research. In general, ample evidence exists to demonstrate that urban green spaces is positively related to health and well-being (Kaplan and Kaplan, 1989, Ulrich, 1986, Hartig et al., 2014). Also, people generally prefer green compared to non-vegetated urban environments, on the basis of sensory (predominately visual) information and symbolically assigned values (Smardon, 1988, Ulrich, 1986).

A few studies have demonstrated that the perception of thermal comfort is related to naturalness, aesthetical appreciation and positive experience of the environment (Eliasson et al., 2007, Nikolopoulou, 2011, Nikolopoulou and Steemers, 2003). Other studies indicated that people's perceived thermal comfort is affected by their perception of spatial environments (Lenzholzer and Koh, 2010, Lenzholzer and Van der Wulp, 2010). Lenzholzer and Van der Wulp (2010) suggested that green spaces could improve perception of places and perceived thermal comfort. The question however remains how people actually perceive thermal comfort related to urban green spaces?

In this study we used an interdisciplinary approach to examine outdoor thermal comfort related to green spaces from a psychological and a physical perspective. Our study answered the following research questions:

1. *How do people generally perceive green places in urban environments during warm summer days with respect to thermal conditions?*
    a. *How do people evaluate the thermal comfort effect of green places?*
    b. *How do people experience thermal comfort in green compared to other places?*
    c. *Are green places more frequently preferred than other places when people seek thermal comfort?*
2. *What are the physical thermal comfort conditions in urban green spaces (during daytime on warm summer days) and what are the dependences with spatial variables of specific sites?*
    a. *To what extent differ air temperature (T_a), mean radiant temperature (T_{mrt}) and physiological equivalent temperature (PET) in urban parks from those in the city centre and open grassland outside the city during daytime, on warm summer days?*
    b. *What is the influence of (1) the size of urban green spaces, (2) the tree canopy cover inside green spaces and (3) the upwind land use characteristics of the built surrounding on physical thermal comfort conditions ?*
3. *Is the impact of green spaces on perceived thermal comfort consistent with the physical thermal environment?*

We aimed at gaining novel insights into the impact of urban green spaces on generally perceived thermal comfort on warm summer days. Additionally, we gathered evidence for the physical cooling effect of green spaces and its variance on city scale. Our study was conducted as part of the Dutch Climate Proof Cities program (Albers et al., 2014) contributing to develop strategies on urban climate adaptation in The Netherlands and other moderate climates.

2.2 Methods and materials

Our research design consisted of two separate studies, which are linked on a conceptual level. Study 1 investigated psychological impacts of urban green spaces on perceived thermal comfort through interviews. Study 2 examined physical thermal comfort conditions of green spaces compared to other urban locations within the city through micrometeorological measurements. We discussed both studies and compared their results to answer research question 3.

2.2.1 Psychological study

Background analysis

When contemplating the concept of perception (i.e., the conscious experience of the world 'out-there' (Jacobs, 2006)), it is important to make a distinction between momentary perception and general or long-term perception. Momentary perception is a mental state at a particular moment. For example, people can experience a particular place as thermally comfortable at a certain moment. General perception refers to a permanent mental disposition and psychological schemata. For example, people can perceive green places as thermally comfortable in general. General perception is constituted by repetitive patterns in momentary perceptions (Jacobs, 2006) and is thus influenced by characteristic events that become engrained in people's memory (Lenzholzer and Van der Wulp, 2010). If people repeatedly experience thermal comfort in green environments relative to non-green environments, this series of momentary perceptions accumulates into a general perception. Thus, people might infer a relationship between green elements and thermal comfort on the basis of recurring patterns in their experiences. This inferred relationship might become a general perception of green environments as being thermally comfortable. As momentary thermal comfort perception was addressed in previous research (Klemm et al., 2013), the present study focusses on general perception, as an attempt to seek complementary knowledge.

Variables

In order to operationalize the abstract concept (i.e., theoretical construct) of general perception of thermal comfort in green environments into psychological self-report measures (i.e., measures that use people's linguistic expressions as a proxy of their experiences or opinions), it needs to be translated into more concrete concepts. As indicated in the research questions 1a-b, we operationalized perceived thermal comfort in relation to green environments into three concepts: (1) evaluation of the thermal comfort effect of green environments, (2) generally experienced thermal comfort in different environment types, and (3) preferred thermal comfort places.

(1) The first concept is the evaluation of the thermal comfort effect of green environments: If people repeatedly experience green environments as thermally comfortable. We expect that this effect would be evaluated positively. For the measurement we used four different evaluative terms – nice, important, essential, and convenient. The specific wording was: "Please indicate to what extent you agree with the following statements: A green environment is nice [or important/ essential/convenient] for my thermal comfort on hot summer days." Responses were asked to indicate their agreement with each of the four statements on a five point scale with "disagree very much" and "agree very much" as the extreme options.

(2) The second concept is the generally experienced thermal comfort in different environment types. We expect that this generally experienced thermal comfort is larger in green places than in other places. We measured the experienced thermal comfort of three different environment types (green, water, built) by four terms for each type. Garden, rural area, forest, and park reflected green environments; swimming pool, beach, lake, and canal represented water environments, and shopping street, square, terrace, and parking lot suggested built environments. For each of these 12 items which were presented in random order, the question was: "Please indicate how thermally comfortable you feel on hot Summer days in each of the outdoor environments below." The five response options varied from "very uncomfortable" to "very comfortable".

(3) The third concept comprises preferred thermal comfort places. We expect that green places are more often preferred than other places if people were to seek thermal comfort. Places of thermal comfort

were mapped by asking respondents to indicate thermally comfortable places within the city on mental microclimatic maps. Mental maps were employed in outdoor thermal comfort studies before (Lenzholzer, 2008, Klemm et al., 2013). Of the 918 places that were indicated in all three cities, 182 places were outside of the cities, and were not considered for further analysis. On the basis of the main spatial characteristics we rated the places as green, water, or built environments using Google Earth. Another 62 places were mixtures of these types, and we thus excluded them from further analysis as well.

Study design

We conducted interviews during summer days in 2011 and 2012. As the general perception of thermal comfort in relation to green places might be sensitive to spatial characteristics (e.g., whether there is abundance or a lack of green places within a city) or to micrometeorological variances (e.g., maritime or continental), we did not confine the psychological study to just one city. We collected data in three cities in The Netherlands: Arnhem, Utrecht and Rotterdam. The cities are characterized by a population and a population density of respectively $151 \cdot 10^3$ and $1.5 \cdot 10^3$ km^{-2} in Arnhem, $330 \cdot 10^3$ and $3.3 \cdot 10^3$ km^{-2} in Utrecht and $619 \cdot 10^3$ and $1.9 \cdot 10^3$ km^{-2} in Rotterdam (CBS, 2014).

Interviewers were present at various places in these cities both on weekdays and during weekends. Interviewers approached passers-by with a request to participate in a study on perception of thermal conditions outdoors on warm summer days. Anonymity and confidentiality was ensured to the interviewees. In total, 559 questionnaires were completed (184 in Arnhem, 181 in Utrecht, and 194 in Rotterdam). The response rate was 31%. As people were approached on the street, many of them being under way to whatever commitment they had, we believe this is an acceptable rate.

Investigating general, i.e., long-term, preferences of thermal comfort was a challenging task as most of the respondents were not very conscious and acquainted with thermal comfort in general. Therefore, we educated all interviewers in advance in how to address respondents. For example, clear introductions to the interviews were important to help respondents understanding the questions in the correct way. Furthermore, even though our study focussed on thermal comfort on warm summer days, we were not able to conduct all interview on warm summer days due to time and actual weather limitations. Therefore, it was important to emphasise in the interviews that the questions related to warm summer weather conditions.

Analyses

We applied frequencies, means and standard deviations as descriptive statistics. Cronbach's alpha was used to assess the reliability across different items that were intended to measure the same concept. The reliability analyses showed that all alphas were larger than .65 (Appendix A), which is the generally an accepted cut-off point for considering scales as adequately reliable (Vaske, 2008). In practical terms, this means that the responses to the items that describe a concept were reasonably consistent. Deleting any item did not increase any of the alphas, and the item-total correlations also suggest that all items could be retained. For all of these reasons, we computed indices, as the average of the four items, for each concept. The indices were used for further analyses.

T-tests were employed for pair-wise comparisons of experienced thermal comfort across different environments. All analyses were carried out with SPSS 19.

2.2.2 Physical study

The study area

The physical study was conducted in the city of Utrecht, which is the fourth largest city of the Netherlands and characterized by a mild mid-latitude climate (Köppen climate classification Cfb). Within Utrecht we selected 13 green urban areas, the old city centre (defined by the old fortifications channel) and an open grassland just outside the north-eastern side of the city as specific case study areas (Figure 2.1).

Micrometeorological measurements

We conducted micrometeorological measurements using two cargo-bicycles equipped with meteorological sensor for mapping the urban thermal environment on a pedestrian level. The cargo-bicycles were employed in previous thermal comfort studies in the Netherlands (Heusinkveld et al., 2010, Heusinkveld et al., 2014, Klemm et al., 2013). The fixed bicycle routes existed of three single loops through the whole city which started and ended in the city centre. The three loops covered 13 parks of various sizes, the city centre and an open grassland just outside the north-eastern side of the city (Figure 2.1). Micrometeorological data from a the rural weather station KNMI in De Bilt (KNMI, 2013), in a distance of about 4 km to the city centre of Utrecht, served as reference data.

The bicycles were equipped with a shielded thermometer, a humidity sensor, a 2-dimensional sonic anemometer and 12 radiation sensors to measure solar radiation and thermal infrared radiation exchange from six directions. The sensors recorded data for every second which we combined with location data from a GPS device. Wind speed measurements were corrected for bicycling speed. For detailed information about instruments we refer to the study of Heusinkveld et al. (Heusinkveld et al., 2014).

We conducted mobile measurements one two days in July and August 2012. On July 24th 2012, we conducted continuous mobile measurements from midnight until 20:00 (UTC time). On August 18th 2012) we conducted random measurements for parts of the whole route to test the reliability of the results of July 24th 2012.

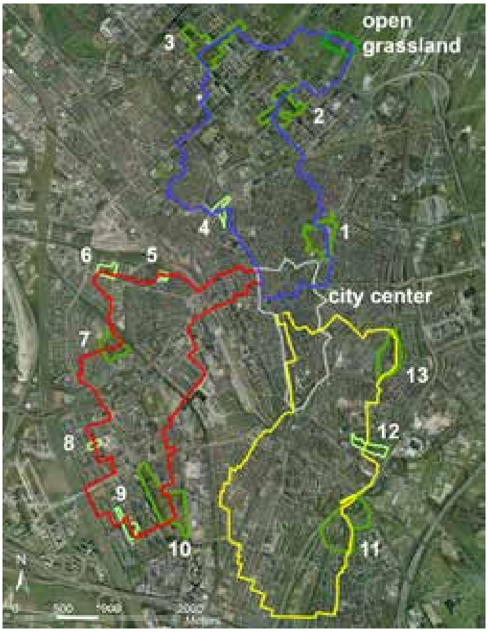


Figure 2.1: Location of bicycle loops (included 13 parks, city centre and open grassland outside the city) in Utrecht, the Netherlands (yellow, blue and red = bicycle routes, green = green spaces, white = city centre)(Aerial photograph by Google Earth)

Analysis of micrometeorological data

To acquire insights into variance and distribution of thermal conditions between parks, city centre and open grassland outside the city we used the data between 9:00-19:00 UTC. This timeframe covers the period of the most intensive use of outdoor open spaces by citizens during summer time. Based on the measurement data of T_a, humidity, wind speed, solar and thermal radiation we calculated T_{mrt} and used the human thermal energy balance model Rayman (Matzarakis et al., 2007) to calculate PET. Then we compared the average values and the variance of all T_a, T_{mrt} and PET measurements of the green spaces to those from the city centre and the open grassland. We chose the open grassland outside the city as our reference location.

To indicate the daily temperature cycle of the open grassland outside the city we used a third order polynomial function through all measurements the open grassland of July, 24^{th} 2012. It appeared that this function reproduced the daytime temperature cycle (T_a) of the nearby rural weather station (KNMI, De Bilt) between 9:00-19:00 UTC well (Appendix B). The T_{mrt} and PET measurement data of the open grassland outside the city was used to compile functions in the same way (Appendices C and D).

We defined the period of 12:00-17:00 UTC as a specific period to compare thermal performances between parks, city centre and open grassland. We chose this period as nearly all areas had measurement data in this period and as it represents the hottest period of the day based on the PET cycle of the undisturbed open grassland outside the city 12:00-17:00 UTC (Appendix E, particularly panel open grassland).

As the measurements were not time synchronised for all locations, they could not be compared directly. We therefore calculated the T_a, T_{mrt} and PET statistics (average and maximum) from the third order polynomial functions for all investigated individual parks, the city centre and the open grassland (Appendix E). We calculated T_a, T_{mrt} and PET intervals of 10 minutes and calculated averages between 12:00-17:00 UTC. It appeared useful to analyse averaged values based on intervals rather than single maximum values of the daily circle. Averaged values refer better to the individual temporal thermal differences (asymmetry) than single maximum values which, furthermore, occur in various parks in various moments in time (Appendix E).

Finally, we checked the measurement results of August 18^{th} 2012 and compared the compatibility with the results of July 24^{th} 2012.

2

Analysis of spatial variables of urban green spaces in Utrecht

In order to describe the spatial characteristics of the 13 parks, we analysed size, tree canopy cover and upwind land use characteristics of all parks. To relate those spatial variables to micrometeorological conditions we analysed the entire parks and a limited area around the bicycle track to confirm that the spatial characteristics along the bicycle tracks were representative of the entire parks. We defined those limited areas as strips of 100 m wide along the bicycle routes exclusively inside the green spaces (Figure 2.2, Appendix F for all 13 parks).

We measured the size of entire parks and strips along the bicycle track using topographical maps (Top10 data by Karthografische Dienst, the Netherlands) and aerial photographs (Bing maps). To define the tree canopy cover we used a tree canopy dataset from Utrecht (Clement, 2013, Rafiee, 2013). To calculate the upwind land use characteristics we used the method described by Heusinkveld et al. (Heusinkveld et al., 2014). We defined the upwind area as a pie-shaped area between 75 and 210 degrees around the average wind direction from 142 degrees with a length of 700 m and the origin at the centre of the parks (centroid). We carried out these analyses in ArcGIS 10.1.

Figure 2.2: Exemplary analysis of spatial variables size and tree canopy cover of the Griftpark in Utrecht, the Netherlands (Aerial photograph Bing maps)

The representativeness study showed strong correlations between the spatial variables of entire parks and strips along the bicycle route (Table 2.1). The correlation was 0.90 for the variable size, 0.89 for the variable fraction of tree canopy cover and 0.99 for the variable upwind land use characteristics. As the strips are good representations of the spatial characteristics of the entire parks, we used the park characteristics for further analyses.

To relate the spatial variables to the measured biometeorological parameters of the green urban areas we applied ANOVA regression analysis (Excel).

Table 2.1: Comparison of spatial variables of 13 investigated parks in Utrecht, the Netherlands related to a strip of 50 m along the bicycle track in each park

		Park			**Strip 100 m along bicycle track**		
		Area	**Fraction of tree canopy cover**	**Upwind vegetation land cover fraction**	**Area**	**Fraction of tree canopy cover**	**Upwind vegetation land cover fraction**
	NAME	**[ha]**	**[-]**	**[-]**	**[ha]**	**[-]**	**[-]**
1	**Griftpark**	10.89	0.15	0.29	4.10	0.23	0.29
2	**Park De Watertoren**	13.43	0.47	0.46	5.67	0.58	0.48
3	**Park De Gagel**	16.34	0.49	0.49	5.34	0.46	0.50
4	**Noordse Park**	2.81	0.43	0.26	1.31	0.31	0.26
5	**HJ Schimmelplein**	0.93	0.54	0.25	0.71	0.66	0.25
6	**Majellapark**	3.02	0.45	0.31	1.95	0.48	0.31
7	**Park Oog in al**	5.46	0.65	0.48	2.57	0.67	0.46
8	**Park Bevinlaan**	1.09	0.38	0.38	0.67	0.32	0.38
9	**Park Columbuslaan**	4.80	0.39	0.46	3.19	0.32	0.45
10	**Park Transwijk**	18.27	0.51	0.45	8.75	0.46	0.48
11	**Beatrixpark**	22.08	0.48	0.54	6.01	0.55	0.55
12	**Park Prinsenbrug**	5.00	0.64	0.59	0.82	0.85	0.60
13	**Wilhelminapark**	10.36	0.70	0.44	5.41	0.82	0.44

2.3 Results and discussion

2.3.1 Psychological study

People generally perceived urban green spaces as thermally comfortable. This main finding was consistent across three tested concepts. (1) The respondents evaluated green environments as having a positive thermal comfort effect on warm summer days. The mean of this item was .82, which is close to the "agree" option. (2) Green environments were rated as thermally comfortable (i.e., .99 corresponds with comfortable on the scale (Table 2.2). Water environments were rated as almost equally comfortable as green environments. Built environments were rated approximately neutral with respect to thermal comfort.

Table 2.2: Generally perceived thermal comfort in different urban environment types (green, built, water)

Index – Experienced thermal comfort	Mean	Standard deviation
Green environment[1]	.99	.55
Built environment[1]	-.15	.72
Water environment[1]	.85	.69

[1] Responses coded on a five-point scale from very uncomfortable (-2) to very comfortable (+2)

Thus, the experienced comfort of green environments was larger than the experienced comfort of built environments. The difference was statistically significant ($p < .001$), and the effect size was very large ($d = 1.78$, which is statistically equivalent to a correlation of .66) (Table 2.3). This means that a large portion of the variance of generally perceived thermal comfort is explained by the type of environment (green versus built in this case). This finding confirms earlier studies pointing out that general perceived thermal comfort is affected by their perception of the spatial environment (Lenzholzer and Koh, 2010, Lenzholzer and Van der Wulp, 2010).

Similarly, the perceived thermal comfort difference between water and built environments was significant with a large effect size. The difference between green and water environments was relatively small, yet statistically significant as well (Table 2.3). Thus, green environments were even perceived as more thermally comfortable than water environments.

(3) Of the 672 specific places that were indicated as thermally comfortable on hot summer days, 59.4% was a green environment, 25.4 was a water environment, and 15.2% was a built environment (Table 2.4).

Table 2.3: Differences of generally perceived thermal comfort between urban environment types

Contrast	Mean difference	Test statistic: t-value	Significance: p-value	Effect size: Cohen's d
Green versus built	1.14	34.31	<.001	1.78 (*r* = .66)
Green versus water	.14	4.68	<.001	.22 (*r* = .11)
Water versus built	1.01	34.22	<.001	1.42 (*r* = .58)

Table 2.4: Preferred thermal comfort places in urban environments

Environment type	Times mentioned	Test statistic: t-value[1]	Significance: p-value	Effect size: Cohen's d
Green	399 (59.4%)	13.74	<.001	1.06 (*r* = .47)
Water	171 (25.4%)	-4.68	<.001	-.37 (*r* = .18)
Built	102 (15.2%)	-13.11	<.001	-1.01 (*r* = .45)
Total	672 (100%)	-	-	-

[1] The number of times each environment type was mentioned, was tested against the expected number if the preferences were not different across environment types (i.e., 672/3 = 224).

For the green environment, this figure is significantly larger than the expected value if the preferences did not differ across environments. In contrast, the results are significantly smaller for the other environments. These results indicate that most people prefer a green urban environment over another urban environment for thermal comfort.

We performed the same analyses for each individual city. These results mirror the same pattern of results. Hence, regardless of the city, people generally perceive green environments as thermally comfortable. Our results emphasize the beneficial role of vegetation in the perception of the urban environment, as they demonstrate a positive influence of green spaces on perceived thermal comfort in addition to the positive influence on health and well-being in general (Kaplan and Kaplan, 1989, Ulrich, 1986, Hartig et al., 2014).

2.3.2 Physical study

The micrometeorological measurements days (July 24th and August 18th 2012) showed similar fair weather conditions without cloud cover nor changing weather conditions. All measurement days showed warmer conditions compared to normal values in this period (Table 2.5).

Table 2.5: Urban climate conditions during the micrometeorological measurement days in July and August 2012 in Utrecht, the Netherlands (KNMI, 2013)

Dates | Urban climate conditions	Daily actual rel. duration of sunshine [%]	Daily normal rel. duration of sunshine [%]	T_a max 9-18 UTC	T_a 9-18 UTC	Wind direction 9-18 UTC [deviation]	Wind speed 9-18 UTC
24-07-2012	92	41	28.8	27.3	141.4 [36.3]	2.2
18-08-2012	78	43	32.0	29.8	157.1 [10.0]	3.4

Air temperature (T_a)
Our results demonstrate that the examined parks are cool islands within the urban area. The measured air temperatures (T_a) were lower than those in the city centre and comparable to those measured above open grassland in the surrounding rural area. Throughout the hottest period of the day, parks were on average 0.8 K cooler than the city centre and 0.3 K warmer than the grassland outside the city (Table 2.6). This is due to evapotranspiration of vegetation, the low fractions of hard surfaces and, in consequence, lower surface temperatures and long wave radiation from surfaces in parks and the open grassland outside the city. The measured cooling effect of parks is in line with earlier studies; Bowler et al. (2010) found a cooling effect of parks during daytime of 0.94 K for T_a based on a meta-analysis of 16 micrometeorological studies.

The difference in maximum air temperature ($T_{a\ max}$) between city centre and individual parks varied from 0.3 K to 1.5 K (Appendix E). This was lower than the 4 K difference measured in an earlier study in Rotterdam (Heusinkveld et al., 2014). The smaller difference is due the fact that maximum values presented here were derived based on a third order polynomial fit function of all measurement points. Moreover, in this study we present area averaged values for certain areas.

Table 2.6: Average and daily maximum T_a, T_{mrt} and PET values in 13 investigated parks, the city centre and above open grassland outside the city based on third order polynomial fit function of all measurement points on July 24th 2012 (12:00-17:00 UTC) in Utrecht, the Netherlands

	Average 12:00-17:00 UTC			Daily max		
	T_a [C°]	T_{mrt} [C°]	PET [C°]	T_a [C°]	T_{mrt} [C°]	PET [C°]
13 parks	27.4	42.7	32.3	27.7	46.4	34.0
City centre	28.2	44.4	34.2	28.5	47.6	35.1
Open grassland outside the city	27.1	56.3	37.3	27.5	60.0	39.2

Our results show a wide variation in ambient thermal conditions, both between different parks and inside individual parks. On average T_a varied up to 2 K between different parks and about 0.25 K (= error bar) inside parks (Figure 2.3, Appendix B). The variance in T_a between different parks is related to upwind land use characteristics (Table 1.1). For example, the low T_a values in the Beatrixpark can be explained by the high fraction of vegetation in the urban upwind area (0.52). In contrast, the Griftpark showed weak T_a performances due to low vegetation cover in the upwind urban area (0.29).

It is notable, that T_a between 12:00 to 14:00 UTC of the city centre is similar to that of the so-called rural weather station 4 km outside the city (Appendix K, top panel). This was observed during the first day, not during the second day. This suggests that the official rural WMO station in De Bilt is influenced by the urban surrounding. Similar observations, also related to other rural weather stations, have been reported by others (Heusinkveld et al., 2014, Van Weverberg et al., 2008, Brandsma and Wolters, 2012).

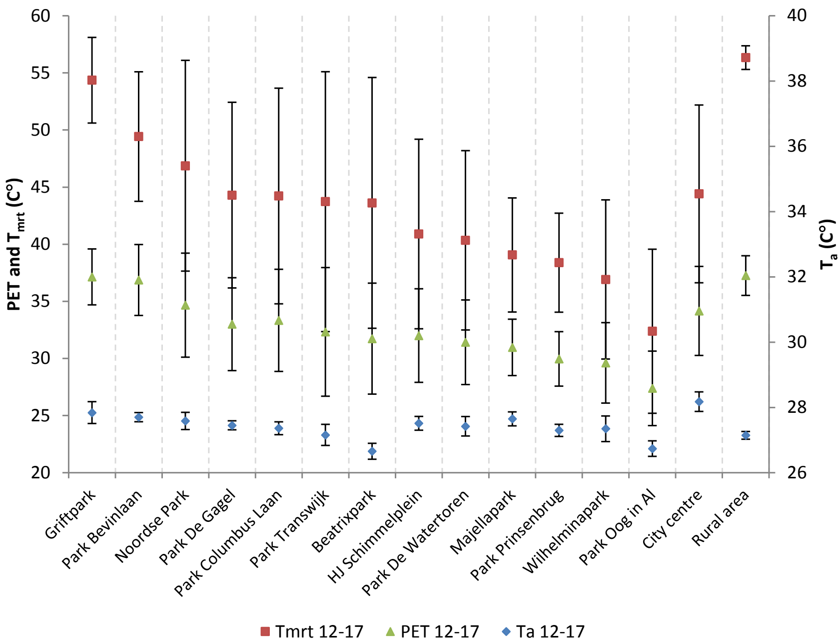


Figure 2.3: Averaged T_a, T_{mrt} and PET values of 13 parks and the city centre compared to the open grassland outside the city. Error bars represent average standard deviation of all individual measurements. On July 24th 2012, 12:00–17:00, in Utrecht, the Netherlands

Mean radiant temperature (T_{mrt}) and physiological equivalent temperature (PET)

During daytime T_{mrt} and PET in parks are on average 13.6 K and 5 K respectively lower than in the surrounding rural area, and 1.7 K and 1.9 K respectively lower than in the city centre (Table 2.6). The difference in T_{mrt} between built and green spaces found here is similar to earlier studies in the city of Utrecht. Klemm et al. (2013) found an average cooling effect in streets with large street trees of 2.5 K compared to non-vegetated streets related to T_{mrt}. Hence, green spaces, like parks are the most thermally comfortable outdoor space from a physical perspective. The smaller differences of T_{mrt} and PET values between parks and the city centre compared to the open grassland outside the city can be explained by shading effects. In the city centre there is either the shading of buildings or (street) trees, in parks there is shading of trees.

Figure 2.3 (and Appendices C and D) illustrates that values of T_{mrt} and PET strongly varied between parks during the hottest period of the day (up to 22 K for T_{mrt} and 10 K for PET). It is a consequence of varying spatial set-ups of parks, especially the present amount of tree canopy cover (Table 2.1).

The distribution of T_{mrt} or PET within the investigated parks is represented by the error bars in Figure 2.3, which illustrate the varying shade and sun patterns, defined by the different spatial set-ups. A park with rather monotonous set-up (Griftpark) has a lower variance than park with diverse spaces (Park Transwijk), 3.75 K compared to 11.38 K. The variance in T_{mrt} of all parks (7.55 K) is similar to that of the city centre (7.78 K). In contrast, a much smaller variance is found (1.04 K) for the open grassland outside the city as it represents a monotonous open space.

As compared to all investigated parks, Griftpark (Figure 2.3) shows the lowest thermal comfort conditions. Relatively high values for T_a, T_{mrt} and PET are obtained. In addition, the park has a small spatial variation in microclimate that is even smaller than in city centre. This would imply that citizens do not have many thermal choices in this park. After all, variance in microclimates is an important requirement for improving personal thermal comfort by changing places, e.g., seeking shade or sun (Nikolopoulou et al., 2001, Thorsson et al., 2004).

The results described above are in accordance with results of the random measurements on August 18th 2012. As the data in August is limited, we could not repeat the same thorough analysis as in July.

We consider the data valuable as the parks show similar thermal performances compared to city centre and open grassland outside the rural area in July and August 2012 (Appendix K). The data suggests that our results are valid through the whole summer period, even though the relative duration of sunshine in August is lower than in July (Table 2.5).

Dependence of thermal conditions of green urban areas on spatial variables

Thermal conditions in parks were significantly influenced by tree canopy cover and upwind vegetation cover. However, we found no significant relationship with park size at a confidence level of 0.05 (Appendix J). T_{mrt} and PET appeared to be significantly related to tree canopy cover ($p < 0.001$) (Table 2.7, Appendix H). 10% tree cover in a park lowers T_{mrt} about 3.2 K and PET about 1.5 K.

The upwind vegetation cover has a significant influence ($p = 0{,}012$) on T_a (Table 2.7, Appendix I). Based on our results and those of earlier studies focussing on nocturnal urban temperatures (Heusinkveld et al., 2014) we can conclude that upwind vegetation cover significantly influences thermal conditions in parks. Our insights suggest that parks do not only influence their built surrounding, the so called Park Cooling Island (PCI) effect (Spronken-Smith and Oke, 1998), but that the built surrounding in turn also influences thermal conditions of parks. This fact emphasises the need of implementing urban green spaces on various scale levels in cities.

Table 2.7: Relationship between maximum values of air temperature (T_a), mean radiant temperature (T_{mrt}), physiological equivalent temperature (PET) on July 24th 2012 (12:00–17:00 UTC) in Utrecht, the Netherlands and spatial variables of the investigated parks

	Spatial variables of the parks		**Spatial variable of the upwind urban area of the parks**
	Size	**Tree canopy cover**	**Vegetation land cover fraction**
T_a **Standard Error/ p**	0.31 / 0.099	0.30/ 0.047	0.27/ 0.012
T_{mrt} **Standard Error/ p**	-	2.74/ 0.00005	-
PET **Standard Error/ p**	-	1.45/ 0.0001	-

2.4 Conclusion

Urban green spaces improve thermal comfort in physical as well as in psychological terms, as our interdisciplinary study on the impact of urban parks on thermal comfort demonstrates. Answering our first research question, results of our psychological study prove that people generally perceive green urban environments as thermally comfortable. Our results confirm this proposition as our findings were consistent across the parameters; (1) the evaluation of the thermal comfort effect of green places was positive, (2) the experienced thermal comfort of green environments was larger than the experienced comfort of water and built environments, and (3) green environments were more often preferred for thermal comfort than other environments. Also, the measures of the parameters were reliable. In addition, the findings were stable across the cities of Utrecht, Rotterdam and Arnhem.

This psychological study focused on general (i.e., long-term), preferences of thermal comfort rather than description of actual sensation and behaviour related to thermal comfort conditions. We demonstrated that a large portion of the variance of general preferences of thermal comfort can be explained by spatial characteristics of the environment. This implies that people's perception of thermal comfort could be increased by creating urban green spaces. This is in line with earlier findings on momentary perception of thermal comfort demonstrating a significant dependence with the present amount of green spaces (Klemm et al., 2013, Lenzholzer and Van der Wulp, 2010). Yet, we do not know the influence of urban green spaces on the actual behaviour of citizens; we therefore recommend further research on this topic.

Answering the second research question, results of our physical study show that green spaces are cool islands within the city. Our results are based on micrometeorological measurements in 13 parks, the city centre and the open grassland outside the city of Utrecht. On average green spaces were characterized by PET values 1.9 K lower than the city centre and 5 K lower than the open grassland outside the city indicating the best physical thermal comfort conditions. The thermal conditions in green spaces were mainly based on T_a values comparable to the open grassland and 1 K lower than the city centre and the T_{mrt} values 2.5 K lower than the city centre and 12 K lower than the open grassland.

Thermal variance between parks was significantly influenced by tree canopy cover (T_{mrt} p = 0.00005) and upwind vegetation cover (T_a p = 0.013), not significantly for park size. We want to point out the marked influence of upwind vegetation cover on green spaces; it shows that the built surrounding also influences thermal conditions of green spaces. This emphasises even more that green infrastructure should be implemented on various scale levels; as the accumulated effect of all green elements and green spaces contributes physically to improved thermal conditions in urban environments.

Answering the third research question, our results confirm that the impact of green spaces on perceived thermal comfort is consistent with the physical thermal environment. Thus, implementing green spaces within urban environments does improve perceived and objective thermal comfort.

Concluding, the results of our study provide novel empirical evidences on thermal comfort related to green infrastructure in The Netherlands. We can confirm popular beliefs that green spaces are appreciated for their thermal conditions on warm summer days. This is important because citizen rely on thermally comfortable outdoor spaces for daily outdoor activities on warm summer days. As people's free time often is restricted to short periods urban green spaces are needed within their living environments. This especially counts for elderly people, one of the most vulnerable groups in terms of heat stress, and for citizens without private outdoor spaces like gardens and terraces.

It should be noted that in our study only one city has been investigated from the physical perspective, whilst the psychological effect of green spaces was investigated in three cities. However, our micrometeorological data from Utrecht is consistent with earlier studies (Bowler et al., 2010). Therefore, we assume that thermal conditions of green spaces in Arnhem and Rotterdam are similar to those of Utrecht.

Based on our investigations in Utrecht, we demonstrated that perceived thermal comfort of green environments reflects the actual physical effect of parks being cooler than other urban areas. Our findings provide scientific evidence for the need of providing more or better green spaces in cities. Evidence-based design guidelines for thermally comfortable cityscapes are needed which support urban planners, policy makers, and city managers in their decision making. Especially in times of financial crises within municipalities, strong arguments in favour of preservation, maintenance and development of urban green spaces are needed. Urban planners, policy makers, and city managers also need to anticipate on increasing urban heat due to climate change and provide healthy and thermally comfortable living environments in the future.

3 Towards guidelines for designing parks of the future

Klemm, W., Van Hove, B., Lenzholzer, S., & Kramer, H. (2017). "Towards guidelines for designing parks of the future." *Urban Forestry & Urban Greening* 21: 134-145.

Abstract

This study investigated human behaviour in parks in order to develop spatially explicit design guidelines considering future climate conditions in moderate climates. Unobtrusive observations (N = 11337) and surveys (N = 317) were conducted simultaneously in two parks in the Netherlands during summer and tropical days ($T_{a\ max}$ > 25 °C and > 30 °C, respectively), the latter representing future climate conditions. Solar exposure preferences of resting park visitors were studied through investigating behavioural responses (park attendance and spatial temporal user patterns) and thermal perception. Outcomes were related to air temperature (T_a) of meteorological reference stations and spatial data on the vegetation structures of the parks.

Observational data show that daily park attendance decreased with rising $T_{a\ max}$. Survey results indicate that resting park visitors perceived a high level of thermal comfort during all investigated days. Park visitors chose resting locations predominantly based on solar exposure conditions (sun, half-shade, shade). Those solar exposure preferences were significantly related to T_a: with increased T_a the number of park visitors in the shade increased and decreased in the sun ($p < 0.001$) with a tipping point of 26 °C. These results indicate that parks in moderate climates may guarantee a high level of thermal comfort, even on tropical days, if a variety of solar exposure conditions is guaranteed. A ratio of 40% sun, 20% half-shade and 40% shade in parks was derived from spatial temporal user patterns, which appear to accommodate preferences of resting park visitors under various thermal conditions (summer and tropical) and on various times of the day. These results and a spatial typology of tree configurations for microclimatic variety provide design guidelines: urban parks need to offer a wide range of sun-exposed, half-shaded and shaded places to accommodate for different user needs and future climate conditions.

3.1 Introduction

Parks, like many other urban green spaces, provide multiple benefits for city dwellers. They are of importance for recreation and mental restoration (Chiesura, 2004) and relieve environmental challenges such as air quality, water storage and urban heat (Demuzere et al., 2014, Roy et al., 2012, Tzoulas et al., 2007, Lafortezza et al., 2013). During warm summer periods parks are preferred urban outdoor spaces to recreate (Lafortezza et al., 2009) and are even favoured to outdoor spaces with open water (Klemm et al., 2015a).

Those behavioural preferences can be ascribed to the well-known fact that urban parks are 'cool spots' in cities during summer periods. Evapotranspiration of the parks' vegetation structures provide lower air temperatures (T_a) compared to the built surroundings (Klemm et al., 2015a, Bowler et al., 2010, Norton et al., 2015, Chen and Wong, 2006, Oke, 1989). Tree canopies reduce solar radiation, significantly affecting the mean radiant temperature (T_{mrt}) and thus contributing to the thermal conditions in parks (Brown et al., 2015, Klemm et al., 2015a, Yang et al., 2013).

The thermal conditions of a park thus are largely determined by the spatial configuration of its vegetation structure (e.g., size and distribution of tree canopies). As a consequence, the creation of thermally comfortable parks depends on designers' decisions (Brown et al., 2015). To inform climate-responsive design decisions spatially explicit information is needed. Quantitative approaches including thermal comfort indices (e.g., the thermal sensation vote) have been used to investigate thermal conditions in parks (e.g., Yang et al., 2013). Though these indices deliver valuable scientific evidence on thermal variety in parks, they are not explicit in spatial terms to inform park design. For generating design guidelines, additional more qualitative thermo-spatial information is needed (Lenzholzer et al., 2018). Understanding how people perceive, value and use environments, such as parks, helps to understand the human dimension of planning and design and informs landscape architecture practice (Meijering et al., 2015).

Designing 'cool-spot' parks will gain importance in the context of global warming. Even in the Netherlands with its moderate climate, the number of summer and tropical days ($T_{a\,max}$ > 25 °C and > 30 °C, respectively) has increased in the last 50 years and future projections feature more 'tropical days' (IPCC, 2014, KNMI, 2015). This will have negative impacts on human thermal comfort and health (Kovats and Hajat, 2008, Daanen et al., 2013, Huynen and Van Vliet, 2009). Additionally, it may influence city-dwellers' use of parks and their behaviour in parks and thus pose challenges for future park design.

The present study therefore aimed at generating spatially explicit design guidelines for parks that are based on human behaviour and that take warmer future climate conditions into account. Early behavioural studies (Whyte, 1980, Gehl, 1987) revealed strong relationships between microclimatic conditions: especially solar exposure degrees appeared critical for the attendance of outdoor spaces in moderate climates. Recent studies demonstrated that the number of park visitors increased with rising temperatures. In a University park in Szeged (Hungary) Kantor et al. (2010) observed a relatively large proportion of people in the sun despite hot thermal conditions during summer. However, for a square in Rome (Italy) Martinelli et al. (2015a) observed that square visitors had a consistent preference for shaded areas throughout summer days. For a park in Stockholm (Sweden), Thorsson et al. (2004) demonstrated that during summer and autumn people visit outdoor places mainly to enjoy the sun. Likewise, Katzschner (2004) showed that sunny spaces on a square in Kassel (Germany) were preferred almost all throughout the year. In the latter two studies, it was observed that people moved from sunny to shady places under extreme hot conditions. Yet, none of these studies derived clear guidelines for park design, neither for current climatic situations nor for future situations.

This study therefore investigated preferred solar exposure of resting park visitors on summer and tropical days at various daytimes in the Netherlands through studying visitors' behavioural response (park attendance, spatio-temporal user patterns) and thermal perception. This way, we obtained evidence-based climate-responsive design guidelines for future park design in moderate climates (Brown and Corry, 2011, Brown et al., 2015). To inform design scientific evidence should be translated into design guidelines in an accessible and understandable way (Prominski, 2017, Nassauer and Opdam, 2008, Ward Thompson, 2013) so that design professionals are encouraged to take microclimate aspects into account when shaping outdoor spaces.

Consequently, the main research question was: *What are design guidelines for future parks that are perceived as thermally comfortable by resting park visitors in moderate climates?* To answer this main question, the following sub-questions were formulated:

- *What is the importance of microclimate on the spatial preferences of resting park visitors?*
- *What is the thermal perception of resting park visitors on summer and tropical days?*
- *How does extreme air temperature in summer influence daily park attendance?*
- *What are the user patterns related to solar exposure of resting park on summer and tropical days?*
- *What are spatial typologies for optimal park use on summer and tropical days?*

3.2 Methods and materials

A combination of quantitative and qualitative methods delivered an empirical database to inform design guidelines for future parks. By combining surveys, unobtrusive observations and spatial analysis we related park visitors' behaviour and thermal perception to meteorological reference data and spatial characteristics of the parks. The conceptual framework of this study is shown in Figure 3.1.

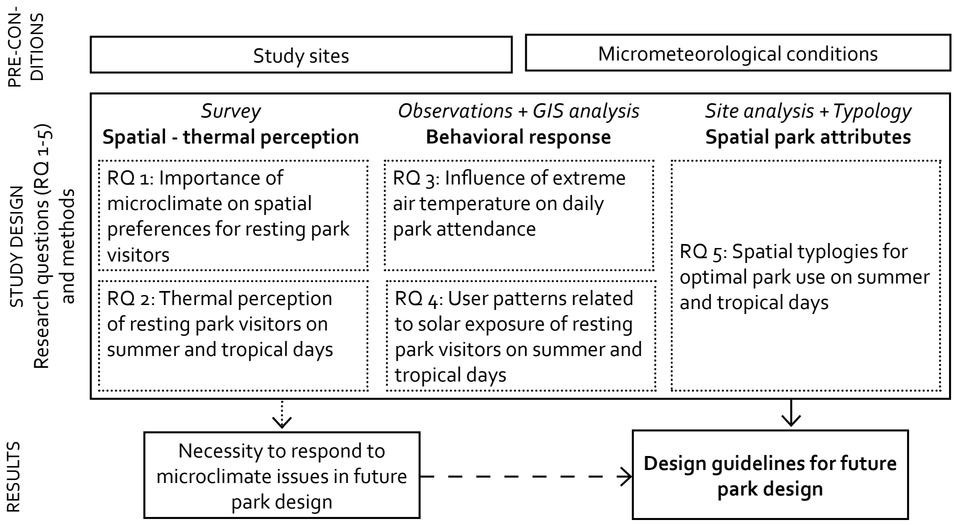


Figure 3.1: Conceptual framework of this study

3.2.1 Pre-conditions

Study sites

Since the study aimed at investigating spatial configurations for optimal park use during summer and tropical periods we chose two parks for our multiple case study (Deming and Swaffield, 2011). Both are situated in the moderate/mild mid-latitude climate of the Netherlands: one in the city of Utrecht and one in the city of Wageningen. Utrecht is the fourth largest city of the country with a population and a population density of 330.000 and 3.300/km2 respectively. In contrast, Wageningen is a relatively small town, with a population and a population density of 37.500 and 1.200/km2 respectively (CBS, 2014). Size and function of the two parks differ considerably. The Wilhelminapark in the city of Utrecht is 10.9 ha large and a popular city park with a public playground, restaurant and terrace in the centre. The Torckpark is a small (1 ha), neighbourhood park with no additional facilities. Despite their differences in size and function, both parks appeared as thermally comfortable parks during warm summer weather conditions in earlier micrometeorological studies (Klemm et al., 2015a, Steeneveld et al., 2014).

Both parks show similar spatial characteristics; they were designed in the English Landscape Style (late 19th century), which is characterized by natural forms, providing successions of spatial impressions and experiences (Vroom, 2006). They feature a mixture of old and young tree populations, open lawns and water surfaces. The two parks comprise a similar spatial variance in open, sun exposed and sheltered, shady spaces and thus display a wide array of different microclimatic conditions (Figure 3.2, Table 3.1).

Table 3.1: Spatial characteristics of the two investigated parks

	Wilhelminapark, Utrecht	**Torckpark, Wageningen**
Park size total [ha]	10.9	1.0
Lawn [%]	21	42
Tree cover [%]	64	32
Water [%]	15	26

Figure 3.2: Aerial photographs (by Google Earth 2014) and schematic maps of the investigated parks

Meteorological conditions

The fieldwork, consisting of surveys and observations, was carried out on 11 days in the summer period (from July 6th to August 2nd 2013) both on weekdays and in the weekend. Clear skies with high global radiation and high temperatures where measured during those days (Table 3.2). The fieldwork period included three days (July 21st to 23rd 2013) of a national heat wave according to the definition of the Royal Netherlands Meteorological Institute (KNMI). The KNMI differentiates between 'summer' and 'tropical' days based on the daily maximum air temperature ($T_{a\,max}$), measured in the rural reference weather station in The Bilt. $T_{a\,max}$ on 'summer days' is above 25 °C compared to 30 °C on 'tropical days'.

The meteorological data (Table 3.2) were obtained from the KNMI weather station in The Bilt (KNMI, 2016), a town at 3 km distance from the Wilhelminapark in Utrecht and from the weather station Veenkampen from Wageningen University (MAQ, 2016), located at 3,5 km distance from the Torckpark in Wageningen. These stations served as reference stations. To evaluate the validity of the data from the reference stations outside the cities we compared these to datasets from measurements taken in one of the parks. We compared data from the

Table 3.2: General daily meteorological conditions (air temperature, relative humidity, global radiation and wind velocity) on the fieldwork days in Utrecht (KNMI, 2016) and Wageningen (MAQ, 2016), the Netherlands (days of heat wave = grey)

			The Bilt, Utrecht (KNMI, 2016)					Wageningen (MAQ, 2016)				
	Day nr	**Date**	**T_a daily mean (°C)**	**T_a daily max (°C)**	**H daily mean (%)**	**Gl.rad daily mean (W/m2)**	**u daily mean (m/s)**	**T_a daily mean (°C)**	**T_a daily max (°C)**	**h daily mean (%)**	**Gl.rad daily mean (W/m2)**	**u daily mean (m/s)**
'summer days'	1	6/7	19.1	22.4	73	294	2.2	19.6	26.1	62	268.5	1.9
	2	7/7	19.6	25.1	72	332	3.0	20.5	27.1	56	333.7	3.1
	3	8/7	19.4	25.0	70	325	4.0	19.8	26.3	60	322.6	3.5
	4	9/7	18.3	23.4	68	327	3.4	18.9	24.8	55	327.8	3.9
	5	15/7	19.3	26.0	70	319	2.0	18.7	25.6	61	288.1	2.2
	6	18/7	21.4	27.1	70	318	3.3	21.9	28.3	58	318.9	3.1
'tropical days'	7	21/7	22.8	30.4	68	314	2.3	22.7	30.2	54	313.9	2.3
	8	22/7	24.9	32.6	63	279	2.0	24.3	33.4	53	299.4	2.3
	9	23/7	24.3	31.6	69	280	2.0	23.7	32.7	62	264.8	2.2
	10	1/8	24.6	30.7	68	297	3.1	24.1	30.1	63	299.3	3.7
	11	2/8	26.4	34.0	65	266	3.0	26.0	34.1	59	275.3	3.8

rural station The Bilt with measurements that had been carried out in the Wilhelminapark (July 24th 2012, August 1st and 2nd 2013). T_a were rather similar for the Wilhelminapark and The Bilt (more detailed information can be found in the Appendix L) and consequently we used the T_a data from the rural stations as reference data at the moments of observations (11:00, 13:00, 15:00 and 17:00, LST +1).

3.2.2 Study design

Surveys

Conducting surveys among visitors present in outdoor spaces is a renowned method to investigate people's thermal perception related to spatial characteristics of the surroundings (Lenzholzer et al., 2018). This study focussed on resting locations in parks (e.g., grass, benches or stairs) that visitors chose to fulfil their microclimatic demands of that moment (see Gehl, 1987, Nikolopoulou et al., 2001, Whyte, 1980). Semi-structured interviews were conducted with park visitors, who were approached at random. The interviews were undertaken by various researchers who were instructed in advance on how to conduct the interviews and respond to questions.

The interview covered individual characteristics of resting park visitors (age and gender), followed by a question on visitors' spatial preferences: "Why did you choose this place in the park?" (refers to research question 1). Then park visitors were asked to evaluate their momentary thermal perception: "How do you experience the microclimate conditions at this moment in this place?" (refers to research question 2). Here multiple answers were possible. People could express their momentary satisfaction with overall thermal comfort and with the single microclimate parameters (air temperature, sun, wind and humidity) on a five-point scale from very uncomfortable to very comfortable (Johansson et al., 2014).

Interview results were analysed by means of descriptive statistics. Inductive coding was applied to analyse responses to question 1. Responses to question 2 were differentiated between interviews held on summer and on tropical days.

Observations and GIS analyses

Observations are a well-known method to investigate the character and use of outdoor spaces that deliver relevant spatial information for the (re-)design of such spaces (Deming and Swaffield, 2011, Meijering et al., 2015). Similar to Goličnik and Ward Thompson (2010) and Kántor and Unger (2010), this study combined unobtrusive observations and GIS analyses.

In preparation for the actual fieldwork observations protocols were developed. They consisted of a top view of the parks with a grid of 10 x 10 m supporting the transfer of the precise location of park visitors to the plan and a table to add date and time of the observation moments. Observations included recording of the locations of resting park visitors on the plan. Each recording was completed by a descriptive note on the solar exposure of the individual, being either sun, half-shade or shade. During the data collection observers had a fixed route visiting all sub-areas in the parks. This procedure was repeated every two hours from 11:00 to 17:00.

Data were examined by GIS analyses that were combined with descriptive statistics in Excel. First, the locations and solar exposure notes of all resting park visitors were transposed into ArcMap 10.3.1 providing an extensive GIS dataset that included information of spatio-temporal park use and solar exposure characteristics of park users. Secondly, this dataset was used to analyse daily park attendance based on the overall number of recorded park visitors per day (refers to research question 3) and park visitors' spatio-temporal user patterns related to solar exposure degrees (refers to research question 4). The latter related the proportions of park visitors resting in sunny, half shady or shady places to T_a . Here, the datasets of both parks had been combined since initial results of both parks corresponded well. Due to the larger sample size of the Wilhelminapark we used T_a from The Bilt as reference T_a.

Thirdly, user patterns of resting park visitors and their solar exposure characteristics were established providing overviews of the spatial distribution of resting park visitors (Figure 3.3). To compare the relation between those user patterns and real solar radiation in the investigated parks we applied the Area Solar Radiation tool from ArcMap 10.3 (ESRI, 2016). It calculated the maximum incoming solar radiation for each moment of observation using the enhanced version (AHN2) of the digital surface model of the Netherlands (Kramer et al., 2014) with maximum

Legend - Resting park visitors: sun, half shade, shade

Figure 3.3: Initial results of user patters in the Wilhelminapark

surface height information per 50 x 50 cm grid cell. Representation of incoming solar radiation is limited to ground level (above ground object height < 0.1 m); other surfaces are hidden by the mask tool. As the model is grid based, solar exposure under tree canopies is not represented. Observations and GIS analyses resulted in spatio-temporal user and solar exposure patterns for all days and observation points in time on both, summer and tropical days.

Site analysis and spatial typology

To generate design guidelines for preferred resting locations during summer and tropical thermal conditions (refers to research question 5) the park configurations that were preferred by resting park visitors were analysed. The analysis included spatial characteristics of vegetation structures, open areas and water features. Special attention was given to spatial characteristics of the tree canopy cover, including various configurations of single or groups of trees, that are significantly related to T_{mrt}, which in turn is a determining variable for thermal comfort in parks during summertime (Brown et al., 2015, Klemm et al., 2015a, Yang et al., 2013). This analysis of the vegetation structure was linked to the spatio-temporal user patterns. Based on those analyses, preferred vegetation structures were identified and categorized in a typology of configurations for optimal park use.

3.3 Results and discussion

3.3.1 Surveys

A total number of 317 resting park visitors were interviewed on 11 fieldwork days (154 in Wilhelminapark and 163 in Torckpark) and the response rate was 83%. More information on the composition and age groups of respondents can be found in Table 3.3.

Table 3.3: Age and gender of respondents in the two investigated parks

	Wilhelminapark Utrecht	**Torckpark Wageningen**
Total number	154	163
Proportion male/ female [%]	39/61	43/57
Age average	31.0	27.2
≤ 20 years [%]	13.3	19.3
21 ≤ 30 years [%]	50.5	59.4
31 ≤ 40 years [%]	19.7	11.8
41 ≤ 60 years [%]	11.2	7.0
≥ 60 years[%]	5.3	2.7

Importance of microclimate for resting park visitors

When people were asked "Why did you choose this place in the park?" the majority of answers related to microclimate (41% in the Wilhelminapark and 57% in the Torckpark, Figure 3.4). Those answers were predominately linked to solar exposure ("in the sun", "shade by the big tree", "both sun and shade in close vicinity"). Other microclimate aspects related to the cooling by wind or water. Additional reasons, besides microclimate, included spatial features and aesthetics ("nice view", "much space around me"), stillness ("a quiet place"), water ("fountain", "feet in the water"), benches, or vegetation ("old tree", "nice flower", "bright green grass"). Survey results showed a dominant influence of microclimate conditions, in particular solar exposure, on resting park visitors' spatial choices.

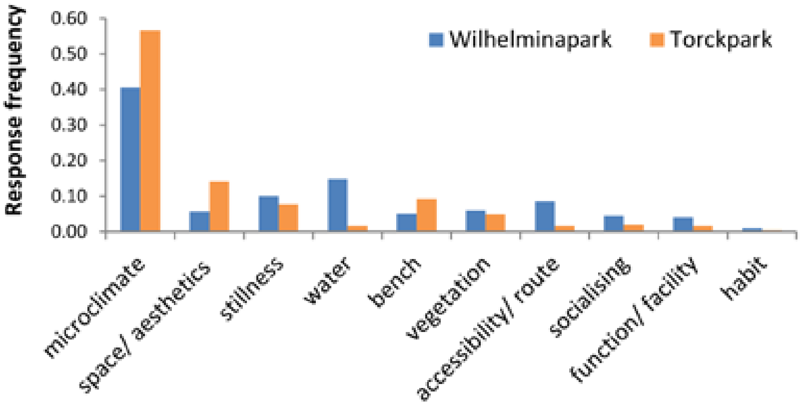


Figure 3.4: Reasons mentioned by park visitors for choosing a resting location in the parks

Resting park visitors' thermal perception on summer and tropical days
Park visitors described their perception of thermal comfort at their actual resting locations on levels between 'comfortable' and 'very comfortable'. On tropical days perception of overall thermal comfort and of single microclimate parameters (air temperature, sun exposure, humidity and wind) was slightly lower than on summer days; however still 'comfortable' (Table 3.4). Thus, even though park visitors experienced a heat wave (see Table 3.2), they were able to find resting locations in the park that they perceived as thermally comfortable. The results show that sitting activities on summer and tropical days only occur in places where microclimate conditions are perceived as thermally comfortable (Gehl, 1987, Whyte, 1980, Nikolopoulou et al., 2001).

3.3.2 Observations and GIS analysis

In total, 10871 (Wilhelminapark) and 466 (Torckpark) resting visitors were observed. The large difference in the number of park visitors was due to the different urban environments as well as size and function of the parks (see Figure 3.2 and Table 3.1).

Daily differences in park attendance (Figure 3.5) can be attributed to workdays and weekend days. Peaks in park attendance occurred on Saturdays and Sundays (6/7, 7/7, 21/7). Slight differences in park attendance between workdays in the beginning (e.g., day 8/7 and 9/7) and the end (e.g., day 22/7 and 23/7) of the fieldwork period may be caused by the beginning of school holidays (July 13th for the secondary, and July 20th for the primary education).

Table 3.4: Momentary thermal perception of single microclimate parameters and overall thermal comfort in two parks on summer days with $T_{a\ max}$ > 25 °C and on tropical days with $T_{a\ max}$ > 30 °C

Park	Interview period	N	Air temperature[a]	Sun[a]	Humidity[a]	Wind[a]	Overall thermal comfort[a]
			Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Wilhelminapark	Summer days	88	1.58 (0.67)	1.38 (0.70)	1.14 (0.71)	1.31 (0.77)	1.50 (0.52)
	Tropical days	66	1.26 (0.56)	1.29 (0.75)	0.55 (0.86)	0.74 (0.99)	1.27 (0.66)
Torckpark	Summer days	95	1.52 (0.63)	1.47 (0.58)	0.93 (0.76)	1.23 (0.66)	1.44 (0.50)
	Tropical days	68	1.00 (0.91)	1.25 (0.71)	0.21 (0.88)	0.84 (0.92)	1.12 (0.70)

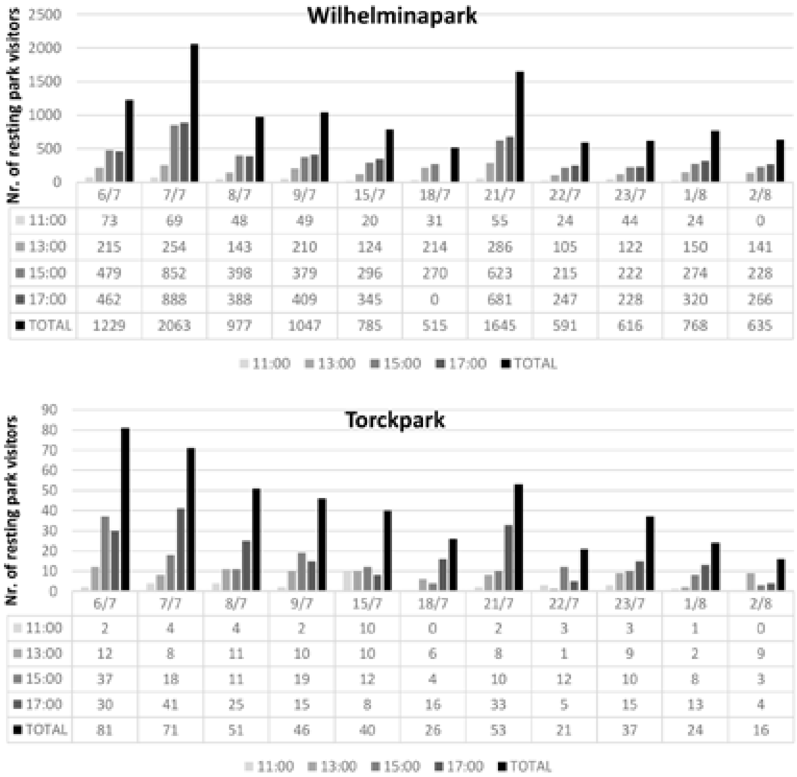
[a] Responses coded on a five-point scale from very uncomfortable (-2) to very comfortable (+2)

3

Daily park attendance

For both parks daily park attendance decreased with higher $T_{a\ max}$. Significant negative linear relationships ($p < 0.04$) between the number of resting park visitors and $T_{a\ max}$ could be assessed (Figure 3.6). For this analysis both Sundays (7/7, 21/7) have been left out, because park attendances, in particular in the Wilheminapark, showed extreme peaks on those days. The comparable park attendance in both parks during similar thermal conditions indicates that extreme T_a may negatively influence the number of resting park visitors.

Those results are in accordance with the widely acknowledged impact of weather conditions on the visit of outdoor places (Eliasson et al., 2007, Nikolopoulou and Steemers, 2003, Thorsson et al., 2004, Lin et al., 2013b, Nikolopoulou et al., 2001). However, they differ from those showing an increase of the number of visitors at increasing thermal conditions in moderate climates (Kántor and Unger, 2010, Nikolopoulou et al., 2001, Thorsson et al., 2004). The variances might be due to differences in experimental design (e.g., longer observation periods, encompassing various seasons). The population of park visitors in the study of Kántor and Unger (2010) consisted mostly of students. Furthermore, park visitors in high-latitude cities (Nikolopoulou et al., 2001, Thorsson et al., 2004) may have a different behaviour compared to those in the mid-latitude cities of the Netherlands.



	6/7	7/7	8/7	9/7	15/7	18/7	21/7	22/7	23/7	1/8	2/8
11:00	73	69	48	49	20	31	55	24	44	24	0
13:00	215	254	143	210	124	214	286	105	122	150	141
15:00	479	852	398	379	296	270	623	215	222	274	228
17:00	462	888	388	409	345	0	681	247	228	320	266
TOTAL	1229	2063	977	1047	785	515	1645	591	616	768	635

	6/7	7/7	8/7	9/7	15/7	18/7	21/7	22/7	23/7	1/8	2/8
11:00	2	4	4	2	10	0	2	3	3	1	0
13:00	12	8	11	10	10	6	8	1	9	2	9
15:00	37	18	11	19	12	4	10	12	10	8	3
17:00	30	41	25	15	8	16	33	5	15	13	4
TOTAL	81	71	51	46	40	26	53	21	37	24	16

Figure 3.5: Daily and hourly park attendance of for Wilhelminapark (top) and Torckpark (bottom) on 11 days, recorded in a two hour interval from 11:00 to 17:00

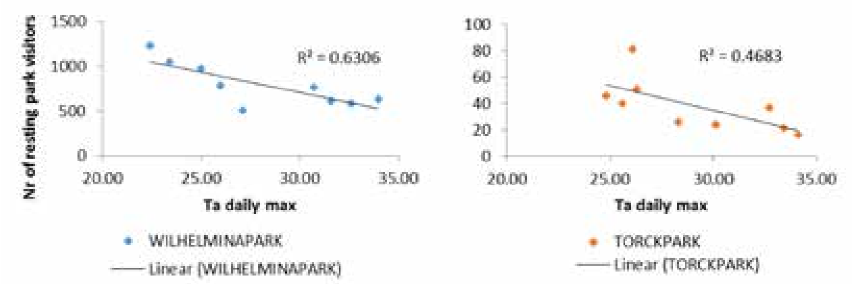


Figure 3.6: Daily park attendance in relation to $T_{a\ max}$ for Wilhelminapark (left, N = 7163, p = 0.01) and Torckpark (right, N = 342, p = 0.04) on nine days (two Sundays are excluded)

Hourly park attendance independently from T_a, showed a constant increase of the number of resting park visitors in both parks ($p < 0.001$) with peaks in the late afternoon (Figure 3.7). Compared to the Wilhelminapark, results from the Torckpark indicated more variation, probably caused by the smaller sample size. Nevertheless, there is a clear correlation between hourly park attendance in the Wilhelminapark and the Torckpark for all measurement days (correlation = 0.773). Those results indicate that the highest number of resting park visitors can be expected in the afternoon.

Influence of air temperature on resting park visitors' user patterns in terms of solar exposure

The analysis of solar exposure preferences was based on a total number of 11048 recorded resting park visitors (10596 in Wilhelminapark, 452 in Torckpark). This dataset displayed a significant relationship between T_a and solar exposure responses: the number of park visitors increased in the shade ($p < 0.001$) and decreased in the sun ($p < 0.001$) with rising T_a (Figure 3.8). Those outcomes are in line with earlier studies on physical adaptation of park users in moderate (Kántor and Unger, 2010, Katzschner, 2004, Thorsson et al., 2004) and subtropical (Lin et al., 2013a, Lin et al., 2013b) climates. Seeking shade under trees is a popular response of physical adaptation (Nikolopoulou et al., 2001, Nikolopoulou and Steemers, 2003) to deal with extreme summer temperatures, even in the moderate climate of the Netherlands.

A tipping point at 25.98 °C (rounded to 26 °C) could be identified: park visitors found their zones of preferred thermal perception in sun exposed places when T_a was lower than 26 °C, and in shady places when

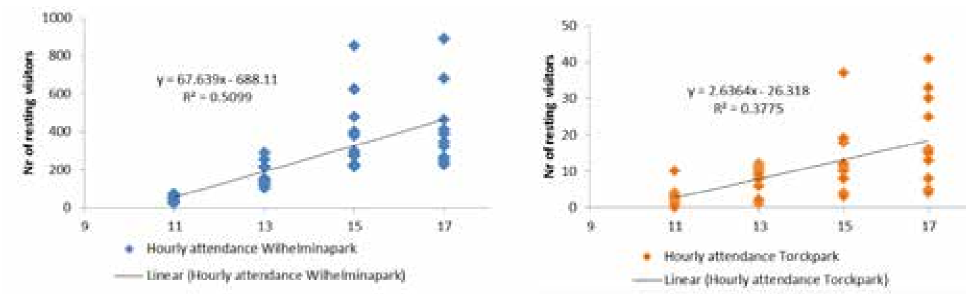


Figure 3.7: Hourly park attendance for Wilhelminapark (left) and Torckpark (right) on 11 days, recorded in a two hour interval from 11:00 to 17:00

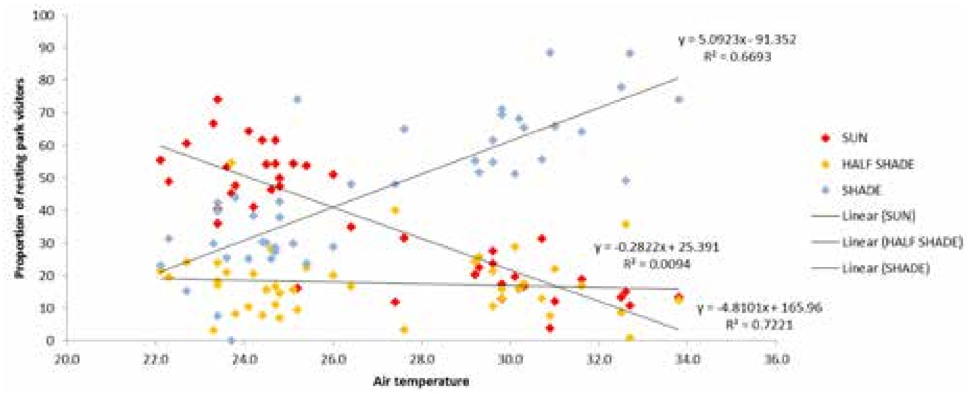


Figure 3.8: General solar exposure preferences of resting visitors (N = 11048) in two parks in relation to T_a (KNMI, 2016) on 11 observation days at 11:00, 13:00, 15:00 and 17:00

T_a was higher than 26 °C. Accordingly, those results indicate that resting park visitors changed their solar exposure preference depending on the air temperature.

A prominent change in people's preference regarding solar exposure degrees occurred on the first 'tropical day' (21/7) starting from 13:00 when the highest numbers of resting park visitors was recorded (Figure 3.9). On the 'summer days' (6/7 until 18/7) the large majority of park visitors preferred to stay in the sun, whereas park visitors predominately preferred shade on 'tropical days' (21/7 until 2/8).

The shift from sun to shade at higher T_a also occurs in spatio-temporal park user patterns (Figure 3.10). In both parks resting park visitors tended to choose locations in the sun during summer days, whereas they preferred locations in the shade during tropical days. User patterns in a park during summer days apparently can be completely different from those during tropical days. Park visitors adapt to thermal conditions and choose places to rest accordingly.

Though, when comparing hourly user patterns regardless of thermal conditions of all fieldwork days, there is an even distribution of resting park visitors in the sun, half-shade and shade (Figure 3.11). At 11:00 resting park visitors in the Wilhelminapark were evenly distributed throughout the whole park. From 13:00, popular places were the more sun-exposed southern, eastern and northern parts and the waterfront. At 17:00 the majority of resting park visitors was located at the eastern parts of the park to enjoy the evening sun. Accompanying quantitative

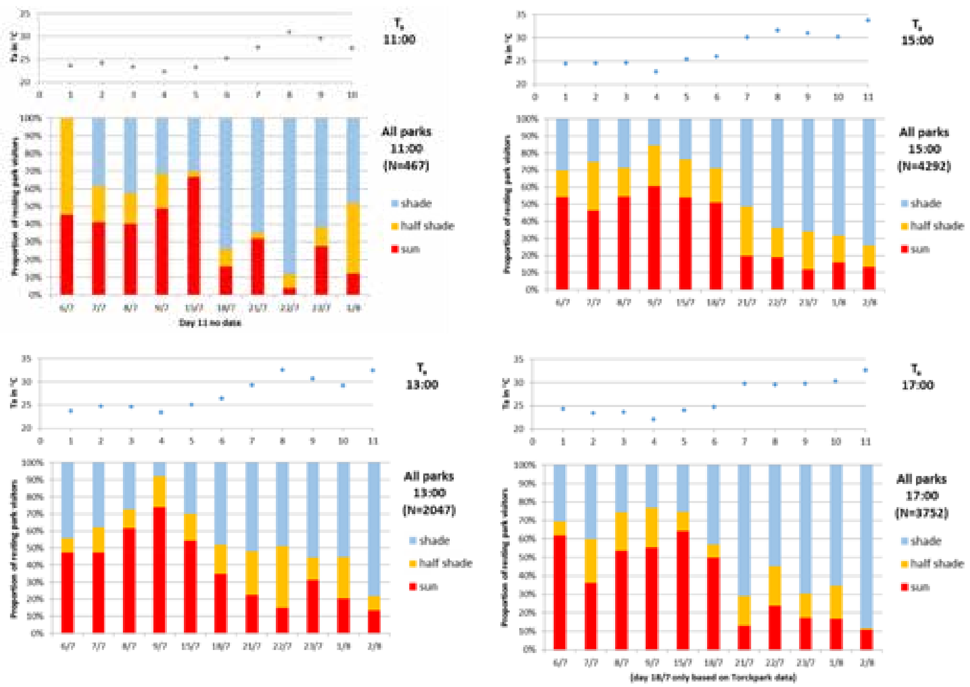


Figure 3.9: Solar exposure preferences of resting park visitors (N = 11048) presented at 11:00 (no data for day August 2nd 2013 = day 11), 13:00, 15:00 and 17:00 in relation to T_a (KNMI, 2016)

results of this analysis (Table 3.5) show that preferred resting places during the day are quite evenly spread, with shady places being slightly more popular than sunny places.

Earlier studies in outdoor spaces in warmer climates called for contiguous shade to improve outdoor thermal comfort and attendance (Huang et al., 2015, Lin, 2009, Lin et al., 2013b, Martinelli et al., 2015a). Results of some studies performed in moderate climates, however, called for a variety of microclimates, i.e., sunny and shaded places (Thorsson et al., 2004, Katzschner, 2004). Our study clearly shows that solar exposure preference is even more nuanced; not only shade but also sun and half-shade spaces are needed to provide places that are perceived as thermally comfortable under summer and tropical conditions and on various times of the day. Based on the results presented in table 3.5, a typical ratio can be derived: of all resting park visitors, about 40% prefers sun, 40% prefers shade and 20% prefers places located in between sun and shade.

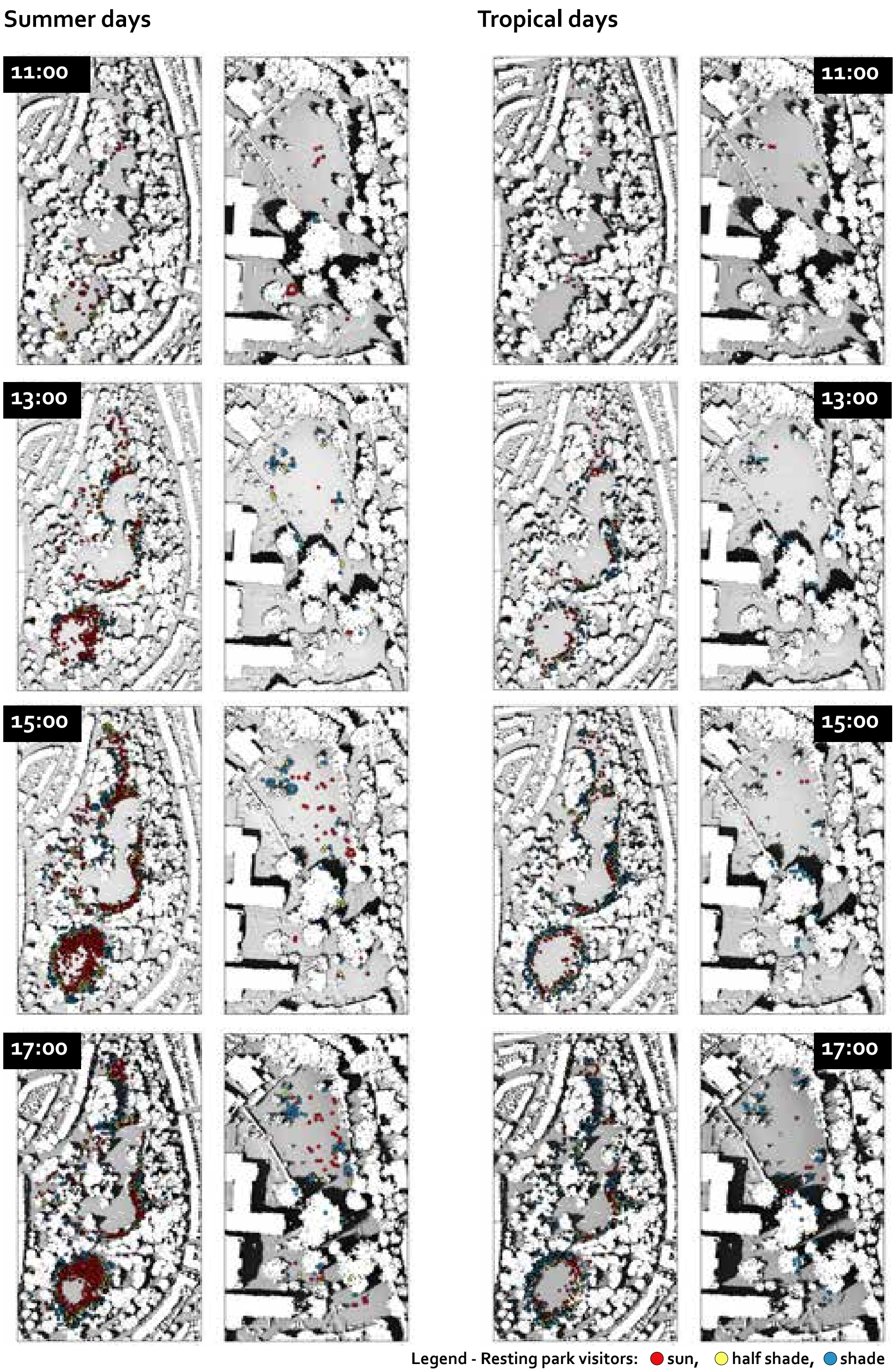


Figure 3.10: User patterns of resting park visitors in the Wilhelminapark (left, N = 10596) and Torckpark (right, N = 452) on 11 observation days on summer days compared to tropical days.

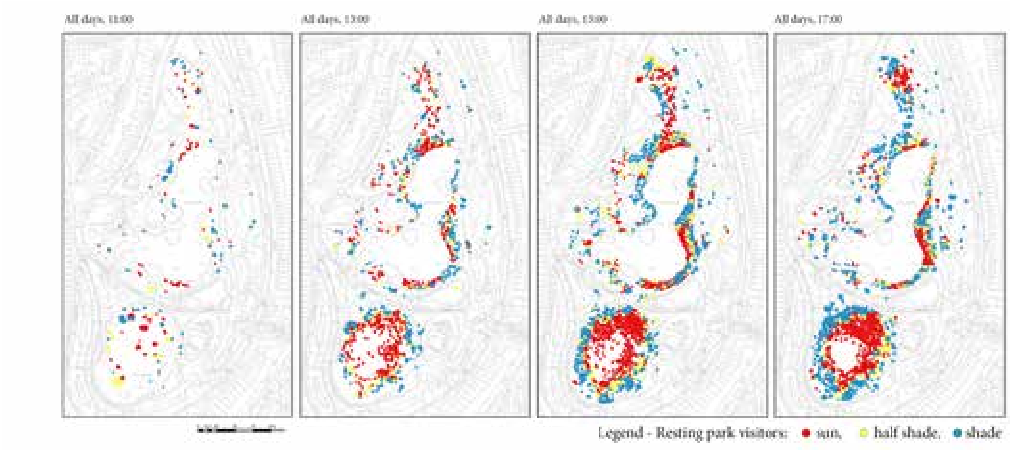


Figure 3.11: Hourly user patterns of all investigated days in the Wilhelminapark (N = 10596)

Table 3.5: Solar exposure preferences (sun, shade, half shade) of resting park visitors (N = 11048) in two parks on 11 observation days

	N	Sun (%)	Shade (%)	Half shade (%)
11:00	467	33.4	47.9	18.7
13:00	2047	41.0	40.7	18.4
15:00	4292	38.7	40.1	18.4
17:00	4242	39.2	44.8	16.0
	Mean	38.1	43.4	17.9

3.3.3 Site analysis and spatial typologies

The park user patterns described above were used to analyse spatial configurations of preferred resting locations. This analysis showed that preferred resting locations in the Wilhelminapark on summer and on tropical days had different types of microclimates in the park (Figure 3.12). Those microclimates enable people to have a wide choice under different conditions. On summer days resting park visitors preferred open lawns and sunny spots around single trees or groups of trees. On tropical days they prefer shaded areas provided by solitary trees, small groups of trees, edge of tree clumps, boscages and scattered trees.

The site analysis of preferred resting locations revealed different spatial configuration types that provide microclimates from sunny to shady places (Figure 3.13). Since the park user patterns (Figure 3.10 and 3.11) as well as the survey results (Figure 3.4) demonstrate that park visitors positively perceived the presence of water in both parks,

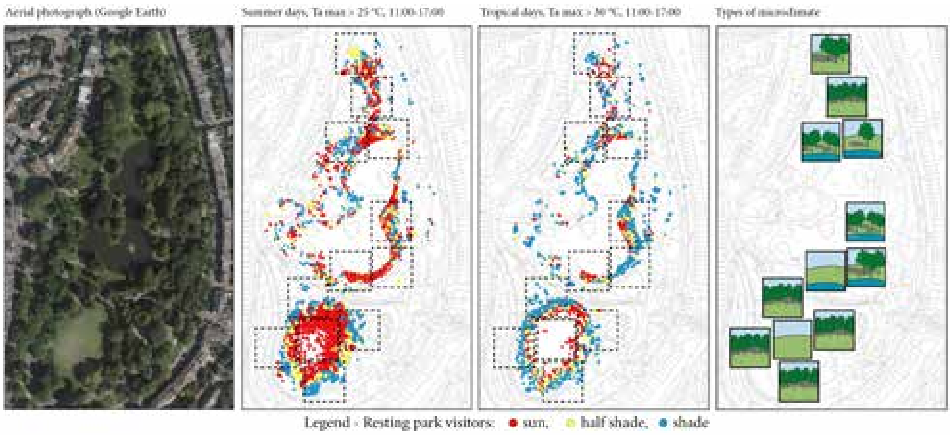


Figure 3.12: Combinations of GIS data on user patterns on all summer days (N = 2453) and on all tropical days (N = 1591) with spatial configurations in which preferred use takes place (Types of microclimate see Figure 3.13)

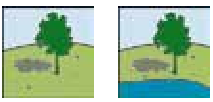
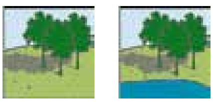
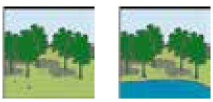
Nr	Type		Explanation	Solar exposure
1	lawn		open grass field, lawn > openness, exposure, sun	○
2	single/solitary tree		solitary tree as single 'object' on a wider lawn > openness, single object, sun/ shade depending on size of tree crown	○ ◑ ●
3	small group of trees		group of trees with overlapping foliage on a wider lawn > objects, edge between openness and enclosure, edge between sun and shade	○ ◑ ●
4	row/ edge of trees		group of trees planted in a row along a lawn > objects, long sharply defined edge between openness and enclosure and between sun and shade	○ ◑ ●
5	scattered trees/ boscage		scattered trees/ boscage on wider lawn > objects, scattered overlapping foliage create mixture of open and enclosed spaces in close vicinity	○ ◑ ●
6	individual objects		means to create a microclimate, like a parasol/ umbrella or another shade device > objects create temporary mi-croclimate spaces for individuals	○ ◑ ●

Figure 3.13: Types of microclimate for the design of future thermally comfortable parks

this typology was set up in dual mode; with and without the presence of water. By varying the number, species and composition of trees on open lawns, varying microclimates can be created. Open lawns and grass fields are sun exposed places. A solitary tree as a single object offers shade whereas a boscage provides additional shelter.

Places on the verge of sun and shade are also important: they afford individuals to alter position (move to either sun or shade) or posture (move body into the sun and head into the shade). Also groups of individuals often choose those liminal areas as people within the group may have different thermal preferences. These liminal conditions can be created by the overlapping foliage at the edges of small groups of trees or boscages (Figure 3.14).

Furthermore, park users proactively create their own thermally comfortable microclimates. They make changes in their environment to improve their level of thermal comfort, for example by installing tents, umbrellas or sunshades (Figure 3.15). Designers can easily facilitate this way of individual thermal adaptation by creating open and multi-functional spaces in parks.

Figure 3.14: Picture representing the 'edge effect' in between sun and shade

Figure 3.15: Examples of proactive physical adaptation

3.4 Conclusions: design guidelines for future parks

Investigations on human behaviour of resting park visitors on summer and tropical days ($T_{a\ max}$ > 25 ºC and > 30 ºC, respectively) clearly indicate the need for creating a variety of solar exposure conditions when designing parks of the future. Regarding research question 1 (*What is the importance of microclimate on the spatial preferences of resting park visitors?*) survey results emphasize the central role of microclimate, in particular solar exposure, for park visitors when choosing resting locations. The survey results regarding research question 2 (W*hat is the thermal perception of resting park visitors on summer and tropical days?*) showed that park visitors described their perception of thermal comfort at their actual resting locations on a high level during both, 'summer' and 'tropical' days. Thus, even though park visitors experienced a heat wave, they were able to find resting locations in the parks that they perceived as thermally comfortable. Observational results related to research question 3 (*How does extreme air temperature in summer influence daily park attendance?*) indicate that daily park attendance significantly decreases with rising air temperature ($T_{a\ max}$). In contrast to earlier studies, our results suggest that park attendance decreases with rising temperatures in moderate climates. This outcome once more demonstrates the need for climate-responsive park design, encouraging outdoor recreation and activity during warmer future climate conditions (Brown et al., 2015). The results concerning research question 4 (*What are the user patterns related to solar exposure of resting park visitors on summer and tropical days?*) indicate that air temperature (T_a) governs solar exposure preferences of park visitors. With increased T_a the number of park visitors increased significantly in the shade and decreased in the sun. A tipping point at 26 °C was found beyond which visitors prefer the shade to the sun.

Observational results, moreover, show that solar exposure preference of park visitors is nuanced; not only sun or shade but also half-shade spaces are resting locations that are perceived as thermally comfortable under various thermal conditions (summer and tropical) and on various times of the day (from 11:00 to 17:00). Based on the observational data we derived a typical ratio of resting park visitors in sun 40%, shade 40% and half-shade 20%. Pertaining to research question 5 (*What are spatial typologies for optimal park use on summer and tropical days?*) this study provides a typology of vegetation configurations, that are spatially explicit and communicated as visual information (icons) to guide future park design (Prominski, 2017, Brown and Corry, 2011). Accordingly, designers should create broad varieties of microclimates, from open lawns and sunny spots around single trees or groups of trees (which are preferred on summer days), to shaded areas provided by solitary trees, small groups of trees, edges of tree clumps, boscages and scattered trees (preferred on tropical days). In order to create such broad ranges of microclimates in parks designers need to systematically analyse solar exposure patterns and consider diurnal and seasonal shapes and sizes of shade provided by different tree species. Shade analyses in GIS applications (as applied in this study) or in 3D modelling software are useful tools for professional designers to analyse existing and new park shade patterns.

In sum, our results indicate that parks in moderate climates may guarantee a high level of perceived thermal comfort, even on tropical days, in case a variety of solar exposure conditions is provided. To inform future park design, a typology of tree configurations for various microclimates (Figure 3.13) and the following main design guidelines were generated:

- Consider solar exposure (especially afternoon solar patterns) and create microclimatic variance including sunny, half-shaded and shaded spaces for various times of the day; the ratio of 40% sun, 20% half-shaded and 40% shade can provide direction.
- Create 'edges' (gradients and borders) between open and shaded areas where sun and shade are provided in close vicinity and alternation.
- Create open and multi-functional spaces in parks, in which park visitors can create their own thermally comfortable microclimates by bringing their own parasols etc.

These guidelines can contribute to park design of the future and to the existing body of knowledge in the field of climate-responsive design of outdoor spaces. In order to further improve climate-responsive designing based on scientific evidence, guidelines as provided in this paper, should to be tested by professional designers and landscape architects in order to improve their usability in urban design practice.

4 Street greenery and its physical and psychological impact on thermal comfort

Klemm, W., Heusinkveld, B. G., Lenzholzer, S., Van Hove, B. (2015b). "Street greenery and its physical and psychological impact on thermal comfort." *Landscape and Urban Planning* 138: 87-98.

Abstract

This study focusses on the benefits of street greenery for creating thermally comfortable streetscapes in moderate climates. It reports on investigations on the impact of street greenery on outdoor thermal comfort from a physical and psychological perspective. For this purpose, we examined nine streets with comparable geometric configurations, but varying amount of street greenery (street trees, front gardens) in the city of Utrecht, the Netherlands. Mobile micrometeorological measurements including air temperature (T_a), solar and thermal radiation were performed, enabling the calculation of mean radiant temperature (T_{mrt}). Additionally, semi-structured interviews with pedestrians about their momentary and long-term perceived thermal comfort and their aesthetical appreciation of the green street design were conducted. Measurements showed a clear impact ($p = 0.0001$) of street greenery on thermal comfort through tree shading: 10% tree crown cover within a street canyon lowered street averaged T_{mrt} about 1 K. In contrast, our results did not show an influence of street greenery on street averaged T_a. Interview results indicated that momentary perceived thermal comfort tended to be related to the amount of street greenery. However, the results were not statistically significant. Related to long-term perceived thermal comfort respondents were hardly aware of influences by street greenery. Yet, people significantly ($p < 0.001$) valued the presence of street greenery in aesthetic terms. In conclusion, street greenery forms a convenient adaptive strategy to create thermally comfortable and attractive living environments. Our results clearly indicate that both physical and psychological aspects of thermal comfort have to be considered in urban design processes.

4.1 Introduction

Heat-related problems are an important issue in many urban areas in the world (IPCC, 2014). This is also true for urban areas in more moderate climates, like the Netherlands (Steeneveld et al., 2011, Heusinkveld et al., 2014, Brandsma and Wolters, 2012). In the next decades urban heat is likely to increase due to urbanization (Seto et al., 2011) and consequences of global climate change (Ballester et al., 2010). High temperatures can be a threat to human health, well-being and thermal comfort (Brown et al., 2015, Daanen et al., 2013, Haines et al., 2006, Huynen and Van Vliet, 2009, Lafortezza et al., 2009).

Many studies have demonstrated the ability of green infrastructure to effectively reduce urban heat and improve thermal comfort (Bowler et al., 2010, Huang et al., 2007, Ng et al., 2012, Streiling and Matzarakis, 2003, Dimoudi and Nikolopoulou, 2003). As such, implementing green infrastructure can be considered as an effective adaptive strategy to limit urban heat and thermal discomfort. Urban green infrastructure encompasses small-scale private gardens and street greenery up to large-scale urban parks, forming a network of green (i.e., vegetated) spaces within a city or an urban area (Demuzere et al., 2014, Fryd et al., 2011, Gill et al., 2007, Lafortezza et al., 2013, Tzoulas et al., 2007). The present study focusses on the benefits of street greenery, represented by street trees and the vegetation in (private) front gardens.

To date studies have concentrated on the physical impact of street greenery on thermal comfort. Tree shade lowers direct solar heat load and reduces heat stored in surfaces and facades (Lee et al., 2013, Shashua-Bar and Hoffman, 2000). In addition, plant leaves convert solar radiation into latent heat (evapotranspiration) that moderates air temperature (T_a) and increases air humidity (Rahman et al., 2011). In particular the reduction in mean radiant temperature (T_{mrt}) through large tree canopies can be substantial, for example measured at 19.3 to 21.0 K (Streiling and Matzarakis, 2003) or 32.8 K (Lee et al., 2013), while smaller tree canopies still reduced T_{mrt} by mean 4 K (Armson et al., 2013). The impact of tree canopies on T_a was limited under large tree canopies to 1.0 K (Streiling and Matzarakis, 2003) and 1.7 K (Lee et al., 2013) and was not significant under smaller tree canopies (Armson et al., 2013).

While the physical benefits of street greenery, in particular of street trees, on thermal comfort are generally recognized, it is hard to predict how different types of street greenery influence perceived thermal comfort, i.e., how a person senses and experiences physical thermal conditions in a vegetated compared to a non-vegetated environment (Klemm et al., 2015a, Nikolopoulou, 2011).

Individual, behavioral and psychological aspects affect the level of perceived thermal comfort

(Chen and Ng, 2012, Knez et al., 2009, Lenzholzer, 2012, Nikolopoulou, 2011, Vanos et al., 2010). Individual aspects include gender and age; behavioral aspects include clothing, level of activity or location. Behavioral aspects can be modified by the individual in order to change their metabolic rate and improve the level of thermal comfort (Nikolopoulou et al., 2001, Thorsson et al., 2004). Psychological aspects include thermal expectations, long- and short-term experiences, transient exposure and perceived control (Katzschner, 2006, Lenzholzer and Koh, 2010, Nikolopoulou, 2011, Nikolopoulou and Steemers, 2003, Thorsson et al., 2004).

Naturalness and aesthetic appreciation of the environment are assigned to be other psychological aspects that influence perceived thermal comfort (Nikolopoulou and Steemers, 2003, Lenzholzer and Van der Wulp, 2010). Naturalness is related to green infrastructure as people generally prefer natural (i.e., vegetated) to non-vegetated urban areas (Smardon, 1988, Ulrich, 1986). This preference is in particular based on visual information, like color preferences, sensory benefits and symbolic assigned values (Smardon, 1988, Qin et al., 2013). Aesthetic appreciation refers to people's visual preferences for vegetated environments in which for example they can experience the interplay of light and shadow and the different layers of plants that enhance the sense of depth (Kaplan et al., 1998). Naturalness and aesthetic appreciation of the environment can both be modified through urban planning and design by means of providing green infrastructure in order to improve people's perceived thermal comfort.

With regard to the spatial context of street canyons, the role of street greenery on momentary and general (i.e., long-term) perceived thermal comfort has not been investigated. In squares, green elements were likely to contribute to improved thermal perception and aesthetic appreciation (Lenzholzer and Van der Wulp, 2010). And for larger urban green spaces, like parks, Klemm et al. (2015a) demonstrated a strong correlation with long-term experience of thermal comfort. More insights into psychological aspects of street greenery on perceived thermal comfort are needed to create thermally comfortable streetscapes for the urban population.

4.1.1 The objective of this paper

This study aims to contribute to design guidelines for street greenery for thermally comfortable streetscapes within moderate climates. To comprehensively describe the impact of street greenery on thermal comfort, we combined investigations on physical thermal conditions and perceived thermal comfort, as suggested by recent studies (Chen and Ng, 2012, Nikolopoulou, 2011, Nikolopoulou and Steemers, 2003, Vanos et al., 2010). Our investigations focused on residential streets in summer weather conditions in the Netherlands and answered the following research questions:

- *What is the impact of street greenery (street trees and front gardens) on the physical thermal comfort parameters T_a and T_{mrt}?*
- *What is the impact of street greenery (street trees and front gardens) on momentary perceived thermal comfort?*
- *How does momentary perceived thermal comfort relate to the evaluation of green street design (aesthetic appreciation)?*
- *What is the impact of street greenery (street trees and front gardens) on long-term perceived thermal comfort?*

4.2 Methods

Research methods from landscape architecture, micrometeorology and social geography were combined to measure the impact of street greenery on thermal comfort. We examined nine street canyons with similar spatial configurations and different amounts of street greenery.

4.2.1 Study area and sites

Our study was conducted in the city of Utrecht (52° 05′ 33″ N; 5° 05′ 47″ E; 4 m elevation) which is the fourth largest city of the Netherlands. It has a population of 330.000 and a population density of 3.300/km^2 (CBS, 2014). Utrecht's climate is characterized as maritime mild mid-latitude (Köppen climate classification Cfb).

We examined nine streets with row houses in the Rivierenwijk neighbourhood (Figure 4.1). This type of residential street was selected because row houses represent almost 50% of the housing production in the Netherlands (SenterNovem, 2006). All nine streets were characterized by similar geometric configurations of the street canyons (Table 4.1, Figures 4.2 and 4.3). Similar geometric configuration encompasses an average street canyon height to width ratio of 0.48 (SD 0.07), a northeast-southwest street orientation (average azimuth of 198°, SD 10), sloping roofs, and ground surface materials of brown bricks, grey tiles and facades of red bricks. The amount and disposition of present street greenery, including street trees and (private) front gardens, differed.

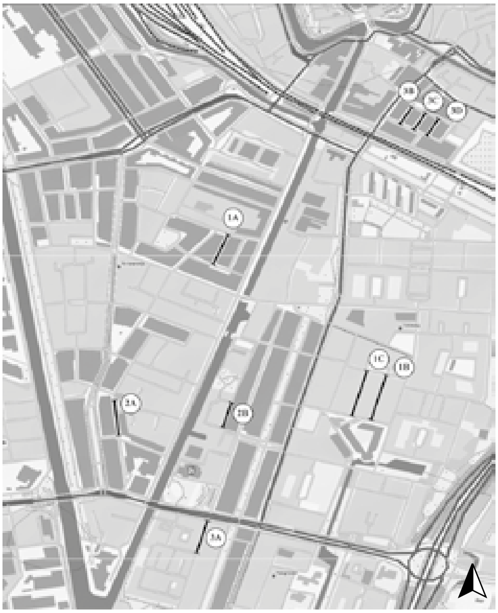


Figure 4.1: Location of the nine streets located in the Rivierenwijk neighbourhood in Utrecht, the Netherlands (TOP10 map)

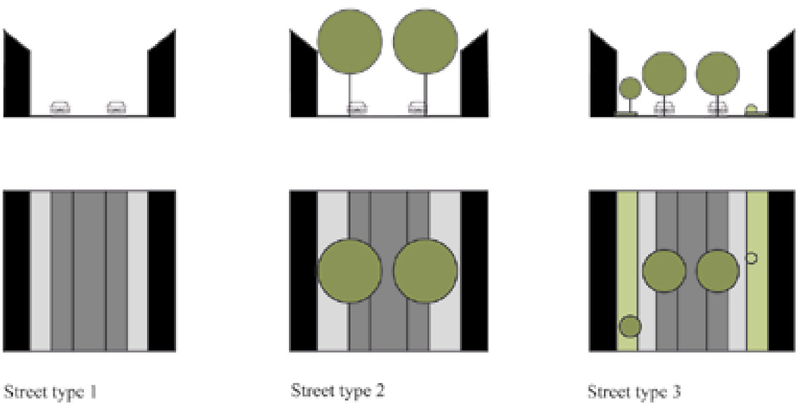


Figure 4.2: Generic street profiles and maps of the three street types: 1. no greenery, 2. street trees on both sides, 3. street trees combined with front garden on both sides

Table 4.1: Geometric configuration of the street canyons and street tree properties in the nine investigated streets

Street type	Nr.	Street name	Street canyon			Street trees						
			Width (m)	H/W ratio (-)	Azimuth (°)	Tree height (m)	Crown diameter (m)	Crown shape	Distance between trees (m)	Distance between tree - facade (m)	Species *	Year of planting *
1: Without greenery	1A	Alblasstraat	12.4	0.50	203	-	-		-	-	-	-
	1B	Soestdijkstraat	10.4	0.60	195	-	-		-	-	-	-
	1C	Noordeindestraat	10.4	0.60	196	-	-		-	-	-	-
		average	11.1	0.57	198	-	-		-	-	-	-
2: With street trees	2A	Berkelstraat	12.0	0.50	174	10	5	upright oval	17-28	3.4	Pyrus calleriana 'Chanticleer'	1995
	2B	Vaartscherijnstraat	15.0	0.40	195	10	7	v-shape	7	3	Crataegus monogyna 'Stricta'	1965
		average	13.5	0.45	185	10	6		14.8	3.2		
3: With street trees and front gardens	3A	Verlengde Hoogravensweg	15.5	0.39	196	6	3	flat oval	6-27	5	Prunus serrulata 'Kwanzan'	1990
	3B	Snipstraat	13.6	0.44	209	6	3	flat oval	27	4.5	Prunus gondouinii 'Schnee'	1990
	3C	Sternstraat	14.0	0.43	208	6	5	flat oval	27	4.5	Prunus gondouinii 'Schnee'	1975
	3D	Duikerstraat	13.6	0.44	208	6	5	flat oval	27	4.5	Prunus gondouinii 'Schnee'	1975
		average	14.2	0.42	205	6	4		24.4	4.6		

* Municipality of Utrecht, T. N. Tree map of Utrecht (Bomenkaart Utrecht) Retrieved October 4th 2013, from http://utrecht.gemgids.nl/bomenkaart/

Figure 4.3: Impression of the nine investigated street divided into three street types: 1. no greenery, 2. street trees on both sides, 3. street trees combined with front garden on both sides (GoogleMaps, 2012)

4

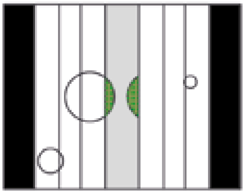
4.2.2 Vegetation and planting parameters of street greenery

We identified three street types: 1. no greenery, 2. street trees on both sides and 3. streets trees combined with front gardens on both sides (Figure 4.2). Compared to street trees in street type 2, street type 3 is characterized by street trees with smaller tree crowns and scattered single trees in the front gardens. Table 4.1 provides an overview of vegetation and planting parameters of the street trees in the nine investigated streets. The parameters height, diameter, shape, distance between trunks, and distance between tree trunks and facade were estimated in the field and checked using maps and high resolution digital photographs (3264 x 2448 pixels, Canon S80). These parameters have previously been identified to affect tree shade within street canyons (Armson et al., 2013, Lee et al., 2013, Berry et al., 2013).

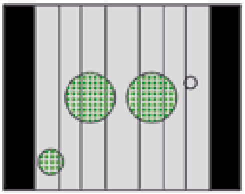
In order to examine the impact of street trees and front gardens on T_a and T_{mrt}, three fractions of vegetation cover in the streets were distinguished using on-site investigations, maps and (aerial) photographs. We defined the fraction of tree cover within the street canyon (including street trees and trees in front gardens) similar to the tree shading coverage investigated in earlier studies (Shashua-Bar and Hoffman, 2000). Additionally, we investigated the fraction of tree cover above the road and the fraction of low greenery within the street canyon (including grass, hedges an bushes mainly in front gardens) (Figure 4.4, Table 4.2).

Table 4.2: Fractions of present amount of street greenery in the nine investigated streets

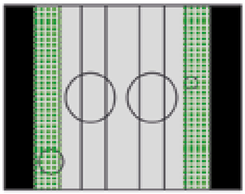
Street type	Nr.	Street name	Tree cover above the road (%)	Tree cover within the street canyon (%)	Low greenery within the street canyon (%)
1: Without greenery	1A	Alblasstraat	0	0	0
	1B	Soestdijkstraat	0	4	0
	1C	Noordeindestraat	0	0	0
		average	0	1	0
2: With trees	2A	Berkelstraat	25	24	0
	2B	Vaartscherijnstraat	8	54	0
		average	17	39	0
3: With trees combined with front gardens	3A	Verlengde Hoogravensweg	3	7	10
	3B	Snipstraat	5	10	5
	3C	Sternstraat	12	15	6
	3D	Duikerstraat	14	18	7
		average	8	13	7



a) Tree crown cover above the road



b) Tree crown cover within the street



c) Low vegetation cover within the street

Figure 4.4: Present amount of street greenery represented by estimated fractions of vegetation cover within the streets: a) Tree crown cover above the road, b) Tree crown cover within the street canyon, c) Low vegetation cover within the street canyon, d) Total vegetation cover within the street canyon

4.2.3 Investigating physical parameters

Micrometeorological measurements

Micrometeorological measurements were carried out on five days in July and August 2012 using a specially developed cargo-bicycle (Heusinkveld et al., 2010, Heusinkveld et al., 2014, Klemm et al., 2015a). The bicycle trajectory covered all nine streets, with cycling on the road, in the middle of the street canyons. This route was cycled continuously between 9:00 and 16:00 UTC.

The cargo-bicycle was equipped with a shielded thermometer, a humidity sensor, a 2-dimensional sonic anemometer and 12 radiation sensors to measure solar radiation and thermal infrared radiation exchange from six directions (Figure 4.5). Detailed information about the measurement equipment is provided by Heusinkveld et al. (2014). The sensors recorded data on T_a, humidity (h), wind velocity (u) and radiation for every second. These data were combined with location data from a GPS device. Wind speed measurements were corrected for bicycling speed. For each parameter we calculated street averaged values as pedestrians or cyclists mostly move through streets and experience changes in sun and shade rather than standing under a single tree.

Figure 4.5: Cargo-bicycle equipped with micrometeorological measurement sensors (Heusinkveld et al., 2010)

Analysis of micrometeorological data

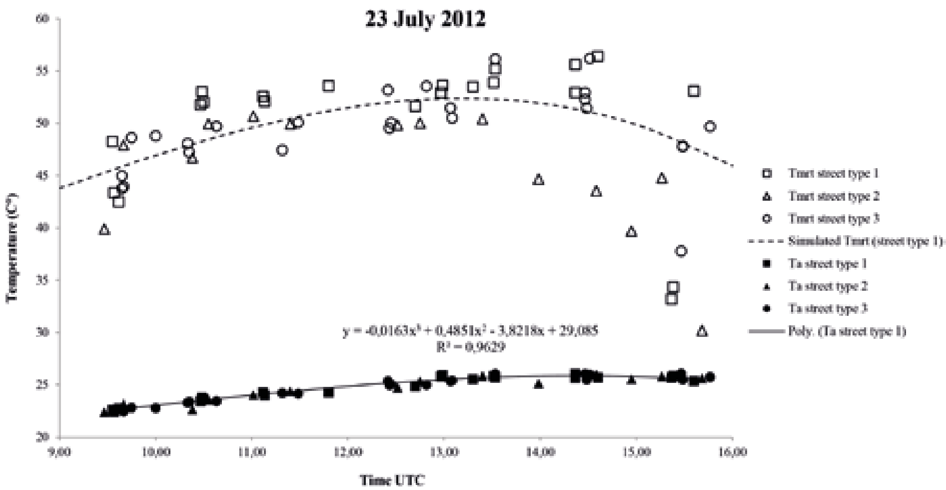
Besides T_a we focused on analyzing T_{mrt}, as it strongly determines thermal comfort conditions during warm Central European summer weather (Holst and Mayer, 2011, Lee et al., 2013, Streiling and Matzarakis, 2003). Furthermore, T_{mrt} represents solar and thermal radiation conditions which are controlled by the local physical environment including the geometric configuration of the street canyon and the present amount of street greenery. We calculated T_{mrt} for the three street types based on the solar and thermal radiation data .

Figure 4.6 exemplarily presents the diurnal cycles related to T_a and T_{mrt} on July 23rd 2012 between 9:00 and 16:00 UTC (an overview of all measurements days is provided in Appendices M to Q). In order to reduce the bias created by shading of the buildings within the street canyons, we focused on the period between 9:00 and 15:00 UTC (in August between 10:00 and 14:00 UTC) for further analyses.

The mobile measurements conducted with the cargo-bicycle resulted in a time delay between the measurements in the different streets (Figure 4.6, Table 4.3). Therefore, simply comparing actual data would be insufficient, in particular as the diurnal cycles of T_a and T_{mrt} in the morning and late afternoon were steep (Appendices M to Q). To minimize the possible bias caused by a time delay between measurements we chose to use the street type without greenery (street type 1) as a reference street and evaluated the differences between the reference street and the vegetated street types (type 2 and 3).

In order to compare T_a between the street types the measurement data for the diurnal T_a cycle were corrected. To do so we fitted a third order polynomial function through the T_a measurements of the reference street for every measurement day. We then calculated the T_a deviation from the fitted trendline for each street type.

T_{mrt} measurements also required a correction for the diurnal radiation cycle, as the reference street T_{mrt} measurements were too scattered to fit a reliable trendline, possibly resulting from cars passing or slight deviations in the cycling trajectory. Therefore, we decided to use global radiation data of the nearby World Meteorological Organization station in De Bilt (KNMI, 2013) and an urban canyon radiation model to simulate the diurnal T_{mrt} cycle of the reference street for each measurement day. We selected the model Rayman (Matzarakis et al., 2007) which required meteorological data (T_a, humidity, wind speed and global radiation) and a digital urban canyon model (the reference street) as input parameters.



T_{mrt} trendline is based on a reference street canyon (street type 1) simulated in Rayman (Matzarakis et al., 2007) using the actual daily global radiation data from a nearby weather station (KNMI, 2013)

Figure 4.6: Air temperature (T_a) and Mean radiant temperature (T_{mrt}) in the three street types: 1. no greenery, 2. street trees, 3. street trees combined with front garden. In Utrecht, the Netherlands on July 23rd 2012

We chose default parameters for albedo (0.3) and emissivity (0.95) to represent the typical materials in the investigated streets. The simulated data were fitted through the measured T_{mrt} (Figure 4.6 and Appendices M to Q) to find the best interpolation line for that canyon. We then calculated the T_{mrt} deviation from the fitted trendline for each street type.

To investigate the influence of street greenery on T_{mrt}, mean averaged street values were compared with the three fractions of vegetation cover (Table 4.2) using ANOVA regression analysis.

Table 4.3: Mean street averaged values for air temperature (T_a), relative humidity (h), wind velocity (υ) and mean radiant temperature (T_{mrt}) in the three street types on all measurement days (10:00-12:00 UTC)

Date	Parameter	Street type 1 Without greenery	Street type 2 With street trees	Street type 3 With street trees and front gardens
23-07-2012	Time UTC [a]	11:21	11:12	11:24 [b]
	T_a (C°)	24.2	24.2	24.2
	h (%)	42.7	42.4	41.7
	υ (ms^{-1})	1.0	0.7	1.4
	T_{mrt} (C°)	52.7	50.3	48.7
25-07-2012	Time UTC [a]	11:35	11:40	11:40
	T_a (C°)	28.7	28.4	28.2
	h (%)	36.2	37.3	37.6
	υ (ms^{-1})	1.5	1.2	0.8
	T_{mrt} (C°)	55.2	52.6	53.1
26-07-2012	Time UTC [a]	11:16	11:34	11:15
	T_a (C°)	25.2	25.7	25.2
	h (%)	46.0	45.0	46.4
	υ (ms^{-1})	1.7	1.2	1.1
	T_{mrt} (C°)	54.5	51.9	52.0
18-08-2012	Time UTC [a]	11:20	11:16	11:30
	T_a (C°)	29.6	29.8	29.6
	h (%)	45.6	43.8	45.4
	υ (ms^{-1})	1.0	0.7	1.3
	T_{mrt} (C°)	56.5	54.1	55.0
19-08-2012	Time UTC [a]	11:58	11:52	11:40
	T_a (C°)	31.9	32.0	32.0
	h (%)	42.8	42.3	42.7
	υ (ms^{-1})	1.2	1.0	1.3
	T_{mrt} (C°)	56.4	54.8	54.4

[a] Mean value of the Time UTC of all single street measurements within a street type
[b] Based on measurements in two out of the four streets in this street type

4.2.4 Investigating psychological parameters

Study design

Semi-structured interviews with pedestrians in the nine selected streets were conducted on eleven days from June to September 2012 between 9:00 and 17:00 UTC. In total, 108 randomly selected pedestrians were interviewed (street type 1: N = 37, street type 2: N = 28, street type 3: N = 43). Respondents represented both sexes and all ages (excluding children) and were mainly inhabitants of the chosen streets or the immediate vicinity. We only selected respondents who had been outdoors for at least 10 minutes to reach their metabolic equilibrium (ACSM, 2006). 87 people did not want to take part in the interview for various reasons.

Interviews

The interview consisted of three parts, starting with the part on respondents' individual characteristics (e.g., age, sex, clothing). The second part took up respondents' momentary thermal perception in the specific street by asking respondents "How do you experience the microclimate at this moment at this place?". We differentiated between single micrometeorological parameters (air temperature, sun, humidity and wind) and the overall experience of thermal comfort. To evaluate the aesthetic appreciation of street greenery respondents were asked "How do you experience the green design of this street?". Additionally, they were asked for possible improvements of the green design.

In the third part, respondents were asked to evaluate their general (i.e., long-term) thermal perception in the specific street. They were asked to indicate comfortable and uncomfortable zones which they had experienced over a longer period in the specific street. Those zones had to be marked either by the respondent or the interviewee on a map during the interview. This cognitive mapping has been applied before to examine thermal perception in urban spaces (Klemm et al., 2015a, Lenzholzer, 2008). Additionally, respondents were asked to explain reasons for their thermal perception.

Investigating perceived thermal comfort with pedestrians needed special attention because most of the respondents, as expected, were not familiar with the term 'thermal comfort'. To avoid misunderstanding about the content of the questions a guiding document was created in advance to help explain certain questions. All interviews were conducted by the same interviewer so that all respondents had similar guidance through the interview.

Data analysis

To analyze the interview results we applied response frequencies, means and standard deviations as descriptive statistics. One-way ANOVA analysis and Post-Hoc tests were used to assess the reliability of the relationship between the different concepts.

Only 27% of the 108 respondents defined comfortable or uncomfortable zones on the maps, based on which we could not indicate common spatial preferences of thermal perception, e.g., of a certain sidewalk. Therefore, we excluded the cognitive maps from the further analyses. However, 73% of all respondents clarified reasons for their thermal perception. Consequently, we focused on those answers. The analyses were carried out in Excel 2010 and SPSS 19.

4.3 Results and discussion

4.3.1 Physical impact of street greenery on thermal comfort

We collected data on July 23rd, 25th, 26th, August 18th and 19th 2012 mainly between 9:00 and 16:00 UTC. The measurement days showed similar fair, cloudless weather conditions and actual sunshine duration was above the long-term average of sunshine duration in that period (KNMI, 2013) (Table 4.4). According to KNMI standards (KNMI, 2013) two of the five days were hot summer days ($T_{a\ max}$ above 25 °C), three were tropical summer days ($T_{a\ max}$ above 30 °C).

Humidity and wind velocity were similar during measurements days. Humidity entities ranged from 57 to 63%; wind entities ranged from 0.2 to 0.5 m/s indicating calm to light air with no noticeable wind (according to the scale of Beaufort) (Table 4.4). Humidity and wind conditions within the investigated street canyons (Table 4.3) were inhomogeneous with little variances, which can be related to large-scale roughness inhomogeneity of wind circulations rather than to the local physical environment.

Air temperature (T_a)

Using street type 1 as the reference street, our measurements did not show significant differences in mean street averaged T_a between the

Table 4.4: General meteorological conditions on the micrometeorological measurement days in Utrecht, the Netherlands

	T_a daily mean (°C)[1]	T_a daily max (°C)[1]	h daily mean (%)[1]	u daily mean (m/s)[1]	Relative sunshine duration (%) (compared to normal rel. sunshine duration (%)[2]) [3]
23-07-2012	21.0	27.3	59	0.4	92 (41)
25-07-2012	24.4	30.3	60	0.2	87 (41)
26-07-2012	26.1	28.9	57	0.5	86 (41)
18-08-2012	26.4	34.2	57	0.4	78 (43)
19-08-2012	27.6	34.4	63	0.4	64 (43)

[1] Weatherunderground, 2013
[2] The normals are long-term averages over the period 1981-2010
[3] KNMI, 2013

different street types (Figure 4.7 and Table 4.5). The scatter in T_a of about 0.3 K standard deviation (Table 4.5) is mainly related to temperature advection and convective turbulence within the streets (Brown and Gillespie, 1990). Accordingly our results do not indicate T_a reductions within street canyons by street trees or front gardens.

These results are in accordance with those of earlier studies (Armson et al., 2013, Mazhar et al., 2015), although measurements in those studies were conducted directly in the shade of trees.

Similar studies in the shade of large single or clustered trees compared to a sunny spot nearby found T_a differences up to 1.7 K (Lee et al., 2013, Streiling and Matzarakis, 2003) in moderate and up to 15.7 K (Abreu-Harbich et al., 2015) in tropical climates.

Studies with more comparable measurements in the middle of the road only were conducted outside moderate climates. Compared to streets without trees, in streets with trees T_a was up to 5.6 K lower in tropical climate (Vailshery et al., 2013) and up to 1.3 K lower in Mediterranean climate (Shashua-Bar and Hoffman, 2000).

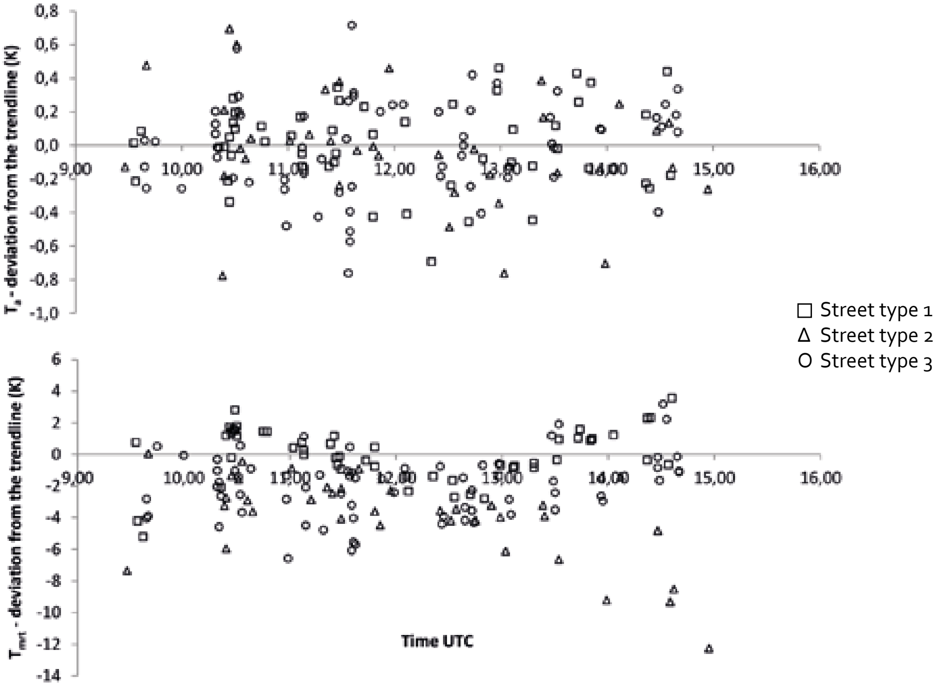
Mean radiant temperature (T_{mrt})

Our results showed a significant impact of street greenery on T_{mrt}, as expected. Street averaged T_{mrt} in streets without greenery (street type 1) was up to 4.8 K higher than in streets with trees (street type 2) and up to 2.6 K higher than in streets with trees combined with front gardens (street type 3) (Figure 4.7 and Table 4.5). Our measurement data of T_{mrt} are in line with results presented by Armson et al. (2013), who found a mitigating effect of 4 K directly under trees comparable to those in street type 2.

*Table 4.5: Mean differences (**Δ**) and standard errors (SD) of air temperature (T_a) and mean radiant temperature (T_{mrt}) for street type 2 and street type 3 in relation to the reference street type 1 (without greenery)*

Date	Δ T_a (C°)[b]			Δ T_{mrt} (C°)[c]		
	Street type 1 Without greenery	**Street type 2** With street trees	**Street type 3** With street trees and front gardens	**Street type 1** Without greenery	**Street type 2** With street trees	**Street type 3** With street trees and front gardens
23-07-2012	0.00 (0.24)	-0.13 (0.35)	-0.08 (0.19)	0.00 (2.22)	-4.77 (3.76)	-1.75 (2.08)
25-07-2012	0.01 (0.30)	-0.02 (0.29)	0.04 (0.33)	0.00 (1.39)	-3.65 (1.97)	-1.86 (1.87)
26-07-2012	0.02 (0.25)	-0.06 (0.43)	0.08 (0.22)	0.00 (1.37)	-4.02 (0.24)	-1.99 (0.34)
18-08-2012[a]	-0.01 (0.07)	0.16 (0.12)	-0.27 (0.15)	0.00 (1.23)	- 2.82 (0.55)	-2.60 (2.08)
19-08-2012[a]	-0.01 (0.26)	0.22 (0.32)	0.24 (0.21)	0.00 (1.48)	-3.35 (1.67)	-2.58 (1.80)
Mean	0.00 (0.25)	0.03 (0.34)	0.00 (0.28)	0.00 (1.45)	-3.72 (1.49)	-2.16 (1.46)

[a] Measurements on August 18th and 19th 2012 were limited between 9:00-12:30 UTC
[b] Based on a third order polynomial function through the T_a measurements of reference street type 1 for every measurement day
[c] Based on a simulated trendline of the diurnal T_{mrt} cycle of the reference street type 1 for each measurement day



* T_{mrt} trendline is based on a reference street canyon (street type 1) simulated in Rayman (Matzarakis et al., 2007) using the actual daily global radiation data from a nearby weather station (KNMI, 2013)

Figure 4.7: (Top panel) Air temperature (T_a) deviation in relation to reference street type 1 and (lower panel) mean radiant temperature (T_{mrt}) deviation in relation to reference street type 1; in the three street types: 1. no greenery, 2. street trees, 3. street trees combined with front garden. In Utrecht, the Netherlands on July 23rd, 25th, 26th, August 18th and 19th 2012

Not surprisingly, our results related to T_{mrt} are lower than the measured effects of large single or clustered tree canopies in temperate climates. The decrease of T_{mrt} by 32.8 K (Lee et al., 2013) and 21.0 K (Streiling and Matzarakis, 2003) can be attributed to the larger and denser tree canopies and measurements of $T_{a\ max}$ directly in tree shade. Comparable to T_a we expect that T_{mrt} differences would have been larger if we would have used measurement points under single trees instead street averaged values based on measurements in the middle of street canyons.

It can be derived from our results that streets with larger street trees (street type 2) are slightly more comfortable during the hot summer days than streets with smaller street trees and front gardens (street type 3). T_{mrt} street averaged values of streets with trees (street type 2) were up to 3 K lower than in streets with trees and front gardens (street type 3). This result can be attributed to the amount of tree crown cover. The tree crown cover within the street canyon in street type 2 (39%) is three times larger than in street type 3 (13%) (Table 4.2). Tree crown cover in street type 2 and street type 3 are adequate to provide a street averaged reduction of T_{mrt} up to 4.8 K and 2.6 K, respectively.

Our results demonstrated that T_{mrt} is significantly related to tree cover within street canyons (p = 0.0001) (Table 4.6). T_{mrt} was less influenced by low greenery within the street canyons (p = 0.16) and tree cover above the road (p = 0.001). Hence, both street trees and trees in front gardens contributed to the T_{mrt} reduction within street canyons. For our investigated streets with estimated tree crown covers up to 54% within street canyons we conclude that 10% tree crown cover lowers T_{mrt} by about 1 K (Figure 4.8). This is in accordance with other studies, that found a strong relationship between tree crown cover and outdoor thermal comfort (Ali-Toudert and Mayer, 2007, Lee et al., 2013, Streiling and Matzarakis, 2003, Abreu-Harbich et al., 2015, Brown et al., 2015, Mazhar et al., 2015).

Table 4.6: Relationship between mean radiant temperature (T_{mrt}) and fractions of present amount of greenery in the nine investigated streets (through ANOVA regression analysis)

	Tree cover above the road (%)	Tree cover within the street canyon (%)	Low greenery within the street canyon (%)
$T_{mrt\ Standard\ Error}$	1.3034	1.0225	2.3281
$T_{mrt\ p}$	0.0010	0.0001	0.1568

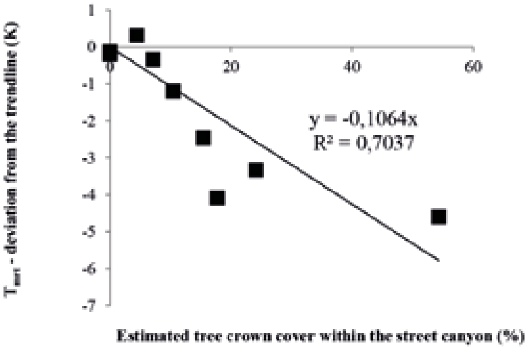


Figure 4.8: Relation between mean radiant temperature (T_{mrt}) and the estimated tree crown cover within the street canyon for the nine investigated streets in Utrecht, the Netherlands on July 23rd, 25th, 26th, August 18th and 19th 2012, 9:00-15:00 (UTC)

These findings are in line with a subsequent analysis on the gap fraction of tree crowns as an indicator for solar permeability (Appendix R). For example, street 2B (Vaartscherijnstraat) has a tree crown cover within the street canyon of 54% (Table 4.2); yet the gap fraction of the tree crowns is comparably high (47%) to those of the other investigated streets (mean 33%). The shading effect within street 2B is thus overestimated (and explains the appearance as outlier in Figure 4.8) by considering tree canopy cover exclusively. Even though it was not a focus of this study, we conclude that solar permeability analyses, such as conducted by Abreu-Harbich et a. (2015), should be included in future studies on effects of tree crown covers on T_{mrt}.

4.3.2 Psychological impact of street greenery on thermal comfort

We collected data on eleven days from June to September 2012 between 9:00 and 17:00 UTC (Table 4.7). The interview days covered weekdays and weekends and represented average summer weather conditions in the Netherlands. Maximum daily T_a values of the city centre varied between 18.8 - 34.4 °C (Weatherunderground, 2013). The actual sunshine duration was on most days above the long-term average of sunshine duration in that period (KNMI, 2013). Wind velocity daily means ranged from 0.1 to 0.5 m/s representing calm to light air with no noticeable wind (Weatherunderground, 2013). Respondents generally were dressed light open (average 0.57 clo) during the warm summer days ($T_{a\ max}$ < 25°C) and lighter (average 0.45 clo) on the hot summer days ($T_{a\ max}$ > 25 °C) according to (ASHRAE, 2005) (Table 4.7).

Table 4.7: General meteorological conditions and clothing parameter of respondents on the interview days in Utrecht, the Netherlands

Date	Period of interviews (UTC)	T_a daily mean (°C)[1]	T_a daily max (°C)[1]	h daily mean (%)[1]	u daily mean (m/s)[1]	Relative sunshine duration (%) (compared to normal rel. sunshine duration (%)[2,3])	Estimated mean clo of respondents[4]
21-07-2012	09-15	15.2	18.8	71	0.1	16 (41)	0.52
22-07-2012	09-15	17.2	22.4	66	0.3	87 (41)	0.50
23-07-2012	09-16	21.0	27.3	59	0.4	92 (41)	0.49
25-07-2012	14-15	24.4	30.3	60	0.2	87 (41)	0.33
09-08-2012	09-16	18.3	22.7	75	0.2	74 (43)	0.54
10-08-2012	09-17	17.6	23.2	67	0.2	87 (43)	0.57
11-08-2012	11-15	17.9	22.1	72	0.3	41 (43)	0.52
29-08-2012	09-14	18.9	25.3	73	0.4	68 (37)	0.47
30-08-2012	10-11	16.7	21.5	82	0.5	41 (37)	0.57
04-09-2012	09-16	19.3	25.2	78	0.3	79 (38)	0.52
07-09-2012	09-15	18.2	23.6	78	0.5	76 (38)	0.74

[1] Weatherunderground, 2013
[2] The normals are long-term averages over the period 1981-2010 (KNMI, 2013)
[3] KNMI, 2013
[4] ASHRAE, 2005

Momentary perceived thermal comfort

Our interview results suggested that momentary perceived thermal comfort was related to the amount of street greenery. The evaluation of air temperature, sun and humidity and the evaluation of the overall thermal comfort (Table 4.8) illustrated that streets with street trees and front gardens (street type 3) were rated slightly more thermally comfortable than the other two street types (i.e., 1.14, compared to 0.92 in street type 2 and 0.84 in street type 1 related to overall thermal comfort). Wind was evaluated differently; it was rated as comfortable in street type 3 (1.00) and slightly less comfortable in streets without greenery (0.95) and in streets with trees and front gardens (0.88). However, the results were not statistically significant; the evaluation of overall thermal comfort was marginal significant ($p = 0.100$). We relate this fact to the small interval between all responses in the ratings (i.e., 0.57 - 1.21), and the low number of respondents for each street type.

When comparing the momentary thermal perception and the physical thermal conditions, represented by T_a and T_{mrt}, we present two findings. First of all, streets without greenery (street type 1) were rated

Table 4.8: Momentary perceived thermal comfort of individual microclimate parameters and overall thermal comfort in the three street types (N = number of respondents)

Perceived thermal comfort[a]		Temperature	Sun	Humidity	Wind	Overall thermal comfort
Street type	**N**	**Mean[b] (SD)**	**Mean[b] (SD)**	**Mean[b] (SD)**	**Mean[b] (SD)**	**Mean[c] (SD)**
1 - Without greenery	37	0.89 (0.61)	0.70 (0.73)	0.57 (0.55)	0.95 (0.73)	0.84 (0.55)
2 - With street trees	28	1.00 (0.62)	0.81 (0.96)	0.65 (0.68)	0.88 (0.58)	0.92 (0.67)
3 - With street trees and front gardens	43	1.21 (0.88)	0.93 (0.90)	0.70 (0.79)	1.00 (0.65)	1.14 (0.67)
Mean		1.03 (0.70)	0.81 (0.81)	0.64 (0.67)	0.94 (0.65)	0.97 (0.63)

[a] Responses coded on a five-point scale from dislike very much (-2) to like very much (+2)
[b] Means are not statistically significant
[c] Means are marginal statistically significant (p = 0.100)

less thermally comfortable than the other street types by pedestrians (Table 4.8). That corresponded with the actual physical conditions characterized by higher T_{mrt} values indicating more radiation in street type 1 than in the other street types (Table 4.5).

Secondly, pedestrians evaluated their overall thermal perception in streets with trees combined with front gardens more comfortable (i.e., 1.14; street type 3) than in streets with trees (i.e., 0.92; street type 2) (Table 4.8). This disagreed with the actual physical conditions. Streets with trees and front gardens (street type 3) showed street averaged T_{mrt} values up to 3 K higher than streets with trees (street type 2) (Table 4.6). Thus, despite the higher radiation in streets with trees and front gardens (street type 3) perceived thermal comfort was rated more positively in those streets than in streets with trees (street type 2). This finding could be explained by the more varied view of different types and heights of vegetation in streets with trees and front gardens (street type 3) than streets with trees only (street type 2). Streets with front gardens offer views for example of arrangements of low vegetation beds, medium high hedges, small trees or climbing constructions. That the visual field contains more varied vegetation in streets with trees and front gardens (street type 3) as opposed to streets with trees only (street type 2) probably leads to a better thermal perception.

However, our interview data on appreciations of green street design (Table 4.9) and on momentary perceived overall thermal comfort (Table 4.8) did not indicate a significant relationship between the two (p = 2.0, r = 0.124). Hence, we cannot conclude that aesthetic appreciation of environments relates to momentary thermal perception (Lafortezza et al., 2009, Lenzholzer and Van der Wulp, 2010, Nikolopoulou and Steemers, 2003).

Respondents significantly valued the presence of street greenery in aesthetic terms (Table 4.9) which confirms earlier studies (Qin et al., 2013, Smardon, 1988, Ulrich, 1986, Kaplan et al., 1998). Respondents appreciated streets with trees and streets with trees and front gardens more than streets without greenery ($p < 0.001$). The strong appreciation for street greenery was also indicated by respondents' proposals on improving the design of the street. 75% of the respondents in streets without greenery (street type 1) gave suggestions for improving the green street design compared to 46% in streets with street trees (street type 2) and 6% in streets with street trees and front gardens (street type 3) (Table 4.10).

Long-term perceived thermal comfort

Respondents were hardly able to locate their general (i.e., long-term) thermal perceptions in a residential street on a cognitive map. Only 27% of the 108 respondents identified (un-)comfortable zones on the map. It has been indicated earlier that people can have difficulties

Table 4.9: Evaluation of green street design in three street types

Evaluation of green street design[a]	Mean[b] (SD)
1 - Street type without greenery	-0.16 (0.79)
2 - Street type with street trees	0.68 (0.60)
3 - Street type with street trees and front gardens	0.98 (0.55)

[a] Responses coded on a five-point scale from very uncomfortable (-2) to very comfortable (+2)
[b] Values with from street types 1 and 2 and values from street types 1 and 3 are statistically significant from each other

Table 4.10: Response frequencies of proposals for improvement of the green street design in three street types

Street type	More overall greenery	More/ larger trees	More/ larger hedges	More grass/ low plants	More/ larger front gardens	More plant and flower boxes
1 - Without greenery	0.32	0.35	0.11	0.05	0.30	0.08
2 - With street trees	0.29	0.00	0.04	0.04	0.18	0.11
3 - With street trees and front gardens	0.09	0.12	0.00	0.02	0.07	0.02

to directly relate spatial configurations to microclimate (Lenzholzer, 2010b, Lenzholzer, 2010a). The majority of respondents (73%) had 'no preferences for specific zones of thermal comfort' or they had 'no idea'. We suppose that the small scale and limited spatial variance of the symmetrically designed NE-SW oriented street canyons made it difficult for respondents to define zones of long-term thermal perception. In contrast to this study, cognitive maps of larger urban configurations have yielded clear results which show that people assess certain spaces in relation to microclimate (Klemm et al., 2015a, Lenzholzer, 2008).

However, when asked for features that determine thermal comfort in a certain space, people indicated that temporal variance, i.e., diurnal (37% of respondents), would play a role (Table 4.11). People were aware of microclimate variance within the street and adapt (i.e., change sides of the sidewalk to either be in the sun or the shade). This form of human adaptation to microclimate has been mentioned before for parks and squares (Thorsson et al., 2004, Nikolopoulou et al., 2001).

Long-term thermal comfort is also associated with sun (33%) and less with shadow (17%) and street greenery (14%) (Table 4.11). That indicates that respondents were more aware of microclimatic variances (presence of sun and shade) than of the influence of street greenery on their thermal perception in a street canyon.

4.3.3 Limitations and potentials of the study design

Since our investigations were carried out in real urban sites, we necessarily did not have ideal 'laboratory' conditions in the study design. This applies to the selection of the nine cases as well as to the restricted amount of micrometeorological measurements during the five days in

Table 4.11: Response frequencies of features defining long-term thermal comfort in three street types

	Spatial/ temporal preferences		Thermal comfort perception reasons				
Street type	**Diurnal**	**Seasonal**	**Sun**	**Shelter**	**Shadow**	**Wind**	**Greenery**
1 - Without greenery	0.43	0.11	0.24	0.05	0.16	0.08	0.16
2 - With street trees	0.32	0.11	0.39	0.00	0.18	0.11	0.07
3 - With street trees and front gardens	0.35	0.05	0.35	0.07	0.16	0.05	0.19
	0.37	0.09	0.33	0.04	0.17	0.08	0.14

summer 2012. Future research applying similar instruments should be set up e.g., with fixed schedules to minimize temporal variance in data collection.

Furthermore, the sample size of respondents in our study was limited by the number of pedestrians passing by in each street. Future research should be conducted in streets with more passers-by to ensure sufficient respondents to be able to draw more reliable conclusions from the statistical analysis.

We explicitly chose to investigate respondent's thermal perception in a real (natural) urban site to get insights into people's natural experience of thermal comfort related to urban greenery, independent from investigating human thermal sensation including metabolic rate or actual sensation vote. Investigating impact of street greenery on outdoor thermal comfort in a more experimental study design as for example applied by Cheng et al. (2012) has the disadvantage that results could be biased or social desirable answers by respondents. Based on our study design we aim to clarify psychological impacts of street greenery on human perception. We assume that this approach potentially could be expanded in the moderate and other climate regions.

4.4 Conclusions

This study reports on investigations on the impact of street greenery on thermal comfort from a physical and psychological perspective. As such our results contribute to the existing body of knowledge in the field of climate adaptive green infrastructure design. We examined nine residential streets with comparable geometric configurations, but varying amount of greenery (street trees, front gardens) in the city of Utrecht, the Netherlands.

Concerning the first research question *(What is the impact of street greenery (street trees and front gardens) on the physical thermal comfort parameters T_a and T_{mrt}?)*, we did not find an impact of street greenery on mean street averaged T_a within the investigated street canyons. In contrast, a significant ($p < 0.0001$) effect on T_{mrt} has been observed which was related to the shading effects of trees. Mean street averaged T_{mrt} in streets with tree covers of 39% were up to 4.8 K lower than in streets without trees. It could be derived that, in general, 10% tree cover lowers T_{mrt} within a street canyon by about 1 K. Therefore, large tree canopies should be applied in new urban developments and within existing urban areas to lower solar and thermal radiation in order to improve physical thermal comfort conditions.

Concerning the second research question *(What is the impact of street greenery (street trees and front gardens) on momentary perceived thermal comfort?)*, perceived thermal comfort tended to be related to the amount of street greenery. However, we could not identify statistically significant differences, which could be attributed to the low number of respondents for each street type. Hence, we suggest that an enhanced ratio of street greenery in the visual field experienced by pedestrians leads to a better thermal perception; this would be an important in-depth-study.

Concerning the third research question *(How does momentary perceived thermal comfort relate to the evaluation of green street design (aesthetic appreciation)?)*: Although people significantly appreciate street greenery in aesthetic terms ($p < 0.001$), no significant relationship with perceived thermal comfort could be assessed. A strong correlation was found between the present amount of street greenery and proposals to increase the amount of street greenery ($p < 0.001$). Urban planners and designers thus are challenged to provide ample street greenery as people prefer vegetated over non-vegetated streets from an aesthetic point of view.

Concerning the fourth research question *(What is the impact of street greenery (street trees and front gardens) on generally perceived thermal comfort?)*, our results imply that respondents were not consciously aware of the influence of street greenery on their general thermal perception. Overall, respondents found it difficult to locate their general thermal perception on a cognitive map. However, interview results showed that respondents were aware of microclimatic variances (on daily basis) and would adapt to improve their level of thermal comfort in street canyons. Consequently, urban planners and designers are advised to use trees in street canyons to create microclimates of sun and shade. Street trees should not be implemented everywhere but effectively.

In conclusion, street greenery forms a convenient adaptive strategy to create thermally comfortable and attractive living environments. Our results clearly indicate that both physical and psychological aspects of thermal comfort have to be considered in urban design processes.

5 Qualitative methods to explore thermal perception in outdoor urban spaces

Lenzholzer, S., Klemm, W., Vasilikou, C. (2018) "Qualitative methods to explore thermo-spatial perception in outdoor urban spaces." *Urban Climate* 3: 231-249.

Abstract

To be able to design thermally comfortable urban spaces, designers require design guidelines that respond to people's thermal and spatial perception. This thermo-spatial perception is influenced by a range of dimensions: the nature and scale of spatial contexts, the kinetic state of the people and the time scale of their perception ('now' or 'the past'). Recently, novel qualitative methods have been developed to link thermal and spatial information of people's perception. To attain an overview of these methods we conducted an extensive literature review. The results show that these qualitative methods respond to the different dimensions by combinations of momentary and long-term thermal perception research in stationary mode and in motion in varying spatial environments. These qualitative methods deliver explicit combination of thermal and spatial information. Based on that evidence, new knowledge relevant to urban design of thermally comfortable urban spaces can be generated.

5.1 Introduction: concepts and methods in outdoor thermal perception research

Careful climate-responsive design of urban spaces is needed to solve existing urban climate problems and face the challenges induced by climate change. To design thermally comfortable urban environments, designers need design guidelines that combine thermal and spatial matters. Such guidelines should be based on evidence about how urban spatial characteristics (e.g., shapes of buildings and open spaces, materials, distribution and type of vegetation) affect human thermal perception. Methods to study this connection between thermal and spatial perception are novel and need to be discussed and compared. Hence, the main aim of this paper is to give an overview of the new methods to investigate outdoor thermal perception and cast light on their usability for different research objectives.

Since the 1920s studies were conducted on human thermal environments (Houghten and Yaglou, 1923) and different thermal indices (mainly based on air temperature and relative humidity) were developed. A classical concept to describe thermal perception was given by Fanger in the 1970s. He described 'thermal comfort' as 'the human satisfaction with its thermal environment'. Fanger defined this concept for indoor environments and also developed a physiological index (PMV) to describe thermal comfort quantitatively (Fanger, 1972). Since that time, various other physiological indices, e.g., the Physiological Equivalent Temperature PET (Mayer and Höppe, 1987, Matzarakis et al., 1999) and lately the Universal Thermal Climate Index UTCI (Höppe, 2002), were developed to describe thermal comfort (also see the reviews of Chen and Ng, 2012, Knez et al., 2009). All studies that dealt with these indices included micrometeorological measurements of the thermal environments and human physiological responses.

Auliciems (1981) critically discussed these physiological thermal indices and decided to sharpen the use of terms. He described the physiological responses of the human body to thermal states with 'thermal sensation' (p.110) and argued that the common use of the term 'thermal comfort' in the literature is not apt to describe uncomfortable thermal stimuli that humans are often exposed to. Moreover, he called for an adequate consideration of psychological influences (e.g., expectations, climate accommodation, etc.) in the description of thermal experience. He suggested a neutral and inclusive term to describe physiological and psychological influences together: 'thermal perception' (p.119). We will use Auliciems' terminology throughout this paper because his work was seminal for the approaches to thermal perception and gained increasing acceptance throughout the past decade. Nikolopoulou et al. further questioned the purely physiological approach. They demonstrated that a physiological approach only accounts for about 50% of the variation between objective and subjective outdoor thermal perception (Nikolopoulou et al., 2001). The other part of the variation is mainly influenced by psychological factors (Nikolopoulou et al., 2001, Nikolopoulou and Lykoudis, 2006, Nikolopoulou and Steemers, 2003). Apart from that, Aljawabra and Nikolopoulou (2010) as well as Knez and Thorsson (Knez and Thorsson, 2006, Knez et al., 2009) indicated that many other factors such as culture or the climate people are used to, affect thermal perception.

Rohles (1980), Auliciems (1981) and later also Nikolopoulou and Steemers (2003) introduced concepts from environmental psychology into the discourse to describe outdoor thermal perception. One major concept that relates to the temporal and ephemeral character of urban climate concerns the duration of experience: short- and long-term memory. They described how short-term experience was involved in thermal perception: "Short-term experience is related to the memory and seems to be responsible for the changes in people's expectations from one day to the following" (Nikolopoulou and Steemers, 2003, p.97). Later on Knez and his colleagues (Knez et al., 2009) specified the interpretation of 'short-term' and 'memory', introducing the scale of the long-term perception. It seems meaningful to differentiate momentary and longer term experience (Figure 5.1).

Momentary experience describes thermal perception at a specific moment in a specific place ('here and now'). The duration of such experience is in the range of seconds (Knez et al., 2009). A person could, for example, express momentary thermal perception this way: 'I feel cold right now, here in the shade of the building'. Typical studies on this momentary thermal perception entailed interviews of people in outdoor spaces such as the studies of Nikolopoulou et al. on the 'Actual Sensation Vote' (Nikolopoulou and Lykoudis, 2006, Nikolopoulou et al., 2001). An indirect way to acquire insights into people's immediate behavioural response to a thermal environment was the use of observations in urban spaces (Kántor and Unger, 2010, Katzschner,

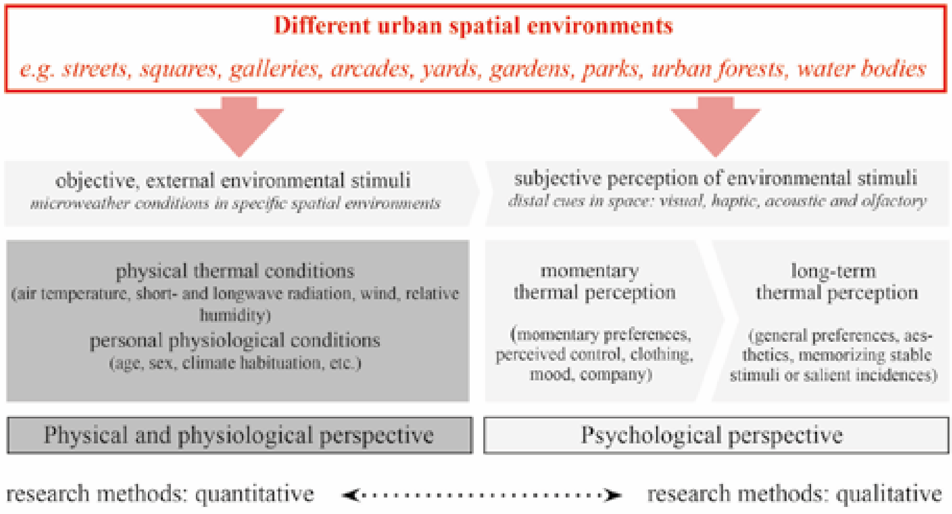


Figure 5.1: Concepts and aspects of outdoor thermal perception and related research approaches

2004, Katzschner et al., 2002). Based on Nikolopoulou's indications (Aljawabra and Nikolopoulou, 2010, Nikolopoulou and Steemers, 2003), Knez et al. (2009) and Lenzholzer (2010b) extended the concept of thermal perception to longer time scales based on so-called 'perception schemata'. These schemata are either based on experiencing a repetition of similar stimuli but they can sometimes also be biased through salient incidences that get 'engrained' in people's memory (Neisser, 1976, Nikolopoulou and Steemers, 2003, Eysenck, 2006, Lenzholzer, 2010b). Perception schemata help to 'pre-sort' information on environmental stimuli and help people to respond adequately. Such perceptual schemata were also described to relate to spatial circumstances (Brewer and Treyens, 1981). A person would talk about long-term thermal perception by expressing the longer duration of the experience clearly, for example: 'It's always too windy over here'. To explore long-term thermal perception, interviews on people's long term experience were conducted in outdoor spaces.

Besides the duration of experience (momentary or long-term), also the spatial and material characteristics of the environment have an influence on thermal perception. Rohles had already indicated, that ambiance and materialization of rooms influence indoor thermal perception (Rohles, 1980). His study indicated that people experience the air temperature in a room as 'warmer' when the room had 'warm' colours and furnishing, although objectively speaking, this did not have an influence on temperature (also see Greene and Bell, 1980, described in: Heijs and Stringer, 1988). Griffiths et al. (1987) introduced 'naturalness' as one part of thermal perception in a spatial environment and the parameter was adopted by various researchers (Nikolopoulou and Steemers, 2003, Nikolopoulou and Lykoudis, 2006, Eliasson et al., 2007). According to Griffiths 'naturalness' is 'the degree of artificiality' of an environment and can thus have spatial connotations e.g., greening areas, creating views on landscape (Nikolopoulou and Steemers, 2003), but it is not very distinct to guide urban design decisions. To provide distinct knowledge for urban design professions, more specific space-related evidence of thermal preferences was needed.

Studies in environmental psychology brought forward that certain urban characteristics (e.g., building configuration, colours, greenery, building materials, etc.) strongly influence human synesthetic experience and behavioural response (e.g., Lindal and Hartig, 2013, Herzog, 1992, Herzog et al., 1976, Smardon, 1988). These considerations of human synesthetic spatial experience guided constituting design guidelines for 'good urban design' (Carmona, 2003, Gehl, 1987). But it is necessary to acquire more specific knowledge about how the spatial environment influences thermal perception as part of the synesthetic experience (Klemm et al., 2015a, Lenzholzer, 2010a, Vasilikou, 2014). The spatial environment (its dimensions, proportions and materials) can be changed through design interventions, whereas other personal factors of thermal perception such as people's clothing, mood, company, etc. cannot be influenced. Therefore it is crucial to understand how spatial environments affect thermal perception. To study the relation of spatial characteristics and thermal perception, existing methods had to be extended and new qualitative methods had be developed that go beyond existing methods from environmental psychology.

Closely linked to the momentary and long-term thermal perception as well as the spatial environment is the kinetic state of the human body – if it is stationary or in movement. It is known that human spatial perception differs significantly in a steady state and in movement (Gibson, 1979). This kinetic state (standstill or movement) can affect thermal perception in space (also see Chen and Ng, 2012, p.119). For instance, the momentary thermal perception has to relate to a specific point in time and space ('here and now') whereas long-term experience can make up for a larger array of experiences. These experiences can entail the 'adding up' of thermal perceptions in smaller scale, but also in larger scale spatial environments and eventually form an engrained mental 'schema' (see Figure 5.2). For urban design, it makes a difference if a space needs to be designed for thermal comfort of people in movement (pedestrian environments) or for people in steady state (e.g., places made for sojourn). Hence, it is essential to study outdoor thermal perception in different kinetic states in space. There have been no earlier studies on these relations and new, especially qualitative methods had to be developed recently to study thermal perception in different kinetic states and different urban spaces.

In the following section we give an overview of such recent qualitative methods to study thermal perception. We attempt to answer the following research question: *Which research methods can be used to investigate thermal perception in relation to the spatial environment?* We describe the qualitative methods using the parameters of temporal and spatial experience in different kinetic states related to thermal experience. Based on that review we reflect on the aptness of the different methods for different research assignments.

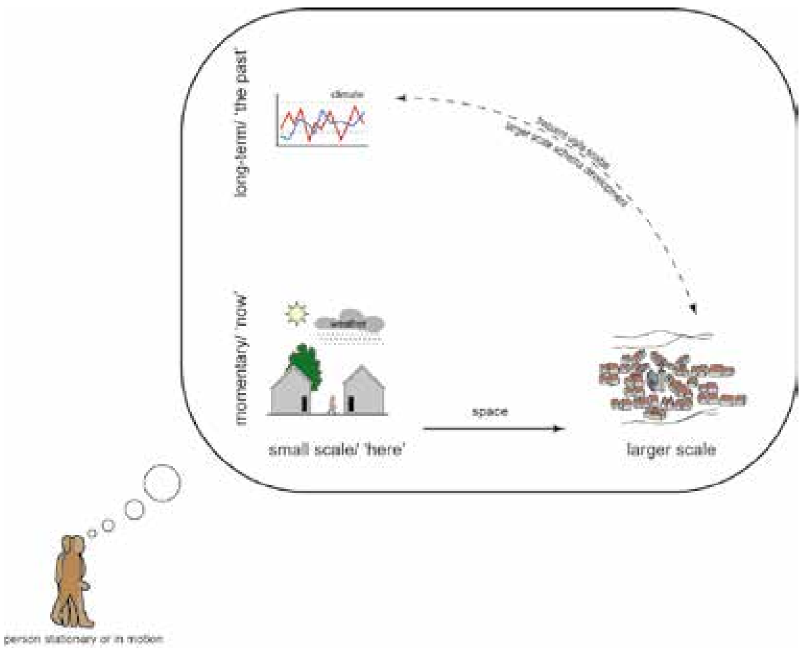


Figure 5.2: Spatio-temporal aspects of thermal perception

5.2 Method and results: Literature review on methods to study spatial aspects of thermal perception

In order to identify methods to investigate thermal perception in relation to space we reviewed the literature (English language only). We selected publications on their content based on our research question: Which research methods can be used to investigate thermal perception in relation to the spatial environment? The first step in the literature search consisted of consulting relevant review papers on outdoor thermal perception explicitly (Chen and Ng, 2012, Johansson et al., 2014, Nikolopoulou, 2011) or implicitly (Blocken and Carmeliet, 2004, Rupp et al., 2015). In these reviews we searched for studies that deal with outdoor thermal perception and spatial aspects and that combined qualitative (e.g., interviews) and quantitative studies (e.g., micrometeorological measurements of physical parameters or with numerical modelling) in order to get a balanced view of the objective and subjective aspects of thermal perception. This first part of the literature study yielded studies that clearly related the spatial setup of a range of urban spaces or sub-spaces with thermal perception (Ahmed, 2003, Lenzholzer and Van der Wulp, 2010, Eliasson et al., 2007, Lenzholzer and Koh, 2010, Mahmoud, 2011). It also yielded some studies about thermal perception in different urban spaces, but these did not elaborate on the impact of the spatial environment explicitly (e.g., Yahia and Johansson, 2014, Tsitoura et al., 2014, Thorsson et al., 2007a). As a second step, we conducted a literature search in Scopus, combining a range of search terms in 'Article titles, abstracts and keywords' that explicitly address spatial connotations. The search terms and relevant yields were the following: "outdoor thermal perception" AND space: 0 relevant yields; "thermal perception" AND outdoor AND spatial: 0 relevant yields; "thermal perception" AND outdoor AND space: 0 relevant yields; "thermal experience" AND space: Lenzholzer and Van der Wulp (2010); "outdoor thermal comfort" AND spatial: Klemm et al. (2015a); "thermal comfort" AND outdoor AND space: Lenzholzer and Koh (2010); "thermal comfort" AND outdoor AND spatial: Klemm et al. (2015a), Lenzholzer and Koh (2010); "thermal comfort" AND urban AND space: Klemm et al. (2015a), Lenzholzer and Koh (2010). Obviously the literature search eventually kept yielding the same results for various search terms and parts of them were already derived from consultation of the general reviews in the first step. In fact, the first two steps of the literature search did not bring forward all the relevant publications known to us. So we terminated the literature search in Scopus and added other relevant publications known to us to the review such as: Böcker et al. (2015), Katzschner (2004), Katzschner et al. (2010), Klemm et al. (2015b), Klemm et al. (2017b), Vasilikou and Nikolopoulou (2014), Vasilikou (2015).

In table 5.1, we provide an overview of all the relevant studies and the crucial parameters guiding the research methods. The parameters relate to the spatial context and scale. When we describe spatial scale as small, this ranges between a few square meters up to a hectare (e.g., around a building, a small street), medium scale concerns spatial areas above a hectare (e.g., a neighbourhood or a medium sized square) and large scale refers to the whole city. Furthermore we differentiate the time-scale of memory and kinetic state of people. Then we sketch the methods used to investigate these parameters (e.g., interviews, cognitive maps, 'thermal walks'). In the subsequent sub-sections we will describe the different studies in detail in the order of publication year.

Thermal perception study in different urban outdoor spaces in tropical Dhaka

The study of Ahmed (2003) was one of the first studies that addressed the possible relation between subjective thermal perception and different spatial surroundings. It was conducted in the tropical climate of Dhaka, Bangladesh and aimed at generating a 'thermal outdoor comfort zone' graph (similar to the graphs provided by Olgyay and Olgyay (1963) for other climates). The study was also supposed to provide urban designers in tropical regions with design guidelines for thermally comfortable outdoor spaces and building configurations. As a consequence, the author was particularly interested in the specific relations of urban configurations and their effect on people's thermal perception and the micrometeorological effects. About 1500 people were interviewed in three different areas of the city that represented different local urban climate zones: one area with low building density and abundant greenery, one area that had intensive land use with tall buildings and no vegetation as well as a zone that had high density urban fabric with smaller buildings close to the river. Within these local climate zones six types of spaces on a small scale were identified in which the interviews took place: street canyon, under an arcade or awning, on a covered gallery, under an overhead canopy, in an open square and an open riverbank space. The interviews held in the different locations considered personal factors (age, sex, clothing level, etc.) and a personal thermal sensation vote of the interviewee on a seven level scale. Parallel with the interview study, microclimate measurements were taken in strategic spots but it is unclear if these spots were situated in the different types of urban spaces or elsewhere. The results of the inquiry are represented as descriptive statistics for some parts of the set of interview data. The measurement data are not translated into a thermal perception index. Instead, a 'comfort temperature', based on the interviewees' votes is set in relation to air temperature and globe temperature for the different spatial types. But the data that directly relate people's comfort vote to the spatial surroundings were not shown. The study did not include a comparison between the 'objective' measurements and the subjective comfort votes because this study attempted to set a first 'thermal outdoor comfort zone' index for Dhaka only. Apart from that the author explicitly refrained from setting narrow indices: "It is not essential to establish a single comfort value in the context of outdoor spaces as it has been found that comfort perception outdoors is a dynamic phenomenon and a person's comfort preference, keeping within a range, continually adjusts to ambient situations [...] defining comfort for outdoor situation may not be considered a tall order [...] comfort perception is a synergistic phenomenon." (p.109). Still, the results allowed some comparison between comfort votes and the spatial categories. For instance, overhead covers were found more comfortable at midday and the more open spaces were considered more comfortable in the late afternoon. Given the high loads of solar radiation that affects the human body during midday in the tropics people's evaluations of the different urban space types make sense and indicate a plausible relation between spatial experience and micrometeorological conditions.

Thermal perception in different spots on urban squares

An investigation of momentary thermal perception in two different squares in Kassel, Germany (Katzschner, 2004) within the RUROS project (also see Nikolopoulou et al., 2014) aimed to produce a strategy for urban design that focuses on the microclimate improvement of the respective places. Field surveys were done in summer and autumn, including combined measurements (air temperature, solar radiation, humidity, dry and wet-bulb temperature, globe temperature, wind speed) and interviews. The interviews focused on how people experienced the

Table 5.1: Overview of reviewed literature according to relevant criteria to categorize qualitative methods

Authors	Spatial context	Spatial scale	Time-scale of memory	Kinetic state
Ahmed, 2003	Different spatial urban configurations	Small	Momentary	Stationary
Katzschner, 2004	Urban square	Medium	Momentary	Stationary
Eliasson et al., 2007	Courtyard, square, urban park, urban waterfront	Medium	Momentary and short-term	Stationary
Lenzholzer and Koh, 2010	City squares	Medium	Long-term	Stationary
Lenzholzer and Van der Wulp, 2010	City squares	Medium	Momentary	Stationary
Katzschner et al., 2010	Neighborhood and square	Medium	Momentary	Stationary
Mahmoud, 2011	Different zones in urban park	Small	Momentary	Stationary
Klemm et al., 2015a	City	Large	Long-term	Stationary
Klemm et al., 2015b	Street	Small	Momentary	Stationary
Klemm et al., 2015b	Street	Small	Long-term	Stationary
Böcker et al., 2015	City	Large	Momentary	In motion
Vasilikou & Nikolopoulou, 2014	Urban street and square sequences	Small and medium	Momentary and long-term	In motion
Vasilikou, 2015	Street and square sequences	Small and medium	Momentary and long-term	In motion
Klemm et al., 2017	Urban parks	Medium	Momentary	Stationary

Investigation methods	Representation of investigation	Match with quantitative data
Interviews, microclimate measurements	Textual, statistics	Only partly comparable, but plausible
Interviews, microclimate measurements	Textual, statistics, maps	Unknown, no comparison
Interviews, microclimate measurements	Textual, statistics	Good, with exception water front
Cognitive mapping, microclimate measurements	Collective cognitive maps	Good
Interviews,microclimate measurements	Textual, statistics	Good, with exception interpretation of colours
Interviews,microclimate simulations	Maps with GPS data of interviewees	Match for 'heat areas' good, other areas partly show differences
Interviews, microclimate measurements	Textual, statistics, RayMan simulations	Good
Interviews, cognitive maps microclimate measurements	Textual, statistics	Good
Interviews, microclimate measurements	Textual, statistics	Good, with few exceptions
Cognitive maps, microclimate measurements	Textual, impossible to produce coll. cognitive maps	Difficult to draw conclusions
Interviews, weather data for the city	Textual, statistics	Good
Interviews, Walks, Observations Maps Microclimatic measurements	Verbal, statistics, thermal notation (maps)	Good
Interviews, microclimate measurements, Observations, Walks	Textual, statistics, Thermal notation (maps)	Good
Interviews	Textual, Statistics	Good

5

thermal environment on a 5 point Likert scale (very cold – very hot) and specific questions dealt with the experience of sun, wind and humidity. As opposed to earlier interview studies, the exact location of the interviews (in stationary mode) and related measurements were recorded. This allowed a precise and comprehensive spatial representation in GIS after completion of the fieldwork. Moreover, microclimate simulations were done in Envi-Met that represented the microclimate in similar weather conditions. The studies were represented in different sets of maps, showing the places where most people stayed (standing or sitting) and their thermal perception (see Figure 5.3). Apart from that, the microclimate simulations were represented in maps. Since the study did not focus on the comparison of the objective climate data with the subjective thermal perception data no conclusions were drawn about the match between objective and subjective data.

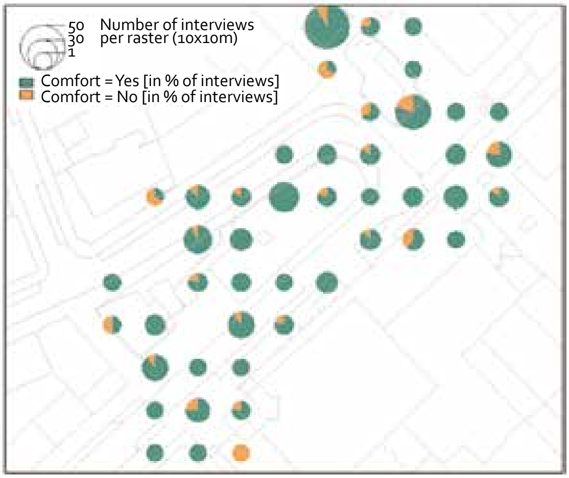


Figure 5.3: Locating spots of thermal comfort and discomfort on the Florentiner Platz, Kassel, Germany (Katzschner, 2004)

Nordic urban places and climate perception

Eliasson and colleagues (Eliasson et al., 2007) conducted a study in different Swedish urban outdoor places of local scale, such as a courtyard, an urban square, a waterfront and an urban park. People's perceptions were studied via structured interviews. In the interviews people were asked about their perception of the weather at that moment and of that specific day, which makes it a study that focuses on a rather short time interval in people's memory, but according to one of the authors of the study these should actually range under 'long(er)-term' perception (Knez et al., 2009). The interviews also comprised questions about people's perception of the place in terms of its microclimate (e.g., calm – windy, cold – warm) as well as the perception of the place (e.g., ugly – beautiful, unpleasant – pleasant, windy – calm and cold – warm). The interview questions did not address spatial information relevant for urban design. However, the study made a statistical connection between the different types of outdoor places in which the interviews were held and the interview outcomes on thermal perception. This allowed to address relations between the influence of the respective urban space on thermal perception.

The interview results were represented textually and analysed by means of statistics. Micrometeorological measurements of air temperature, relative humidity, long- and short wave radiation as well as wind-direction and speed were measured at human body height in intervals of few minutes. The thermal perception in the three places was generally better when the micrometeorological situation was rather calm. One exception was the positive perception of the water front, although it is very windy. This was explained with the 'naturalness' of the place (also see Nikolopoulou and Steemers, 2003). But in general, the matches of the microclimate measurements and people's thermal perception were very plausible.

Spatial microclimate perception in Dutch squares

The study of Lenzholzer and Koh (2010) focused on people's thermal perception in urban squares and how this relates to different types of spaces in which people stay (e.g., street entrances, middle of the square, etc.). The scale of the study covered mid-sized squares that people could overlook, so the scale addressed was medium. To respond to the knowledge gap about thermal perception in relation to space, this study employed research methods that were used in other studies about people's spatial memory (e.g., orientation, choices for spaces to stay): cognitive maps. Cognitive or 'mental' maps were invented by the urban design scholar Lynch (1960) as a means to represent people's perception of space. This spatial perception often differs from geographical description of space and meanings are assigned to space which cannot be made quantifiable. Lynch sparked the development of a whole range of different mental and cognitive map techniques (e.g., Kaplan, 1973, Downs and Stea, 1973, Kitchin, 1994). More recently, cognitive maps have been described as people's spatial schemata of their environment that are shaped by long-term experience and interaction with this environment (Kitchin, 1994, Kitchin and Blades, 2002, Heft, 2013). To study these schemata pertaining to microclimate and space perception, it was necessary to find respondents who knew the respective places for a longer time because of regular visits. Interviewees were selected accordingly. Eventually, hundreds of respondents on three squares (average N = 232 per square) were asked to draw different zones on a map to which they assign certain thermal perceptions. In case the respondents found it difficult to draw on a map, they alternatively pointed out the areas to which they assigned these perceptions and the interviewers drew them on the map. Additionally, respondents were asked to give an explanation for this perception ("What are the reasons for this thermal comfort or discomfort: e.g., sun, shade, shelter, wind?").

This approach resulted in one individual 'cognitive microclimate map' per interviewee that reflects the interviewee's microclimate perceptions of sub- areas (see Figure 5.4, left). All the individual 'cognitive microclimate maps' were transferred into GIS, overlaid and summarized

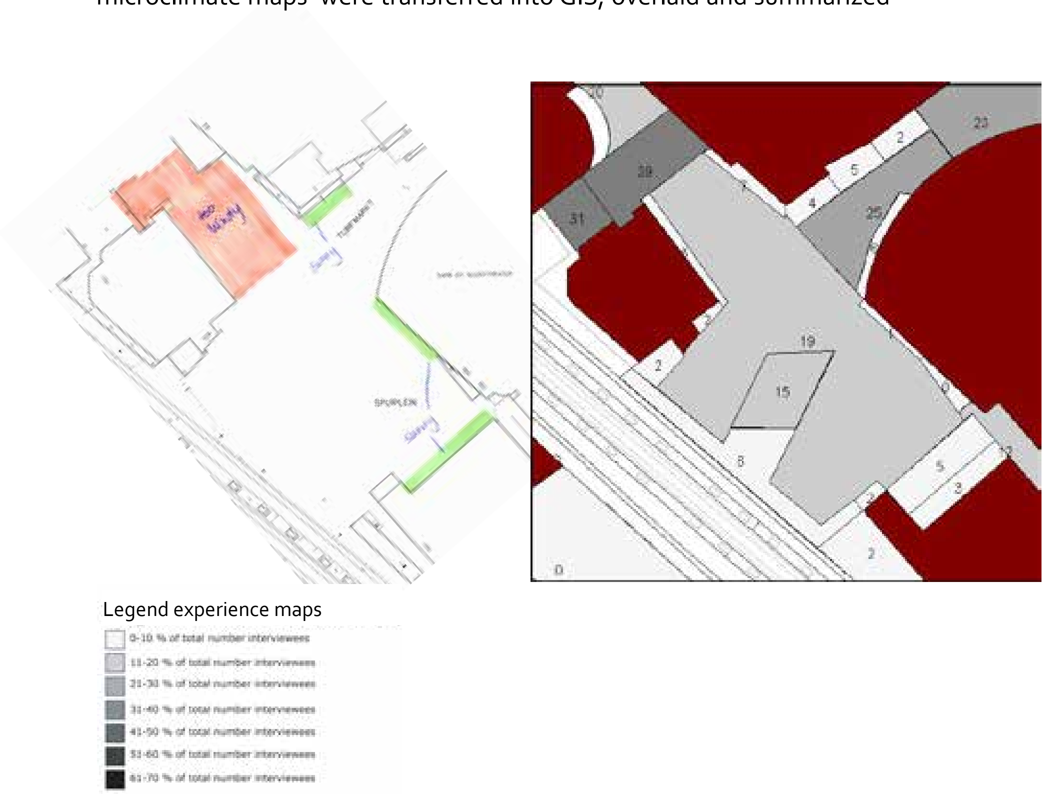


Figure 5.4: Example of an individual (left) and a collective (right) cognitive microclimate map for Spuiplein, The Hague, the Netherlands (Lenzholzer and Koh, 2010)

into common ‘cognitive microclimate maps’. These maps depict the generalized perception of the interviewees that were representative for the local population (see Figure 5.4, right).

The collective cognitive microclimate maps have proven to offer very explicit insight into people’s spatial memory and when compared to the measurement results and general urban physics (e.g., concerning wind and shadow patterns), the match between maps and measurements was good.

‘Ambiance’ and thermal perception in urban squares

Lenzholzer and Van der Wulp (2010) intended to gain specific information about the descriptors of ‘ambiance’ in relation to thermal perception for Dutch urban squares. This ‘ambiance’ entails various spatial parameters that can be influenced by urban design interventions such as a space’s proportions or colours. This study was conducted on three Dutch urban squares of medium scale.

The study comprised semi-structured interviews about the square’s spatial properties in relation to momentary thermal perception. In a test-run, respondents seemed to find it difficult to relate thermal and spatial perception directly. Therefore, separate questions were posed for thermal perception and for spatial perception. Interview questions were: “How do you experience the proportions of this square (too wide – good – too narrow)? What do you think about the openness of this square? (I like it – no opinion – I do not like it) and if you don’t like it, what would you change in the spatial setup (open question)? Which of the materials used in this square, in the facades, furniture, the floor, etc. in your opinion have a warm and which have a cold appearance?” These descriptors were related to people’s momentary thermal perception based on a 5-point Likert scale from ‘very cold’ to ‘very hot’. The interview outcomes of the study were represented in statistics (ANOVA) and compared to quantitative measurement results and shadow simulations (SketchUp). It appeared that people’s thermal perception in relation to the measurements and simulation outcomes made sense. The only exception was that people experienced materials with warm colours (e.g., certain colours of plaster of brick stones) as ‘thermally comfortable’. However, not all of these materials have the physical properties to really feel thermally comfortable.

Thermal perception maps in German neighbourhoods

Within a research project on climate adaptation strategies, studies were conducted about people's momentary thermal perception in specific spots in the Vauban neighbourhood in Freiburg and the Opera square in Kassel (Katzschner et al., 2010). The aim of this study was to set an example how reliable data can be generated to inform design decisions on improvement of thermal conditions in these urban places. The scale of the study was situated on a medium scale. To acquire spatially explicit information, the momentary thermal perception of people in the outdoor spaces was studied via short interviews during hot days. The outcomes were related to spatial GPS data of the place where the respondents gave this interview. Based on these data, GIS maps were generated that showed the respondent's thermal perception in space and these could be interpolated in GIS into a collective map of people's thermal perception. To compare these perception maps with objective data, BOTworld© (dynamic) and ENVI-met (static) simulations were done for the respective places. The simulations represented hot weather situations in line with the circumstances during the interview series. A comparison between the simulation and interview results shows that there can be some local differences, but the most important areas that need adaptation – the hot zones – show a good match between the thermal maps based on interviews and the simulation results.

Thermal perception study in different urban park spaces in Cairo

In order to extend the hitherto scarce research regarding outdoor thermal perception in hot and arid climate regions the study by Mahmoud (2011) was conducted in different zones of an urban park in Cairo. The author also tried to gain evidence of the effects of layouts of sub-spaces on outdoor thermal perception. These sub-spaces ("Peak, Spine, Entrance, Fountain, Lake, Canopy, Pavement, Seating, Cascade") were distinct small scaled zones that were expected to have different microclimates. About 300 interviews were conducted in summer and winter in the total park (interview numbers evenly distributed over all park zones) and the main aim was to identify people's individual thermal sensation votes in the respective spatial zones. Simultaneous with the individual interviews microclimatic measurements were conducted. Additionally, Ray Man simulations were generated for the spatial zones to visualize the respective Sky view factors. The survey results were represented through descriptive and correlational statistics between

PET and thermal sensation vote for the different spatial zones in summer and winter. The statistical relation of PET and mean thermal sensation vote indicated that in the different zones studied in the park rather high percentages of discomfort was experienced. A close statistical relationship between the PET and mean thermal sensation vote could be identified for most of the park zones analysed. Pertaining to the spatial setup of these zones, close relationships were found between thermal votes and the influence of the sky view factor, wind speed and albedo, based on the microclimatic influence of landscape elements such as the presence of vegetation and fountains. But the author also emphasized that other aesthetical factors might be influential and that the physical factors of microclimate "cannot completely describe the heat balance of the human body of users" (p.2655).

Thermal perception of urban green infrastructure on city scale

Klemm et al. (2015a) examined outdoor thermal perception in open, and especially green urban spaces in the Netherlands. They investigated how people perceive these spaces during warm summer days with respect to thermal conditions in urban green spaces (during daytime on warm summer days). To study people's perceptions, semi-structured interviews with pedestrians were conducted in three Dutch cities on warm summer days. In total 559 questionnaires were completed with citizens who were well-acquainted with the city. The interviews had three focuses. First, the evaluation of the thermal effect of green environments was measured by respondents' opinion on the statements "A green environment is: a) nice, b) important, c) essential, d) convenient for my thermal comfort on hot summer days". Secondly, respondents described long-term thermal perception in green, water and built environment types (garden, rural area, forest and park for green environments; shopping street, square, terrace or parking lot for built environments; beach lake, swimming pool and canals for water areas), by answering the question "Please indicate how thermally comfortable you feel on hot summer days in each of the four types of outdoor environments." (based on a 5-point-Likert scale from "very uncomfortable" to "very comfortable"). The questionnaires were analysed and results were represented by means of descriptive statistics, reliability analysis and statistical hypothesis testing. Thirdly, people's long-term perception of thermally comfortable spaces in urban environments was studied by employing cognitive microclimate maps (Lenzholzer, 2008). Respondents were asked to indicate urban spaces that they prefer because of their thermal conditions on hot summer days on a map (Figure 5.5 above). A combination of all indicated thermally comfortable urban spaces are shown in collective cognitive microclimate maps (Figure 5.5 below). Additionally, the study comprised micrometeorological measurements using bicycles equipped with meteorological sensors for pedestrian levels. Those measurements were conducted in 13 parks in the city of Utrecht. This study demonstrated a positive influence of green spaces on long-term thermal perception and that long-term perception is consistent with the physical thermal circumstances: respondents generally assessed green spaces as more thermally comfortable than water and built environments on hot summer days. This matches well with the 'park cool islands' effect that was indicated by the micrometeorological measurements.

Street greenery and momentary thermal perception

The study by Klemm et al. (2015b) addressed aspects of momentary thermal perception. The research question: 'What is the impact of street greenery on momentary thermal perception and how is that related to air temperature and mean radiant temperature?' was studied with semi-structured interviews with pedestrians (N = 108) in the nine streets. Respondents were asked to evaluate single meteorological parameters (air temperature, sun, humidity and wind) and the overall experience of thermal comfort in the specific street ('How do you experience the microclimate at this moment at this place?') based on a five-point Likert scale from 'very uncomfortable' to 'very comfortable'. Additionally to the interviews, micrometeorological measurements at pedestrian level were conducted. The results generally matched well with people's momentary perception; for example streets without street greenery showed the highest values of mean radiant temperature and also were evaluated by interview respondents as the least comfortable of all street types. However, people preferred streets with front gardens and small trees over streets with tall trees. This is surprising, because streets with tall trees showed lower mean radiant temperature and thus more thermal comfort than streets with smaller trees and front gardens.

The other research question: 'How does momentary thermal perception relate to the evaluation of green street design in terms of aesthetic appreciation?' was investigated in the interviews by asking the respondents: 'How do you experience the green design of this street?' evaluated through a five-point Likert scale from 'dislike very

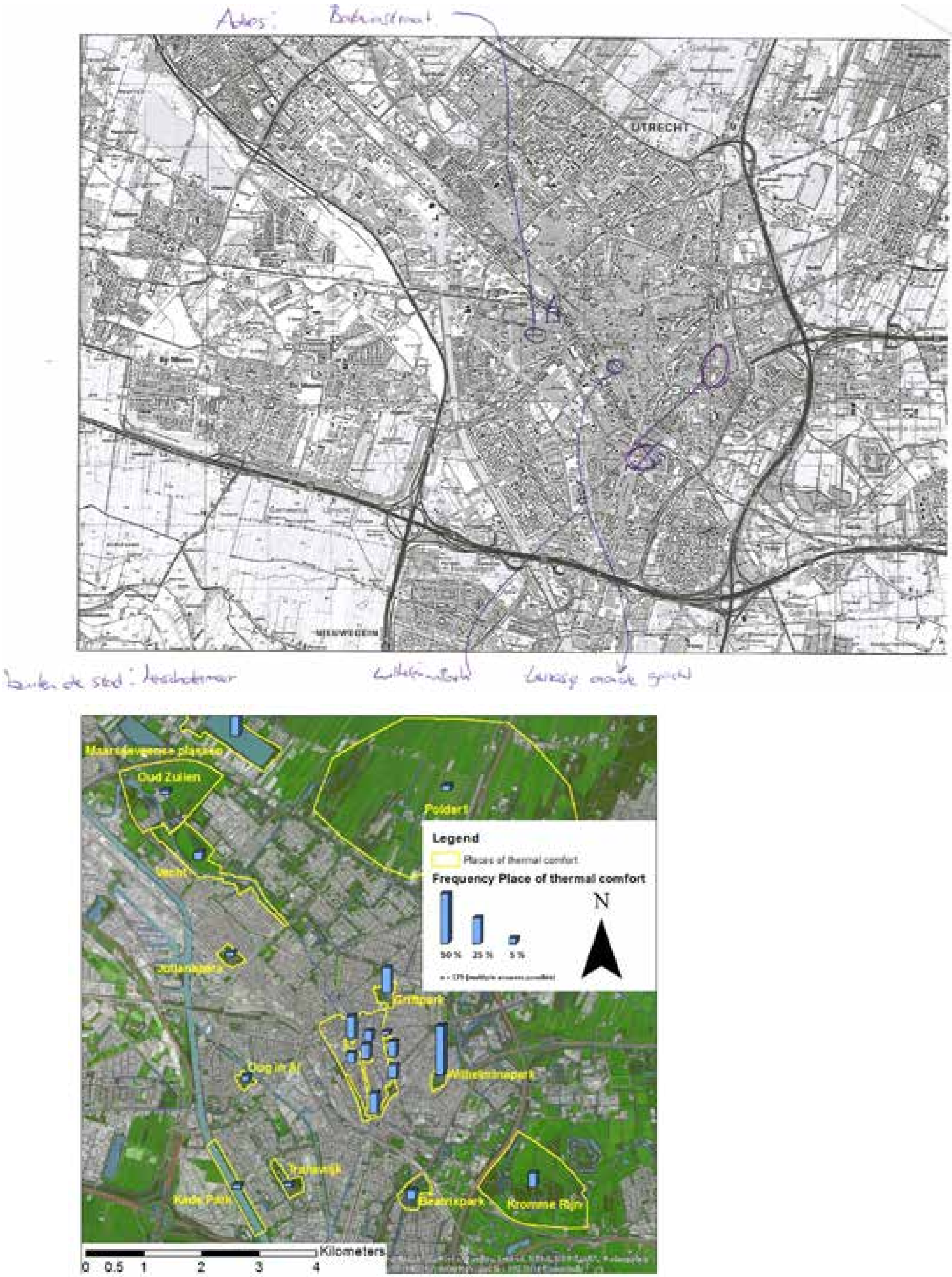


Figure 5.5 above: Typical example of an individual cognitive map, Utrecht, the Netherlans
below: collective cognitive map of places that people experience as thermally comfortable (Drost, 2013)

much' to 'like very much'. Additionally, people were asked for possible improvements of the green design in an open question. Interview results for both research questions were represented with statistics. Even though respondents strongly valued the presence of street greenery (which was also expressed by the answers on improvement of green street design), there was no significant relationship between aesthetic appreciation of street greenery and momentary thermal perception due to the low number of respondents.

Street greenery and long-term thermal perception

Parts of the study by Klemm et al. (2015b) also focused on benefits of street trees and front gardens for thermally comfortable streetscapes in nine Dutch residential streets. They investigated physical thermal conditions and thermal perception of pedestrians in streets with similar spatial setup (e.g., aspect ratio, orientation towards the sun, materials) and varying amounts and distribution of street greenery. They inquired the impact of street greenery on long-term thermal perception through cognitive mapping techniques and conducted measurements of micrometeorological conditions (air temperature and solar radiation, wind speed and relative humidity) in the same period. Respondents were asked "Can you indicate zones of thermal comfort and discomfort in the street that you have experienced over longer time?" and were invited to motivate their indications. Respondents and interviewees stood in one of the streets to be investigated with a wide view of the rather small street canyon. From this spot respondents could point to comfortable or uncomfortable subspaces in the street or indicate them on the map that was part of the interview materials. It appeared unfeasible for respondents to locate their long-term thermal perception in the residential street on a map; the majority of respondents (73%) had 'no preferences for specific zones of thermal comfort' or they had 'no idea'. Interestingly, even though respondents could not locate thermal perception zones on the map, they were able to motivate their thermal perception: it appeared that people were aware of microclimate diurnal and seasonal variance (shade patterns). The comparison with the micrometeorological data showed that these evaluations of the diurnal patterns was correct, but no further comparison was possible because it was impossible to generate collective cognitive maps.

Place experience and thermal conditions related to different transport modes

Transportation modes (on foot, bicycle, car, etc.) that citizens choose can largely differ, but some of the reasons for that choice of transport mode were not very clear. Hence, Böcker et al. (2015) studied transport mode choices of citizens in relation to weather, people's thermal perception and spatial experience of the routes travelled (amongst other variables that are not relevant in the context of this review). To do so, they conducted a travel diary survey during half a year amongst a panel of hundreds of respondents (N = 11,759 individual trips). During their travels, respondents reported about their experiences of the microclimate conditions in situ. They described their thermal experience with a 9-point Likert scale from very cold to very hot. The aesthetic evaluation of the places encountered and route comprised the following factors that were evaluated on a 5-point Likert scale: very little green – very green, sheltered – open, beautiful – ugly, lively – boring/ monotonous, very busy – very quiet, very little wind – very windy. The respondent' routes were also traced in GPS, so that they could be directly related to place evaluations. Apart from that, the authors gathered measured weather data of the KNMI (the Royal Dutch Meteorological Institute) dating from the study period for further comparison. The results were analysed and represented with multivariate statistical modelling techniques. This wealth of data enabled the authors to show for instance, that warmer thermal subjective experiences have a positive effect on place evaluation. The relation of people's thermal perception and the weather data showed a relatively good match (Böcker et al., 2016).

'Thermal walks' in streets and squares

Vasilikou commenced to investigate the variation in thermal perception between spaces of different geometrical characteristics that form part of a larger pedestrian route (Vasilikou, 2015, Vasilikou and Nikolopoulou, 2016) in three European locations. The study aimed to identify the change in thermal perception of participants as they are moving between interconnected spaces, but also to identify the thermal perception of people in movement. The scale of the studies ranged from small to medium urban spaces, including streets and squares of different density and geometrical qualities. People's momentary thermal perception was investigated in the form of 'thermal walks' (Vasilikou and Nikolopoulou, 2014). The core of the 'thermal walk' finds its roots in the technique of sensewalking, initially developed by Southworth (1969) on studies of the sonic environment. Sensewalking is a systemic approach with the aim to investigate and analyse the way people understand, experience and utilize urban space. The approach may focus on multi-sensory experiences that are site-specific (Lucas and Romice, 2008) or to particular sensory experiences that enable participants to express their subjective perception of an environmental aspect (Henshaw et al., 2009). A limited number of examples investigating thermal aspects of the urban environment through walks have been identified, but have generally excluded people surveys during walks and were based solely on the researcher's own observations on the thermal perceptions of specific urban routes (Potvin, 2000, Ouameur and Potvin, 2007).

To engage in a thermal walk, participants would consent to the longitudinal nature of the study, reiterating the walk between times of day, days and seasons. Walk participants were asked to assess their thermal sensation and comfort on a 5-point Likert scale for specific points of the walk ('how do you experience the thermal environment at this precise moment?' and 'how thermally comfortable do you feel at this precise moment?'). During the walk participants also evaluated changes in their thermal perception and were asked to explain the reasons of a potential change in their thermal perception (e.g., why do you think this thermal variation exists?). The effect of movement and spatial variation was assessed by the question 'is there anything different in the spatial characteristics around you?' and further questions concerning microclimatic aspects in each space. These interviews were combined with *in situ* measurements of microclimatic data and recording of spatial data. Results were interpreted with thermal mapping techniques (Vasilikou and Nikolopoulou, 2014). To facilitate communication of collected data during fieldwork, a design tool of data representation was developed specifically for 'thermal walks', called 'thermal notation' (see Figure 5.6).

The novelty of 'thermal notation' lies in the combination of both qualitative (people's responses) and quantitative (microclimatic data) in the same diagrammatic depiction, making the collected data readily accessible by designers during the early design stage of a project. The results match well with microclimatic measurements. The outcomes of thermal walks show that subtle variations in microclimatic conditions between interconnected spaces result in significant changes in the thermal perception of pedestrians for the duration of the walk. Wind

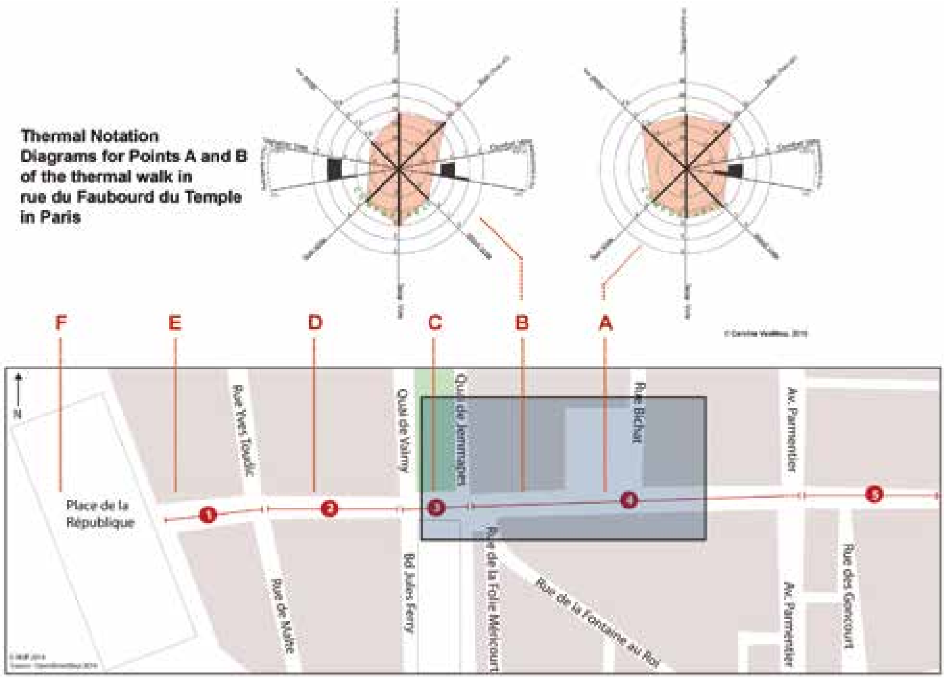


Figure 5.6: Mapping example of thermal walk assessment for rue du Faubourg du Temple in Paris, using the 'thermal notation' tool to compare the variation in thermal perception between different spatial characteristics (Vasilikou, 2014)

speed, turbulence and mean radiant temperature had the most significant impact on the momentary thermal perception. In addition, at street level, ground-floor spaces that use active microclimatic control (such as air-conditioning or heating devices) in semi-open spaces created 'cool' or 'hot spots'. Finally, participants distinguished different prevailing thermal sensations between streets and connected squares. Most of the participants evaluated the general thermal experience of walking on the basis of specific points of the walk that were highlighted by a distinct experience of thermal comfort or discomfort. The degree of variation and spatial complexity allowed for more opportunities of thermally diverse urban experience.

Long-term thermal perception studies of people in movement

Within the 'thermal walks' method Vasilikou and Nikolopoulou (2014) also applied a different approach that focused on the long-term perception of people. They conducted a study of the thermal perception of people using outdoor urban sequence in the city centres of Rome and London and thermal perception at the scale of the urban sequence and the overall experience of the walk. The study took place during summer and winter, using the same participants between seasons. The study covered urban sequences of approximately 500 m in length. The method was based on thermal walks to inquire people's perception with structured questionnaire completion, in terms of the microclimatic conditions as well as spatial perception and quality of walk that were relevant to urban design practices. Participants were invited to respond to questions in relation to the thermal perception of the whole walk (based on an 5-point Likert scale), to identify places of thermal pleasantness and unpleasantness after the completion of the walk and to provide an evaluation of their change in thermal and spatial perception during the walk. The results of the thermal walks were presented with descriptive statistics and mapping analysis. An aspect of long-term memory (where frequent visits seem to enable large scale schemata) was addressed through the longitudinal nature of the study, which included the same thermal walks participants walking along the same route during different times of year (and different times of the day). The effect of walking activity was assessed with questions regarding the overall walk evaluation and thermally-pleasant and –unpleasant parts of the walk. Participants were asked to draw points of perceived thermal variations on the map of the walk. This approach results in building a database of thermal perceptions, identifying for example a pattern of a particular thermal 'identity' in a specific street or square according to seasonal conditions and microclimatic characteristics accredited to interconnected spaces based on a comparative analysis. Here, again participants' responses can be represented graphically through mapping tools, such as 'thermal notation' maps, used for the mapping analysis in Figure 5.6.

Impact of summer and tropical weather on park visitors' momentary thermal perception

The study by Klemm et al. (2017b) focused on park user's behaviour and thermal preferences on summer and tropical days ($T_{a\ max}$ > 25 ºC and > 30 ºC, respectively). Amongst other factors they examined park visitors' preferred resting locations and momentary thermal perception under these warm and tropical conditions. The study areas were two public parks of medium scale in two Dutch cities. Semi-structured interviews were conducted to investigate people's momentary thermal perception and spatial preferences. Resting park visitors (N = 317) were asked how they experience thermal conditions at the moment of the interview and why they chose this specific place. Park visitors' momentary thermal perception was examined by asking them 'How do you experience the microclimate conditions at this moment in this place?'. The evaluation of overall thermal perception and of single parameters (air temperature, sun, wind and humidity) was evaluated based on a five-point Likert scale from very uncomfortable to very comfortable. Air temperature data of the conditions during the fieldwork days were gained from official weather stations in the vicinity of the two cities. Daily means and hourly data at the moments of observations (11:00, 13:00, 15:00 and 17:00) were analysed. The results were represented through descriptive statistics. The interview results indicated the essential role of microclimate for people's choice of resting locations in parks. In particular solar exposure and shade appeared to be most influential. On tropical days respondents clearly preferred shady to sunny places. Interviewed resting park visitors generally perceived a high level of momentary thermal comfort during all days; however overall thermal comfort was evaluated slightly more comfortable on summer than on tropical days. Largest differences in thermal perception of individual thermal comfort parameters were found for humidity and wind velocity, followed by air temperature and solar radiation.

5

5.2.1 Overview of different qualitative methods in relation to spatial and temporal scales

As a next step in our review the different studies were configured in a matrix that is organized according to dimensions most relevant to generate urban design relevant evidence: the spatial scales and the time scale of people's thermal perceptions as well as their kinetic state (Figure 5.7). This matrix maps the current state of the art. It shows the different methods used in the studies discussed above and enables a discussion of the suitability of the methods related to scale and time dimensions and people's kinetic states.

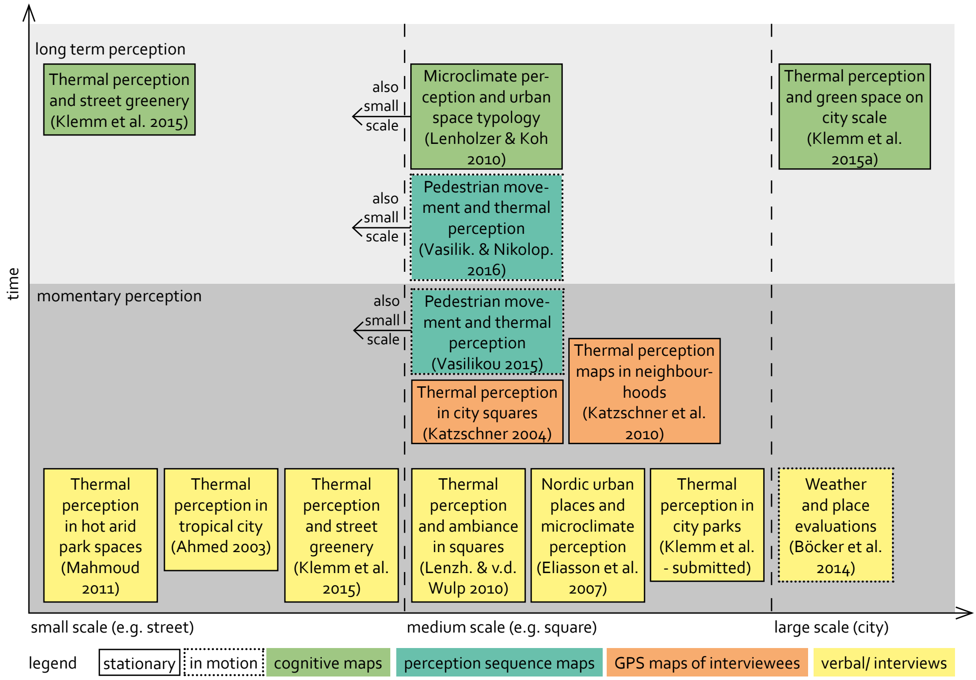


Figure 5.7: Matrix of the qualitative methods to study thermal perception

5.3 Discussion and conclusions: which method when?

Our review resulted in a range of studies that investigated people's thermal perception in relation to spatial environments in stationary or in motion mode. In this section we reflect on the results of the review in general and on which kind of knowledge should be generated for which spatial and time scales. We discuss which methods are apt for which type of research focus, limitations of certain methods and provide outlooks into future research.

5.3.1 Spatial aspects

A very striking pattern occurs in the overview (Figure 5.7): there is a large number of studies about the small or middle scale of urban squares, parks or streets and most of the studies are based on interviews about momentary perception. Probably this is related to the fact that most of these studies aimed at generating knowledge that was not in the first place related to spatial aspects but rather to acquire knowledge about thermal perception *per se*. The focus on small scale studies might also relate to the fact that urban microclimates can best be influenced through urban design on the smaller scale (Brown and Gillespie, 1995, p.46). On a medium scale mapping techniques (GPS mapping and cognitive maps) can provide a general picture of thermal perception but also allow to show how smaller partial areas are perceived. So they can actually also provide additional small scale information. Yet, mental mapping techniques may be less applicable in streets were people only move from one place to the other without much attention to the entire space, as was shown in the study of Klemm et al. (2015b). We could identify only two studies that address larger scale thermal perceptions. However, the implications of large scale studies can also be a valuable basis for climate-responsive urban planning (e.g., 'heat refuge areas' with bigger forests or waterfronts in- and outside the cities) and therefore, future research should address thermal perception on larger scales more prominently.

To inquire the spatial aspects on all scale levels we suggest to use spatially explicit methods, especially mapping techniques. For future research, it is not only important to represent knowledge in maps (planar projection), but also to represent the vertical dimensions (e.g., profiles, sections) and 3D visualizations. A first step towards such representations was made by Klemm et al. (2015a) where perception of street greenery was represented in profiles. Recently this representation was extended and 3D perspective views were used in 'visual interviews' on thermal perception (Tang et al., 2016). We suggest ample use of such 3D representations in the future. Future use of three-dimensional GIS also has interesting potentials. In three- dimensional GIS, spatial properties (e.g., proportions, materials, etc.) can be analysed and the expected human thermal perceptions can be assigned. Such data that directly predict the thermal perceptions enable direct interaction with urban design processes.

5.3.2 Temporal aspects

Another very striking pattern in the overview (Figure 5.7) concerns the large amount of studies on momentary perception. As mentioned above, this is probably due to the fact that most research up to now aimed at thermal perception *per se*. Most studies on momentary thermal perception also comprised parts on generating actual sensation votes for a certain climatic region or to calibrate existing thermal perception indices. Research on both, momentary and long-term thermal perception was conducted on all scale levels. As opposed to the momentary perception, long-term experiences are more independent from the 'here and now', but all studies on long-term experience needed to presuppose that participants are well acquainted with the locality of the study through frequent visits during various points in time.

In a few cases collective cognitive maps were used to represent long term experience, in two cases the interview results of momentary experience were shown in a GIS map and in another case results were shown in maps of thermal sequence notation. The collective cognitive maps studies provided fundamental knowledge on how people assign thermal perception to spatial typologies. For purposes related to climate-responsive urban design (e.g., to generate design guidelines) studies on long-term perception can be more useful because the spatial setup of the city does not change as quickly as momentary thermal perception does. But more attention should be given to seasonal and diurnal changes or the most problematic urban climate situations in future research by tapping respondent's long-term memory on these aspects and represent them in spatially explicit ways.

5.3.3 Kinetic state

There are many studies that consider people's thermal perception in stationary mode and only a few very recent studies focus on thermal perception in motion. However, we need to add a critical note on our subdivision of the studies into 'stationary mode' and 'in motion'. Our review indicated that there are various studies on people's thermal perception in stationary mode, both on their momentary and their long-term thermal perception. These methods employ people's knowledge that is taken at specific points in time. In the studies we ranged under 'in motion' people stopped to fill their diary (Böcker et al., 2015) or groups of interviewees paused during their walks to fill in questionnaires (Vasilikou, 2015, Vasilikou and Nikolopoulou, 2016). Very strictly speaking, these could also be called inquiry techniques in stationary mode. But since these studies are explicitly part of the 'in-motion' experience, we decided to differentiate these from the inquiries of typical stationary kinetic states in the overview matrix.

When the research is focused on places where people tend to stay and rest, e.g., urban squares, yards or gardens, it is advisable to use methods that represent steady state perception. When these spaces (squares, gardens, etc.) become part of a larger urban sequence, then hybrid methodologies should be used, which take into consideration both sedentary activities and dynamic movement. Here, mental mapping techniques can offer useful data on long-term spatial and thermal perception of the environment. However, in some cases, respondents seemed to find it difficult to directly relate thermal perception and spatial perception (Klemm et al., 2015b, Lenzholzer and Koh, 2010). To tackle this problem, conscientious pre-testing of the methods is required. During the communication with respondents careful explanation of terms in non-scientific vocabulary is necessary as well as explanation of maps to assist people with orientation. It can be useful to use additional observation methods (see Katzschner, 2004, Klemm et al., 2017b). When urban areas where people tend to move such as roads or shopping streets should be represented, it is advisable to employ methods that represent people's perception in motion, and then preferably methods that record perceptions in real time when people are moving. We found only one study that focuses on the long-term perception in motion. But studying people's daily routes (e.g., cycling to work, walking for errands, etc.) and how they are perceived in terms of thermal and spatial conditions on a long- term basis is useful because these daily experiences make up for a large part of our experience of our daily environments. Hence, this should be a field of research that should be extended. Moreover, when people's perceptions in motion are to be studied, inquiry techniques should accurately represent experience simultaneously with people's thoughts. We see valuable future use of such methods, for instance by simultaneous recordings of verbalized thoughts (Kitchin and Blades, 2002, Vasilikou and Nikolopoulou, 2016).

5.3.4 Relation between quantitative and qualitative methods

In almost all cases the results of the qualitative methods used in the studies showed a good 'match' and plausible relation with the quantitative data raised. This indicates a close relation between the 'objective' measurable and 'qualitative' subjective reality. Still, some space types or spatial attributes were identified that received a different evaluation than the quantitative data would suggest. For instance, people assessed the objectively thermally uncomfortable water fronts in Sweden positively and people in the Netherlands assigned materials with a 'warm' colour with 'thermally comfortable' associations although there were no objective reasons for that. Another example on street scale showed that visual perception may influence thermal perception, independent from the micrometeorological evidence (Klemm et al., 2015b). The fact that urban design has to respond to both 'realities': the functional physical environment and how people subjectively experience it demands for appropriate representation of both. We suggest that the objective reality should be studied through quantitative methods (e.g., microclimatic measurements, simulations) and the human experience through qualitative methods that represent people's synesthetic experience of urban space. These qualitative methods should address the perception of spatial dimensions, of proportions and materials in relation to the thermal environment. Successful design of urban spaces has to address all these factors integrally and thus depends on this qualitative evidence.

5.3.5 General considerations

A large part of the studies discussed in this review concerned fundamental research on momentary thermal perceptions in different spaces and often the main purpose was to generate knowledge about thermal indices in the first place. Thermo-spatial experience was of secondary importance. Most of these studies employed statistics to show the interview results, although in some cases the amount of interviews was not sufficient for very reliable statistics (e.g., ANOVAs, descriptive statistics). Statistics based on interviews were also used in some studies about long-term perception, in movement and stationary and for different scale levels. This indicates the great flexibility of such representations and explains the broad use. However, the downside of such purely verbal and quantitative descriptions is that it they are often not specific about spatial configuration and exact localizing. And such spatial knowledge is needed when the synesthetic experience of the urban environment is pivotal in the research or when conclusions about urban design such as design guidelines should be drawn from the research. Spatially explicit ways of representing thermal experience in maps, 'thermal notations' or other spatial representations (e.g., Katzschner, 2004, Klemm et al., 2015a, Lenzholzer and Koh, 2010, Vasilikou, 2015) are very useful for urban design related research. Future research should deliver even more specific recommendations on the use of suitable methods for different types of urban spaces (e.g., open and enclosed spaces), but such methodological research would require a larger set of spatially explicit qualitative studies than hitherto conducted. Therefore, we hope that future research on thermal perception will involve more qualitative methods that provide spatially explicit results.

6 Development of green infrastructure design guidelines for urban climate adaptation

Klemm, W., Lenzholzer, S., Van den Brink, A. (2018) “Development of green infrastructure design guidelines for urban climate adaptation” *Journal of Landscape Architecture* 12: 60-71.

Abstract

In the context of global warming and increasing urban climate problems, urban green spaces and elements have been recognized as a strategy for urban climate adaptation. Yet, despite increasing scientific evidence of the positive impacts that urban green infrastructure (UGI) is having on the urban microclimate, this evidence is not being incorporated into urban design practice. This explorative study was executed to create design guidelines for climate-responsive UGI that stem from scientific knowledge and are useful to design practice. A participatory 'Research through Design' (RTD) approach was applied in two design studios to have landscape architects test evidence-based preliminary guidelines. The researchers made observations, plan analyses, and executed questionnaires in the studios to assess the usefulness of the preliminary guidelines and, subsequently, to refine them. This paper presents the revised guidelines for the city, park, and street scale levels and elaborates the knowledge on the microclimate and operational principles needed for implementation. This paper argues that a participatory RTD approach helps to link knowledge from research to practice.

6.1 Introduction

One of the major challenges in urban design is advancing strategies for urban climate adaptation. Climate change impacts (e.g., IPCC, 2014, KNMI, 2015) require re-thinking urban design, in particular the design of green urban spaces and elements, such as urban parks, forests, gardens, and street trees. These spaces and elements are generally referred to as urban green infrastructure (UGI) (e.g., Lovell and Taylor, 2013, Norton et al., 2015) and provide benefits through ecosystem services (e.g., Andersson et al., 2014). Microclimate regulation is one of these services. UGI is increasingly recognized for its ability to reduce heat levels in cities and improve citizens' health, well-being, and thermal comfort (e.g., Lafortezza et al., 2009, Fryd et al., 2011, Demuzere et al., 2014). The positive effects of UGI on thermal conditions are described on various urban scales (e.g., Bowler et al., 2010, Jamei et al., 2016, Klemm et al., 2015a, Klemm et al., 2015b) and for different urban vegetation structure types (Lehmann et al., 2014). Besides enhancing physical thermal conditions, UGI has been proven to improve people's thermal perception (e.g., Nikolopoulou and Steemers, 2003, Klemm et al., 2015a). Additionally, there is a growing body of knowledge of climate-responsive design. Such urban design takes advantage of positive microclimate effects and combats adverse microclimate effects (Brown, 2010, Brown and Gillespie, 2017, Eliasson et al., 2007, Lenzholzer, 2015). Through climate-responsive design, outdoor places are thermally comfortable and facilitate activity all year round. Still, knowledge of the benefit of UGI for the microclimate has not been incorporated into urban design practice (Norton et al., 2015, Fryd et al., 2011, James et al., 2009, Mathey et al., 2011). Clearly, there is an 'application gap' that hampers the translation of microclimate knowledge related to UGI into useful knowledge for climate-responsive urban design. So the question arises: What knowledge on the benefits of UGI for the urban microclimate can contribute to climate-responsive design in practice?

The usefulness of scientific knowledge about the microclimate for design practice depends on various factors. These factors include the accessibility of scientific evidence to those involved in design processes (Pijpers-van Esch, 2015, Prominski, 2017). Also, the multifunctional character of urban design is vital: the knowledge of the microclimate needs to be integrated into the design of other functions such as infrastructure, hydrology, or ecology; the demand for these are sometimes conflicting (De Schiller and Evans, 1996, Lenzholzer, 2010a, Mathey et al., 2011). A more fundamental factor is the limited understanding that practising designers have of the scientific knowledge of the microclimate (De Schiller and Evans, 1990), including both the scientific microclimate terminology and the type of knowledge needed that is relevant for design practice (Fryd et al., 2011). Several authors emphasized that the knowledge of the microclimate should be presented in a way that is comprehensible for practicing designers, ideally in a clear graphic manner. The knowledge should be applicable, easy to use in design processes (Brown and Corry, 2011, De Schiller and Evans, 1990, Eliasson, 2000, Lenzholzer, 2010a, Norton et al., 2015, Pijpers-van Esch, 2015). Also, the knowledge should be feasible in practice, since incorporating UGI spaces or elements into design often involves practical constraints. Those include implementation issues, such as the availability of land, space, property, or finances. Essentially, scientific knowledge about the microclimate that informs the design of UGI should meet a set of criteria: be comprehensible to designers, be applicable to design processes, and be feasible to implement in practice. A crucial issue occurs: How should the 'informing' of urban design take place?

Various scholars consider design guidelines to be a possible tool with which to inform design – to transfer key knowledge of the microclimate from science to design practice (Eliasson, 2000, Lenzholzer, 2010a, Nassauer and Opdam, 2008, Prominski, 2017). Lenzholzer (2010a, p.120), for example, characterized such guidelines as "easily applicable, pre-processed scientific knowledge" that is "supposed to be applicable to many situations". Recently, Prominski (2017, p.194) stated "that a design guideline gives guidance for design action, meaning that it suggests a specific direction by excluding many other possible, and by implication, less suitable ones". Following these authors, in this article design guidelines are considered a body of evidence-based, universally applicable knowledge that guides urban design actions in a variety of site-specific spatial and functional circumstances, and that is considered useful by design practitioners. In the field of landscape architecture, however, little has been written about how to develop design guidelines based on scientific evidence. The active employment of 'designing' (the activity of giving shape) in research, 'Research through Designing' (RTD), is considered as a method to generate and/or evaluate design guidelines and further develop them (Lenzholzer, 2010a, Prominski, 2017).

Especially participatory RTD is understood as a method to improve the ownership of knowledge and user commitment (Lenzholzer et al., 2013), although it has not yet been used to test and enhance the practicality of scientific knowledge.

Against this backdrop, this study aimed to develop design guidelines for climate-responsive UGI that are based on scientific evidence and considered useful in urban design practice. Our main research question was: *What are evidence-based design guidelines for climate-responsive UGI that practitioners consider useful, specifically in terms of comprehensibility, applicability, and feasibility?*

6.2 Study design

To answer the research question, one needs to understand whether and how design practitioners apply scientific evidence in site-specific design processes and how scientific evidence needs to be communicated to designers to increase its usefulness in practice. Therefore, we used a novel participatory RTD approach (Lenzholzer et al., 2013). Owing to the newness of the participatory RTD approach, the study had an explorative character, which informed the choice of an in-depth, qualitative study with a limited number of respondents (Creswell and Plano Clark, 2011).

The RTD approach consisted of the following three steps (Figure 6.1). First, we generated the preliminary design guidelines for climate-responsive UGI from existing scientific literature. Second, we asked design practitioners to incorporate those evidence-based preliminary design guidelines in design processes. Through observations of those processes and analyses of the design proposals, we studied how and to what extent design practitioners in a practical design setting apply the preliminary design guidelines. More specific insights into the criteria appreciation of the guidelines, comprehensibility for designers, applicability in design and feasibility in practice were gained through questionnaires participants filled in. Third, we subsequently used the results of step two to revise and improve the preliminary design guidelines, to turn them into guidelines that can inform climate-responsive urban design practice. The study design is explained in more detail in the following sections.

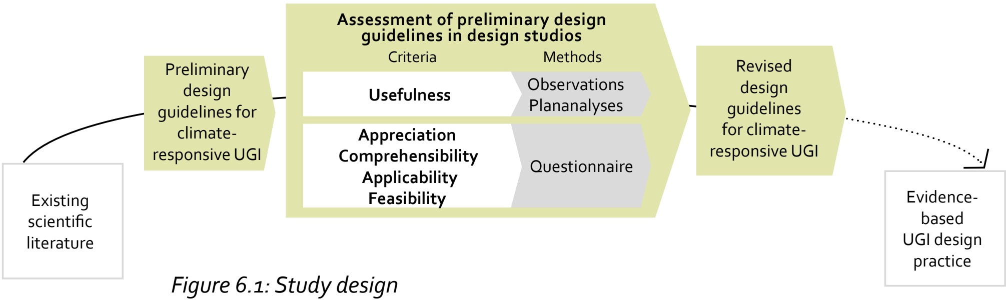


Figure 6.1: Study design

6

6.2.1 Developing the preliminary design guidelines

The information on the microclimate taken from scientific literature and exemplarily used in this study focused on the objective and subjective impacts of the microclimatic of UGI at the city (Klemm et al., 2015a), park (Klemm et al., 2017b), and street level (Klemm et al., 2015b). The results of these studies are listed in Table 6.1 (column microclimate scientific evidence).

This scientific evidence was presented in a lecture at the beginning of the two design studios, to ensure that the participants had a common understanding of key information on the microclimate. It appeared that the participants had severe difficulties understanding the descriptive nature of the evidence and its direct links to design processes. The descriptive scientific evidence was therefore transformed into prescriptive guidelines. This step of pre-processing included adding explanatory spatial and functional information and using less microclimate-specific terminology. It resulted in preliminary design guidelines for climate-responsive UGI (Table 6.1, column preliminary design guidelines). These preliminary guidelines comprise normative, universally applicable knowledge that should be useful in various site-specific spatial and functional circumstances.

To clarify how these general guidelines should be applied in site-specific design proposals, they were accompanied by operational principles. These operational principles are scale specific, that is on city, park, and street level (Table 6.1, right column). The principles originated from the academic and professional experience of the authors. They were also discussed with academics and professionals in the fields of botany, forestry, meteorology, and air quality, as well as landscape architects and urban designers from municipalities and urban design offices. The feedback of these stakeholders helped to sharpen this general set of operational principles that provide guidance for context-specific implementation of the design guidelines.

Table 6.1: Overview of preliminary design guidelines and operational principles

Scale level and source	Microclimate scientific evidence	Preliminary design guidelines for climate-responsive GI	Operational principles
CITY **(Klemm, Heusinkveld, Lenzholzer, Jacobs, & Van Hove, 2015a)**	People generally perceive urban green spaces as thermally comfortable and make use of green spaces on warm summer days. In terms of air temperature parks are cool spots compared to the city centre.	**1** (1) Preserve and maintain, (2) improve qualities within or expand existing green spaces and (3) develop new green spaces in cities.	Check design principles on park and street level for site designing
	People without private outdoor spaces as well as elderly people (and families with young children) make more use of green spaces in the direct surrounding of their home.	**2** Guarantee the presence of public green spaces in neighbourhoods without or with minimal private outdoor spaces and in neighbourhoods in which inhabitants are mainly elderly people and young children.	
	Green fraction of the built surrounding on the wind side of a park influences thermal conditions of parks.	**3** Preserve and, whenever possible increase the green fraction (including private and public green elements and green spaces) on the wind side of the prevailing summer wind direction.	
PARK **(Klemm, Hove, Lenzholzer, & Kramer, 2017)**	People in parks adapt to thermal conditions to ensure their (momentary) thermal comfort Spatial condition of parks, in particular the diversity of microclimates, have a facilitating role to enable the process of human adaptation.	**4** Create diversities of microclimates combined with park furniture, i.e. sitting elements, both in sun and shade in parks.	Shadow needed the most during periods with highest radiation (12:00 - 16:00) Species resistant against heat, drought, cold and salt (for icy roads) Appropriate planting circumstances (incl. sufficient space for the root system, high quality ground, sufficient irrigation during summertime)
	People behave proactive to create their own thermally comfortable microclimates (bringing their own parasols, elements to sit etc.)	**5** Create flexible and multi-functional spaces in parks to facilitate individual thermal adaptation.	
	Edges between sun and shade are popular places to stay in parks, as people easily are able to adapt to diverse thermal conditions.	**6** Create gradients/borders of open areas and shading elements where sun and shade are provided in close vicinity and alternation.	

Scale level and source	Microclimate scientific evidence	Preliminary design guidelines for climate-responsive GI	Operational principles
STREET **(Klemm, Heusinkveld, Lenzholzer , & van Hove, 2015b)**	10% tree cover in a street lowers mean radiant temperature about 1 K.	**7** Implement trees with large canopy covers in streets with high solar radiation.	Effective implementation of street trees (instead of trees everywhere) depending on specific site characteristics (H/W ratio, orientation toward sun) Shadow needed the most during periods with highest radiation (12:00 - 16:00) Deciduous trees are preferred (shade during summer/ radiation during winter) Avoid 'tunnel effect' in streets with heavy traffic by creating space for wind circulation between the tree canopies Species resistant against heat, drought, cold and salt (for icy roads) Appropriate planting circumstances (incl. sufficient space for the root system, high quality ground, sufficient irrigation during summertime)
	People are aware of their momentary thermal comfort (depending on their personal situation) and adapt in case of discomfort (change of location).	**8** Create diversities of microclimates (sun/ shade) in street canyons to enhance people's choice in which places they would like to walk.	
	Interviewees feel more thermally comfortable in streets with greenery. Aesthetical appreciation of street greenery enhances perceived thermal comfort.	**9** Implement aesthetic (meaningful, beautiful) green elements in street canyons, preferably at various heights (including public and private spaces) to improve thermal perception of pedestrians.	

6.2.2 The setup of the design studios

Two separate design studios were organized, (1) one with professional landscape architects and (2) another with landscape architecture students, both representing the group of end users of the design guidelines. Participants of both studios had little to no experience in climate-responsive urban design.

(1) Twenty-one professionals participated in the first design studio, which consisted of a two-day interdisciplinary studio organized in collaboration with Aorta Centre of Architecture in the city of Utrecht, the Netherlands (May 19th and 27th 2014). The design assignment was to create "design proposals that contribute to more healthy and climate-responsive outdoor urban spaces" (Paalvast, 2014). Three neighbourhoods in Utrecht were selected as study areas; they each had different spatial and socioeconomic characteristics. The participants were selected and invited by Aorta based on their expertise in the

design of outdoor urban spaces in Utrecht. They were divided into two groups of ten and eleven persons, respectively. Each group consisted of participants from landscape architecture and planning as well as other disciplines (Table 6.2), and was moderated by a professional landscape architect. Each group produced a design proposal, including intermediate sketches and notes for the final presentation.

(2) The second design studio, with twenty-four students, was part of a Master's programme in landscape architecture at Wageningen University (April 14^{th} to May 9^{th}, 2014). The design assignment was to improve "microclimate conditions in combination with enhancing spatial, recreational or ecological values in the city of Utrecht" (Van Etteger, 2014). Students were free to choose a specific location in Utrecht as their study area. Each of them produced a design proposal with visual materials accompanied by text.

The setup of both design studios was similar. Lectures on microclimate design were given in advance to provide the participants with general microclimate knowledge, such as the consequences of global warming and adaptive strategies for urban areas. Furthermore, the participants received an explanation regarding the preliminary guidelines, their scientific sources, and the operational principles (Table 6.1). Although the design briefs mentioned climate-responsiveness as a main goal, the participants were still free to decide to what extent this would play a role in their design proposals. This was deliberately done to challenge them to step into 'design dialogues' (De Jonge, 2009) and decision-making processes that could reflect real life design processes.

Table 6.2: Disciplines of participants (N = 21) in the professionals' design studio (according to themselves; more than one response was possible)

Discipline	**Number of responses**
Landscape architect	5
Human-geographer	3
Supervisor public spaces	3
Urban planner	2
Urban designer	1
Economist	2
Policy advisor	1
Project manager	2
Manager public spaces	1
Artist	2

6.3 Methods

This section describes: (1) the observations made of the design processes, (2) the plan analyses of the generated design proposals, and (3) the analyses of the questionnaires, used to assess the usefulness of the preliminary guidelines.

6.3.1 Observations

Observations were carried out to study how the preliminary guidelines were used during the design processes. In the professionals' studio, two researchers were involved, each observing the design process of one of the two groups. In the students' studio, researchers conducted the observations alongside the weekly individual tutoring. Researchers observed the design processes, the tutoring, and took notes on how the design guidelines were used by the participants in a logbook. Data analysis included inductive coding of the written accounts of observations.

6.3.2 Plan analysis

Plan analyses of the final products of the design studios were conducted to study how and to what extent the preliminary guidelines were used. All twenty-six reports – two group reports by professionals and twenty-four individual reports by students – consisted of written and visual materials such as maps, cross sections, and schematic illustrations. The plan analyses first focussed on how the microclimate analysis was carried out (no microclimate analysis, limited microclimate analysis, and proper microclimate analysis). A 'proper' microclimate analysis included an analysis of sun/ shade and wind patterns and urban heat distribution with seasonal and diurnal variations on the appropriate scale level (like described in: Lenzholzer and Brown, 2012). If the analysis was incomplete or incorrect, the microclimate analysis was scored as 'limited'.

Then, the design proposals were analysed on the extent to which the preliminary guidelines were implemented (not present, present in design, characteristic of the design). Design proposals in which the preliminary design guidelines were 'characteristic of the design' visibly reflected the application of the guideline(s) as well as the use of the relevant operational principles. In these design proposals, the function of microclimate regulation was prioritized compared to or well-balanced with other functional requirements, and thus characteristic of the spatial design. The score ‘present in design’ was given to proposals in which preliminary guidelines were only partly or not entirely correctly applied.

The plan analysis applied deductive coding using the qualitative data analysis and research software ATLAS.ti. To increase reliability, the coding was randomly checked by an urban microclimate expert at Wageningen University who was not involved in the design studios.

6.3.3 Questionnaires

In order to acquire a more precise understanding of the usefulness of the preliminary guidelines, all of the participants, both students and professionals, were asked to fill in a questionnaire after the design studios. The semi-structured questionnaire included the measure of the general appreciation of all preliminary guidelines as well as the evaluation of the criteria comprehensibility, applicability, and feasibility of each of the nine guidelines. Each of these criteria was broken down into three dimensions (Table 6.3). Responses were given on a five-point Likert scale from strongly disagree (-2) to strongly agree (2). Additionally, participants were asked to provide suggestions for improvement to the individual guidelines in an open question.

The data analyses included descriptive statistics (Excel), as the sample size of participants was too limited for an extensive statistical analysis. Responses to the criterion ‘feasibility’ were reverse coded: a positive answer illustrates agreement with the statement. Responses to the open questions were analysed using inductive coding.

Table 6.3: Assessment criteria and their statements for evaluation

Appreciation	I see the sense of urgency to include aspects of thermal comfort in current design- and planning processes. The design guidelines are of added value for the design- and planning process. Actively applying the design guidelines in an actual design process has helped me to apply the guidelines easier in the future.
Comprehensibility	I understand the meaning and content of this design guideline. I understand the operational principles related to this design guideline. I know when and where to apply this design guideline in order to improve microclimate conditions.
Applicability	This design guideline is easily applicable in design- and planning processes. This design guideline can flexibly be applied in different spatial conditions. This design guideline can be integrated in on-going urban renewal and construction processes.
Feasibility	The availability of space above and below ground hinders the implementation of this design guideline. The construction and maintenance cost hinders the implementation of this design guideline. The ground property situation hinders the implementation of this design guideline

6.4 Results

6.4.1 General results

Observations

Professionals and students applied the preliminary guidelines to different degrees. In the design processes, the professionals did not give them a prominent role and scarcely discussed the role of the microclimate. An observer described: "The preliminary guidelines have not been applied as such during the design process. Participants seemed to assume that any type of UGI positively affects the urban climate. The idea that designing in a climate-responsive way can even enhance this positive effect was not applied" (May 27th 2014). One reason might be that participants felt a limited sense of urgency to include microclimate aspects in the urban design. One of the participants stated: "Heat is not a problem in the Netherlands" (May 19th 2014). Professionals prioritized other functional requirements in their design dialogues, such as recreation or air purification ("We need to concentrate on problems regarding particulate matter and noise, not the microclimate", May 27th 2014). Yet, they generally acknowledged the positive effects of UGI on health and well-being and thus incorporated green spaces and elements in their design proposals.

In contrast, the students did integrate the preliminary guidelines at some stage in their design processes. Initial design proposals – similar to the professionals' design process – focussed on other functional requirements, like recreation or ecology. During the studio, the students increasingly addressed the microclimate in their analyses and design proposals. This was possibly caused by the advice of supervisors and the longer duration of the studio in comparison with the design process of the professionals, or had to do with the specific learning-and-application environment of studio-based training. The integration of guidelines in the design processes often began with site-specific microclimate analyses, for example the simulation of diurnal shadow patterns. These helped the students to investigate if more shade was needed and if so, what type of greenery and which location would be most suitable. One student concluded: "Before, I always made my designs without [microclimate/shadow] analysis. I just looked at what looks nice. But now I became aware of what I can achieve additionally, when planting trees [on the right spot]" (June 5th 2014). Similar to the professionals, the students acknowledged the multifunctional benefits of UGI in urban areas and combined microclimate interventions with other functions like recreation, food supply, or biodiversity.

Plan analysis

Analysis of the design proposals showed that the majority of participants analysed the microclimate precedent to the designs (Figure 6.2, left column 'Microclimate analysis'). Of all twenty-six design proposals, the microclimate analysis of 58% was 'proper', of 19% was 'limited', and 23% did not include a microclimate analysis. Of the projects with a proper microclimate analysis, 53% also included the design guidelines as 'characteristic of the design'. Design proposals at the street and park levels featured more 'proper' microclimate analyses than proposals at city level.

The preliminary guidelines were applied to varying degrees and at varying scale levels in the design proposals (Figure 6.2, right column 'Implementation of the preliminary design guidelines'). The guidelines were implemented extensively in design proposals at their assigned scale. Additionally, the guidelines were applied in design proposals on other scales. Park design guidelines, for example, were also implemented in park-like situations, thus spaces where people spend time, in city- or street-level projects. The spatial and functional variety of design proposals in which the guidelines were used, for example business areas, neighbourhoods, parks, or riverbanks, indicates a good applicability of the guidelines in various site-specific conditions, and at various scale levels.

Questionnaires

Participants generally appreciated the preliminary guidelines. The majority of professionals (80%) and students (88%) acknowledged the sense of urgency to include aspects of thermal comfort in current design processes (Table 6.4, right column). Interestingly, professionals emphasized the sense of urgency (80%) and the added value of design guidelines (80%), but in the actual design process they barely considered the preliminary guidelines, as discussed in section 6.4 Observations. One professional commented: "[We did] not yet use the guidelines actively." Still, 80% of the professionals and 71% of the students positively evaluated the active application of the guidelines in actual design processes.

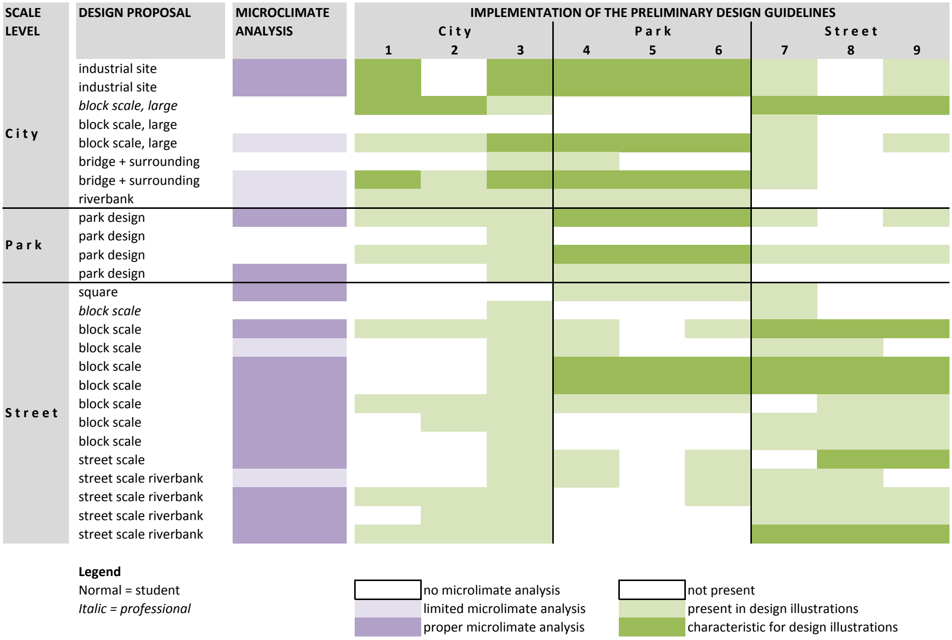


Figure 6.2: Microclimate analysis (left) and implementation of the preliminary design guidelines (right) according to scale levels in design proposals (N = 26)

Table 6.4: General appreciation of design guidelines by all participants (N = 29)

Survey statements*	**N**	**disagree [%] -2/-1**	**neutral [%] 0**	**agree [%] 1/2**
	prof | stud	**prof | stud**	**prof | stud**	**prof | stud**
I see the sense of urgency to include aspects of thermal comfort in current design and planning processes.	5 | 24	0 | 8	20 | 4	80 | 88
The design guidelines are of added value for the design and planning process.	5 | 24	0 | 0	20 | 17	80 | 83
Actively applying the design guidelines in an actual design process has helped me to apply the guidelines easier in the future.	5 | 24	20 | 0	0 | 29	80 | 71

* Statements appear in the same order as in survey

Both groups of participants agreed on the comprehensibility of the preliminary guidelines (Table 6.5), which they evaluated on a range from 0.67 (professionals, Guideline 2) to 1.53 (professionals, Guideline 7).This range indicates the participants' agreement with the statements on comprehensibility (Table 6.3). Participants generally indicated that the guidelines should be 'specifically microclimate related' and 'not too general'. Guidelines at park and street levels were more clear and helpful for design decisions, compared with the city level. Participants found the guidelines for the city scale rather 'obvious'. Both groups requested additional visual information, such as icons, and project examples to support the comprehensibility of the guidelines. Applicability was evaluated positively (from 0.60 to 1.24) for all guidelines by the students. The highest values were given to the guidelines at park level, which is in line with the evaluation by the professionals. The professionals, however, expressed concerns about the applicability of guidelines at city and street level (from -0,20 to 0.47). Regarding feasibility, the professionals aired more concerns than the students. This might be caused by their longer work experience in practice. Other than the guidelines at the park level, which they evaluated from neutral to slightly positive (from 0.33 to 0.53), the professionals mostly disagreed with the feasibility of the preliminary design guidelines at city and street level (from -1.00 to -0.47). The students evaluated the feasibility of the majority of the guidelines as neutral (from -0.47 to 0.21). A detailed evaluation of the questionnaire results per statement per group is provided in Appendix S.

Table 6.5. Evaluation of the nine preliminary design guidelines

	Guidelines	**CITY**			**PARK**			**STREET**		
	mean [SD] *	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Professionals (N = 5)	Comprehensibility	0.80 [0.59]	0.67 [0.67]	0.73 [0.73]	1.47 [0.49]	0.87 [0.65]	1.33 [0.58]	1.53 [0.49]	0.87 [0.48]	1.00 [0.27]
	Applicability	0.93 [0.60]	0.27 [0.56]	0.00 [0.87]	1.27 [0.66]	1.00 [0.27]	1.33 [0.58]	-0.20 [0.62]	0.47 [0.43]	0.53 [0.55]
	Feasibility	-0.60 [1.00]	-0.87 [0.73]	-0.47 [0.68]	0.53 [0.70]	0.33 [0.92]	0.33 [0.86]	-1.00 [0.76]	-0.53 [0.55]	-0.47 [1.12]
Students (N = 24)	Comprehensibility	0.75 [0.74]	0.96 [0.62]	0.99 [0.75]	1.36 [0.60]	1.00 [0.81]	1.20 [0.61]	1.18 [0.71]	1.00 [0.75]	1.01 [0.85]
	Applicability	0.87 [0.68]	0.70 [0.74]	0.60 [0.85]	1.24 [0.74]	0.97 [0.85]	0.93 [0.72]	0.68 [0.91]	0.72 [0.82]	0.90 [0.86]
	Feasibility	-0.25 [0.76]	-0.24 [0.71]	-0.34 [0.81]	0.21 [0.94]	0.20 [0.90]	-0.11 [0.87]	-0.63 [0.92]	-0.47 [0.88]	-0.31 [0.94]

* SD = standard deviation

Legend: disagree (-1,5 to -0,5) neutral (-0,5 to 0,5) agree (0,5 to 1,5)

6.4.2 Implications for the design guidelines

This section explores the implications of the research results described above for the nine individual preliminary guidelines. To do so, we elaborate, per guideline, on the conclusions that can be drawn from the observations, plan analyses, and questionnaires for the usefulness of the guidelines and their comprehensibility, applicability, and feasibility (presented as CAF). The conclusions drawn lead to consideration of whether to revise the preliminary guidelines (for example 1.0) or not, followed by the revised guideline, indicated with '.1' (for example 1.1). For the ordering, numbering and wording of the revised guidelines at city, park, and street level, we refer to Figures 6.3, 6.4 and 6.5, respectively. They provide an icon and reference image per guideline and the respective operational principles.

City level

Guideline 1.0: (1) Preserve and maintain, (2) improve qualities within or expand existing green spaces, and (3) develop new green spaces in cities.

Usefulness: This guideline was used in 46% of the design proposals at all scale levels. Most examples related to the preservation of and improvement to large green spaces, like parks or green networks. Participants needed an explanation regarding the three sequential aspects ((1) preserve, (2) improve and (3) develop).

CAF: Participants agreed with the comprehensibility of the guideline, but indicated that the guideline is 'too general', 'self-evident in urban areas' and 'should be more precise'. They evaluated the applicability of the guideline positively and indicated that a combination with other design functions is possible. There were concerns regarding feasibility, particularly for the statements on available space above and below ground and on ground property.

Improvements: This guideline is rather complex due to the three sequential aspects. The improvement made includes a stronger link to microclimate-related design and simplification through combining the similar preliminary Guidelines 1.0 and 3.0 (see below). The revised Guideline 1.1 thus focusses on maintenance and improvement, while the revised Guideline 3.1 focusses on expansion and new green spaces (Figure. 6.3).

Guideline 1.1: Maintain and improve a network of interconnected green spaces in cities, including all types of urban vegetation (green elements and green spaces in private and public realms).

Guideline 2.0: Guarantee the presence of public green spaces in neighbourhoods without or with minimal private outdoor spaces and in neighbourhoods in which inhabitants are mainly elderly people and young children.

Usefulness: This guideline was used in 46% of the design proposals in all scale categories. It was 'characteristic of the design' in a design proposal that in particular addressed the accessibility of urban green spaces ranging from private outdoor spaces up to green city networks.

CAF: Participants generally confirmed the comprehensibility of the guideline, but again it was 'very vague'. The students agreed on the applicability of this guideline. The professionals questioned the availability of space above and below ground and expect the property situation to hamper implementation. One remark was that 'demographic situations constantly change in neighbourhoods'.

Improvements: The 'presence' of public green space is difficult in terms of feasibility, particularly when developing new green spaces in existing urban environments. Consequently, the aspect 'accessibility of green space' has been added. The guideline was simplified by focussing on the spatial characteristics of neighbourhoods (Figure. 6.3).

Guideline 2.1: Guarantee the presence and/ or accessibility of public green spaces in neighbourhoods without or with minimal private outdoor spaces.

Guideline 3.0: Preserve and, whenever possible, increase the green fraction (including private and public green elements and green spaces) on the wind side of the prevailing summer wind direction.

Usefulness: This guideline was used in almost all design proposals (96%) throughout all scale categories. We found an overlap with respect to Guideline 1.0 (preserve and increase green space). Owing to the broad range of elements and spaces in Guideline 3.0, it was applied in all the design proposals in which greenery of any type was added. Participants experienced difficulties in the analysis of and designing with wind directions and requested more site-specific wind information to inform design decisions.

CAF: Even though the participants acknowledged the comprehensibility of this guideline, additional remarks were made on the wind aspect. Designing with wind was described as 'complex', 'hard to predict', and 'unclear', which is in line with the observational results. The professionals evaluated applicability neutrally and feasibility negatively; their concerns were similar to those related to Guideline 1.

Improvements: The duplication in Guidelines 1.0 and 3.0 was removed and an explanation regarding wind was added (Figure. 6.3).

Guideline 3.1: Increase the green fraction in cities (including private and public green elements and green spaces) on the windward side of the prevailing summer wind direction and keep cold air corridors open.

CITY 1.1	Maintain and improve a network of interconnected green spaces in cities, including all types of urban vegetation (green elements and green spaces in private and public realm).
CITY 2.1	Guarantee the presence and/or accessibility of public green spaces in neighbourhoods without or with minimal private outdoor spaces.
CITY 3.1	Increase the green fraction in cities (including private and public green elements and green spaces) on the windward side of the prevailing summer wind direction and keep cold air corridors open.

Operational principles: Check operational principles on park and street level for site designing

Figure 6.3: Revised design guidelines for climate-responsive UGI at city level

Park level

Guideline 4.0: Create diversities of microclimates combined with park furniture, for instance sitting elements, both in sun and shade in parks.

Usefulness: This guideline was applied in 65% of the design proposals in all scale categories. Participants largely created microclimate diversity in their spatial designs. Still, mistakes occurred in a few cases: the use of greenery and the provision of shade was either over- or underutilized, resulting in either uniformly shaded and/or mostly sunny places. On the other hand, various proposals suggested innovative flexible solutions that could be adapted to different microclimate conditions and user needs, for example benches that could be moved between sun and shade.

CAF: Both groups acknowledged both the comprehensibility and applicability of this guideline. This guideline was considered 'quite precise, and easy to understand and apply'. The students assessed feasibility neutrally while the professionals agreed that this guideline is feasible. One participant commented: 'For a park, it is easier than for the city, because the park is usually public property.'

Improvements: Outcomes of the design processes largely confirmed the usefulness of this guideline. Additional information was provided on how to create diverse microclimates (also see Klemm et al., 2017b). Furthermore, the solar condition 'half-shade' was added, which was also illustrated in the respective icon (Figure. 6.4).

Guideline 4.1: Create diversity of microclimates (sun, half-shade, shade) through diverse tree plantings (such as open lawn, single/ solitary tree, group of trees or boscage) and combine them with park furniture, for instance sitting elements.

Guideline 5.0: Create flexible and multifunctional spaces in parks to facilitate individual thermal adaptation.

Usefulness: This guideline was used in 46% of the design proposals in all scale categories. It was used not only in park designs, but also in 'park-like' spaces in business areas or residential neighbourhoods. Design proposals included open grass fields, lawns, or terraces, which are familiar elements in the design of outdoor spaces.

CAF: All participants agreed on the comprehensibility and applicability of this guideline; its feasibility was assessed neutrally.

Improvements: In general, this guideline was considered easy to use, so no improvements were necessary (Figure. 6.4).

Guideline 5.1: Create flexible and multifunctional spaces in parks to facilitate individual thermal adaptation.

Guideline 6.0: Create gradients/ borders of open areas and shading elements where sun and shade are provided in close vicinity and alternation.

Usefulness: Guideline 6.0 was also extensively applied. It was present in 62% of the design proposals on all scale levels. Even though this guideline was barely mentioned in the design processes, the majority of design proposals included gradients between sun and shade.

CAF: All of the participants acknowledged the comprehensibility and applicability of this guideline; its feasibility was assessed neutrally.

Improvements: In general, this guideline was considered easy to use, no improvements were needed. The new icon clearly illustrates the spatial conditions of this guideline (Figure. 6.4).

Guideline 6.1: Create gradients/borders of open areas and shading elements where sun and shade are provided in close vicinity and alternation.

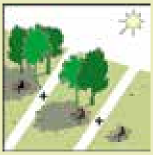
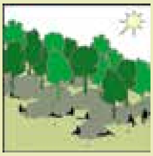
PARK 4.1	Create diversity of microclimates (sun, half shade, shade) through diverse tree plantings (e.g. open lawn, single/solitary tree, group of trees or boscage) and combine them with park furniture, i.e. sitting elements.			Operational principles: ▪ Shadow needed the most during periods with highest radiation (12:00 - 16:00) ▪ Use species resistant against heat, drought, cold and salt (for icy roads) ▪ Appropriate planting circumstances and effective maintenance (incl. sufficient space for the root system, high quality ground, sufficient irrigation during summertime)
PARK 5.1	Create flexible and multi-functional spaces in parks to facilitate individual thermal adaptation.			
PARK 6.1	Create gradients/borders of open areas and shading elements where sun and shade are provided in close vicinity and alternation.			

Figure 6.4: Revised design guidelines for climate-responsive UGI at park level

Street level

Guideline 7.0: Implement trees with large canopy covers in streets with high solar radiation.

Usefulness: This guideline was applied in 81% of the design proposals. In the design processes, we noted that the participants mainly attempted to preserve existing tree canopies. In cases where this was not possible due to new spatial concepts, new trees were planned in close proximity, as compensation. The locations of the trees were often determined by the results of site-specific shadow analyses. In a few of the design proposals, shading through the placement of trees was either missing or overutilized. Too many trees and trees planted too closely together created compact tree canopies above streets that – on busy traffic routes – could hinder wind circulation and the rejuvenation of the polluted air. These examples demonstrated that this guideline could be used incorrectly when the operational principles (Table 6.1, right column) were not taken into consideration.

CAF: All participants acknowledged the comprehensibility of this guideline and assessed its applicability neutrally. Participants noted that 'trees need time to grow into large canopies' and suggested 'using some temporary types of shading' in the short run. Feasibility was assessed negatively by both groups mainly due to the lack of space above and below ground. Participants mentioned the 'limited space in street profiles' and 'limited space for tree roots'.

Improvements: In general, this guideline was rated as comprehensible and easy to use; no improvements were needed. (Figure. 6.5).

Guideline 7.1: Implement trees with large canopy covers in streets with high solar radiation.

Guideline 8.0: Create diversities of microclimates (sun/ shade) in street canyons to enhance people's choice in which places they would like to walk.

Usefulness: This guideline was used in 54% of the design proposals. It was mainly applied in streets with additional functions, like boulevards or wide streets in neighbourhoods. Similar to Guideline 7.0, the implementation of this guideline depended on a proper microclimate analysis.

CAF: Participants found this guideline comprehensible. Applicability was evaluated positively by the students and neutrally by the professionals. Feasibility was assessed negatively by both groups, stemming from the major constraints in space.

Improvements: In general, this guideline was comprehensible and easy to use; no improvements were needed. Concerning feasibility, see the improvements to Guideline 7.0 above (Figure. 6.5).

Guideline 8.1: Create diversities of microclimates (sun/ shade) in street canyons to enhance people's choice in which places they would like to walk.

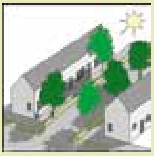
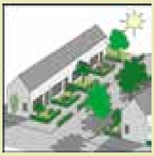
Guideline 9.0: Implement aesthetic (meaningful, beautiful) green elements in street canyons, preferably at various heights (including public and private spaces) to improve the thermal perception of pedestrians.

Usefulness: This guideline was present in 62% of the design proposals. It seemed that participants almost unconsciously applied this guideline without microclimate considerations, when designing functionally and visually attractive green spaces, probably because creating appealing spaces is a 'familiar' task in design practice. Examples include linking street greenery to architectural styles in the built environment and seasonal variation though combination of species.

CAF: Both groups of participants agreed on the comprehensibility and applicability of this guideline. Comments of participants included the need for explanation of the terms 'aesthetic', 'meaningful', and 'beautiful', and suggested providing pictures and visual information. The professionals commented on constraints to feasibility, such as construction and maintenance costs, and access to property.

Improvements: The design process and results showed that this guideline was applicable. The ambiguous terms, picked up by the participants in the text, were replaced by spatially explicit terms (Figure. 6.5).

Guideline 9.1: Implement green elements in street canyons at various heights (including public and private spaces) to improve the thermal perception of pedestrians.

STREET 7.1	Implement trees with large canopy covers in streets with high solar radiation.		
STREET 8.1	Create diversities of microclimates (sun/shade) in street canyons to enhance people's choice in which places they would like to walk.		
STREET 9.1	Implement green elements in street canyons at various heights (including public and private spaces) to improve thermal perception of pedestrians.		

Operational principles:
- Effective implementation of street trees (instead of trees everywhere) depending on specific site characteristics (Height to Width ratio, orientation towards the sun)
- Shadow needed the most during periods with highest radiation (12:00 - 16:00)
- Deciduous trees are preferred (shade during summer/ radiation during winter)
- In streets with heavy traffic: avoid disturbing traffic flows for safety reasons and avoid 'tunnel effect' by creating space for wind circulation between the tree canopies
- Use species resistant against heat, drought, cold and salt (for icy roads)
- Appropriate planting circumstances and effective maintenance (incl. sufficient space for the root system, high quality ground, sufficient irrigation during summertime)

Figure 6.5: Revised design guidelines for climate-responsive UGI at street level

6.5 Discussion and conclusion

This study aimed at the development of design guidelines for climate-responsive urban green infrastructure (UGI) that are considered useful by design practitioners. Usefulness is defined by the following criteria: comprehensible for the designers, applicable in design processes, and feasible to implement in practice. The study was explorative in nature; this informed the choice of an in-depth qualitative study with a limited number of participants, namely, landscape architecture professionals and students. Our main research question was: *What are evidence-based design guidelines for climate-responsive UGI that practitioners consider to be useful in terms of comprehensibility, applicability, and feasibility?*

We conducted a novel participatory 'Research through Designing' (RTD) approach (Lenzholzer et al., 2013) to test and develop the guidelines based on scientific evidence (see study design in Figure 6.1). A crucial first step in the process was to transform the descriptive, scientific knowledge into prescriptive preliminary guidelines. The design process demonstrated that those normative preliminary guidelines were appreciated and widely considered useful. Participants responded that they comprehended the preliminary guidelines, yet they asked for additional visual information. This confirmed the outcomes of earlier studies (e.g., De Schiller and Evans, 1990, Prominski, 2017, Eliasson, 2000, Norton et al., 2015). Participants' responses regarding to applicability showed that they were able to apply the preliminary guidelines in the design processes. The preliminary guidelines are widely transferable to various urban design contexts for different scales (city, park, street), urban surroundings (business, recreational, or residential environments) and urban contexts (new developments or retrofit). Even though participants questioned the feasibility in practice, particularly limitations in availability of space and access to properties at city and street levels, the design proposals also showed creative, multifunctional solutions that adequately coped with the urban climate challenges. In a final step of the RTD process the preliminary design guidelines were improved based on the results of the observations of the design processes, the plan analyses of the design proposals, and questionnaires with the participants. The study resulted in nine revised design guidelines on the city, park, and street levels. To clarify implementation in a site-specific context, they were accompanied by icons, reference images, and operational principles at the respective scale levels (Figures 6.3, 6.4 and 6.5).

To ensure a proper application of the design guidelines a microclimate analysis of the design location is vital: in climate-responsive UGI design there is no one-size-fits-all solution (Mathey et al., 2011, Norton et al., 2015). Typical microclimate analyses (such as shadow and wind pattern analyses (Lenzholzer and Brown, 2012)) help to answer design questions such as: Is cooling desirable during the day or at night time? Should cooling be effective inside or outside buildings? Does urban vegetation create adverse effects, such as limiting daylight in buildings or the reduction of air quality on streets with heavy traffic? The additional operational principles (Figures 6.3, 6.4 and 6.5, right column) support to answer those questions and guide decisions on design (vegetation species and planting circumstances) and on maintenance (irrigation, for example) in the specific circumstances. Only comprehensive, site-specific spatial and functional analyses can bring about design solutions with optimal shape, structure and distribution of UGI that improve thermal conditions and that possibly contribute to other UGI benefits, for example visual appeal or air purification, in urban areas.

Reflecting on the study design, we consider the participatory RTD approach used in this study valuable for the development of evidence-based design guidelines (Lenzholzer et al., 2013).This approach enabled us to link the scientific knowledge on urban microclimate with the practical knowledge of urban designers through active design processes. Insights gained in the design processes confirm that additional knowledge (Prominski, 2017) (here on microclimate analysis, for example provided though operational principles) is needed to ensure a proper implementation of the design guidelines. Though the RTD approach still has some limitations. For instance, the development of the design guidelines was based on a non-exhaustive series of UGI microclimate studies (Klemm et al., 2015a, Klemm et al., 2015b, Klemm et al., 2017b). In addition, there were clear differences how the professionals and the students included the guidelines in their designs. This may have been due to the fact that part of the study was undertaken in a class setting and the other in a workshop setting. This initial study should be followed up by more exhaustive research to indicate how design guidelines are applied in design practice, and how they are evaluated in terms of comprehensibility, applicability and feasibility. Such research may create more generalizable knowledge and test the learnings of our findings further.

The design guidelines and operational principles presented in this paper contribute to strategies for urban climate adaptation. They may help urban designers to explore the new territory of microclimate-responsive design and to include microclimate considerations into their daily design practice. However, the applicability of design guidelines is limited to the types of spaces for which they are created. Applying climate-responsive design in other contexts is beyond the scope of these design guidelines.

In a general perspective this study showed that climate-responsive design is a new topic in urban design and when it came to creating a balance between competing functional demands in the design process, focus on the microclimate seemed to have lower priority. The limited sense of urgency about urban climate issues experienced by the participants confirms earlier studies (Pijpers-van Esch, 2015). Campaigns to enhance the sense of urgency for (public) commissioners of design assignments as well as for urban designers are needed and additional advice by microclimate experts during design processes may activate a consciousness of climate-responsive design in future design processes. Last but not least education – also in life-long learning settings – can help to increase the incorporation of climate-responsive-design strategies in urban design practice. Therefore, we recommend teaching climate-responsive design to students and professionals in design studio learning environments, and supporting them to apply this knowledge in site-specific conditions. This learning on the task helps to create tacit and 'embodied' design skills that incorporate climate responsive in a natural way.

7 Discussion and conclusions

7.1 Introduction

In the context of global climate change and urban heat problems, climate-responsive design of urban areas can create healthy and thermally comfortable living environments. This thesis was motivated by the need to provide landscape architects and other urban design professionals with specialised knowledge on how to shape urban green (i.e., vegetated) spaces and elements, referred to as urban green infrastructure or UGI (e.g., Young et al., 2014, Norton et al., 2015). Such evidence-based knowledge, rather than popular general beliefs like '*green is good*' or '*the more green, the better*', should inform climate-responsive design of outdoor urban spaces to mitigate heat stress and to create thermally comfortable environments, in all seasons and in all possible future climates (e.g., Lenzholzer and Brown, 2012, Brown, 2011, Eliasson et al., 2007).

Urban green infrastructure moderates urban climate conditions on various scale levels. To date, research has predominately investigated the impacts of UGI on objective thermal conditions (e.g., Bowler et al., 2010). Such micrometeorological studies are limited in the moderate climate of the Netherlands, and the knowledge available does not match the demand of spatially explicit information by urban designers. Besides moderating objective thermal conditions, UGI impacts peoples' subjective thermal perception (Lenzholzer et al., 2018), that is how a person senses and experiences physical thermal conditions in a vegetated as compared to a non-vegetated environment. Research on subjective thermal perception linked to the spatial characteristics of the environment provides thermo-spatial knowledge, that can guide the design of climate-responsive UGI. Yet, studies on subjective thermal perception have been underrepresented in urban microclimate research. Consequently, the scholarly knowledge on UGI available has hardly impacted current design practice (e.g., Norton et al., 2015, Fryd et al., 2011, Mathey et al., 2011). To enhance the impact of scientific microclimate knowledge in urban design practice, the knowledge needs to be more spatially-explicit to be relevant for design practice (Bowler et al., 2010, Fryd et al., 2011) and to be communicated and presented in a way that it is regarded as useful by urban design practitioners (e.g., Brown and Corry, 2011, De Schiller and Evans, 1990, Eliasson, 2000).

Design guidelines are considered as tool with which to inform design practice (e.g., Lenzholzer, 2010a, Prominski, 2017). But there are only a few studies that elaborate on definitions and methodologies how to develop design guidelines. This thesis considers design guidelines to be a body of evidence-based, generally applicable knowledge that guides urban design actions in a variety of site-specific spatial and functional circumstances, and that design professionals consider to be useful. Usefulness in this thesis is defined by three key criteria: comprehensibility, applicability in design, and feasibility in practice. Concerning the development of evidence-based and useful design guidelines, models are described that use fundamental knowledge to generate evidence-based design in landscape architecture (Nassauer and Opdam, 2008, Brown and Corry, 2011), and that assess and assure the usefulness of guidelines in design practice (Lenzholzer et al., 2013). Yet, the practicality of these models needs to be confirmed.

This research set out to generate evidence-based and useful design guidelines for climate-responsive UGI. I answered the main research question: *What are useful, evidence-based design guidelines for climate-responsive urban green infrastructure (UGI)?* This research question is divided into the following sub-questions:

1. *What is the impact of UGI on peoples' subjective thermal perception in relation to objective microclimate conditions?*
2. *What is spatially explicit evidence regarding effects of UGI on thermal perception?*
3. *What are evidence-based and useful design guidelines for climate-responsive UGI and how can they be developed from the empirical evidence generated in this thesis?*

For this purpose I applied a multiphase, mixed methods approach consisting of two independent, sequencing studies. The two phases include first a 'Research for Design' study, and second, a participatory 'Research through Designing' (RTD) study. First, I systematically examined UGI impacts on subjective thermal perception and objective thermal conditions in multiple cases at city, park and street level (Chapters 2, 3 and 4). The studies combine quantitative (micrometeorological measurements) and qualitative (surveys, observations) methods and focus on warm summer periods in the moderate climate of the Netherlands. To put the methodological findings of the previous chapters into a broader scientific context, I subsequently conducted a literature review on studies that similarly investigate thermal perception (Chapter 5). Second, I translated the gathered scientific evidence of the first phase into preliminary design guidelines and tested them on their usefulness in practical design settings (Chapter 6). Observations of the design processes, plan analysis of the design proposals, and questionnaires conducted with the participants provided insights into the usefulness of the preliminary guidelines. These insights directed the refinement of the preliminary guidelines into revised design guidelines for climate-responsive UGI that can contribute to create healthy and thermally comfortable living environments.

7.2 Answering the research questions

The findings of Chapters 2, 3 and 4 reveal the wide-ranging positive impacts that UGI has on thermal perception and the urban microclimate. UGI generally improves subjective thermal perception as well as objective thermal conditions on various scale levels in urban environments. The comprehensive evidence provided in this thesis demonstrates that '*green is perceived to be cool*' and underpins the general belief that '*green is cool*'. This evidence offers quantitative and qualitative measurement results of UGI impacts on thermal comfort in the moderate climate of the Netherlands. Additionally, it clarifies scale and spatially explicit characteristics of climate-responsive UGI. From a methodological perspective, those research results underpin the relevance of using qualitative methods to study thermal perception (Chapter 5).

The results in Chapter 6 provide design guidelines for climate-responsive UGI on city, park and street level. Development of those nine guidelines was based on scientific evidence; their usefulness has been tested in practical design settings. Together with the operational principles provided and a basic understanding of microclimate processes, these nine design guidelines are relevant for 'clever' climate-responsive design of UGI, rather than the adage '*the more green, the better (adapted to urban heat issues)*'. Instead of the ubiquity of UGI, this thesis thus argues for urban green that is '*clever and cool*': climate-responsive UGI that is designed resource efficiently, is based on site-specific microclimate analysis, and considers spatial conditions as well as the behavioural demands of urban dwellers.

In the following sections I answer the sub-questions through describing people's subjective thermal perception related to UGI, and how the subjective reality relates to the objective reality (7.2.1), spatially explicit characteristics of climate-responsive UGI (7.2.2), useful design guidelines for climate-responsive UGI and how they can be developed from scientific evidence (7.2.3). Subsequently, I synthesise these findings to answer the main research question (7.2.4).

7.2.1 Subjective and objective thermal reality

The first sub-question of this thesis concerns the relationship between two realities: the subjective reality of individuals who perceive, use and value UGI elements and spaces on warm summer days, and the objective reality of the physical impacts of UGI elements and spaces on micrometeorological parameters. This research illustrates the positive impacts UGI spaces and elements have on both realities: on people's subjective thermal perception, and on objective thermal conditions in urban environments. A comprehensive overview of research results at the three scale levels is provided in Table 7.1 (see column 'UGI impacts on subjective and objective thermal comfort') and elaborated below.

At city scale (Chapter 2), results from 559 questionnaires in three Dutch cities (Arnhem, Utrecht, Rotterdam) showed that green environments were considered thermally comfortable on warm summer days. People rated green environments more thermally comfortable than water or built environments. Of the 672 specific places that were indicated as thermally comfortable on hot summer days, 59.4% was a green environment, 25.4% was a water environment, and 15.2% was a built environment. Results were consistent across all investigated cities. Independent micrometeorological measurements in Utrecht confirmed people's subjective thermal perceptions from the objective perspective. Results of the physical study in Chapter 2 show that large green spaces, such as parks, are 'cool spots' in cities during warm summer days. On warm summer days the average air temperature (T_a) in parks is 1 K lower than in the city centre and comparable to the T_a in open grassland outside the city. The mean radiant temperature (T_{mrt}) can be up to 12 K lower in a park than in the built city centre. The average T_{mrt} of all investigated parks was 1.7 K lower than the city centre, and 13.6 K lower than open grassland outside the city (Table 7.1). The subjective perspective is in line with the objective reality: during warm summer days parks are relatively cool spots in the city because of lower T_a and, in particular, in T_{mrt} values compared to the city centre; people subjectively experience such spaces as thermally comfortable. Respondents to the interviews had repeatedly experienced green urban environments as thermally comfortable in the past. This infers a positive relationship between their general (or long-term) thermal perception and UGI in urban environments: on warm summer days they prefer green to non-green environments.

Results at park scale (Chapter 3) of a subsequent study in the Wilhelminapark in Utrecht and the Torckpark in Wageningen confirm the subjective perspective described in Chapter 2. The parks investigated were well-visited urban outdoor places on warm summer days, as evidenced by the large numbers of resting park visitors on eleven summer days, for example, a total of 10.871 in the Wilhelminapark. The majority of all 317 interviewees in both parks also described their level of momentary thermal perception on levels between 'comfortable' and 'very comfortable' on both summer and tropical days ($T_{a\ max}$ > 25 °C and > 30 °C, respectively). Interview results on momentary thermal perception on park scale (Chapter 3) and on long-term thermal perception on city scale (Chapter 2) produce the same finding: during summertime people experience parks as thermally comfortable.

Results at street scale (Chapter 4) in living environments also showed that people prefer green to non-green environments, as with the results at city scale (Chapter 2). Pedestrians evaluated streets with street greenery, that is, street trees and green front gardens, as more thermally comfortable on warm summer days than streets with only bare, hard surfaces. Results of interviews with 108 pedestrians indicate that people's momentary thermal perception tends to be related to the presence of street greenery. Independent micrometeorological measurements of objective parameters in the respective streets support this subjective thermal perception. Compared to streets without greenery, street average mean radiant temperature (T_{mrt}) was up to 4.8 K lower in streets with large street trees, and up to 2.6 K lower in streets with small street trees and front gardens.

Interestingly, pedestrians evaluated their overall thermal perception in streets with trees combined with front gardens more comfortable than in streets with solely trees. This did not correspond with the actual objective thermal conditions. Streets with trees and front gardens showed street averaged T_{mrt} values up to 3 K higher than streets with trees due to smaller tree canopy covers. Thus, despite the higher radiation in streets with trees and front gardens, thermal perception

Table 7.1: Overview of research results of field studies – Thermal perception field studies

Scale level	Research questions	UGI impacts on subjective and objective thermal comfort	Climate-regulating variables of UGI
CITY	**Objective impacts**: ▪ What are the physical thermal conditions in urban green spaces (T_a, T_{mrt}, PET) during warm summer days, and what are the dependences with spatial variables of specific sites?	▪ parks are relatively cool spots (on average T_a 1 K lower than the city centre and Tmrt values 1.7 K lower than the city centre and 13.6 K lower than open grassland) ▪ thermal variation between parks depending on tree canopy cover, upwind vegetation cover, not on park size ▪ 10% more tree canopy cover lowers T_{mrt} by about 3.2 K	▪ the accumulated effect of upwind vegetation cover contributes to improved physical thermal conditions in urban environments ▪ physical thermal conditions in parks determined by tree canopy cover ▪ a large portion of perceived thermal comfort can be described by the spatial type of environment (e.g., green vs. water or built)
	Subjective impacts: ▪ How do people generally perceive green places in urban environments during warm summer days with respect to thermal conditions?	▪ strong correlation between large urban green spaces and long-term thermal perception	
PARK	**Objective impacts:** ▪ How does extreme air temperature in summer influence daily park attendance? ▪ What are the user patterns related to solar exposure of resting park visitors on summer and tropical days? ▪ What are spatial typologies for optimal park use on summer and tropical days?	▪ decreasing daily park attendance with increasing ambient $T_{a\,max}$ ▪ resting park visitors physically adapt (i.e., change location to either be in sun, half-shade or shade) in relation to ambient T_a ▪ with increasing T_a > fewer people in the sun, more people in the shade, tipping point at T_a = 26 °C ▪ regardless Ta: preferred resting locations evenly spread throughout the days (40% sun, 40% shade and 20% half-shade)	▪ variety of microclimates needed (i.e., 40% sun, 40% shade and 20% half-shade) ▪ preferred locations are liminal areas between sun and shade (edges) ▪ create open areas in which park visitors can create individual microclimates (umbrella etc.)
	Subjective impacts: ▪ What is the importance of microclimate on the spatial preferences of resting park visitors? ▪ What is the momentary thermal perception of resting park visitors on summer and tropical days?	▪ microclimate, in particular solar exposure, is the most important aspect for choosing resting locations in parks ▪ both on summer and on tropical days resting park visitors expressed their level of momentary thermal comfort as comfortable	

Scale level	Research questions	UGI impacts on subjective and objective thermal comfort	Climate-regulating variables of UGI
STREET	**Objective impacts:** ▪ What is the physical impact of street greenery (street trees and front gardens) on the parameters T_a and T_{mrt}?	▪ tree canopy cover in public and private spaces impacts physical thermal conditions, no impact from low vegetation ▪ 10% more tree canopy cover lowers T_{mrt} by about 1 K ▪ no relation found between tree canopy cover and Ta (street averaged value)	▪ physical thermal conditions in streets determined by tree canopy cover, both in public and private spaces; determining factors are size and solar permeability (leaf density) ▪ more green, especially at eye height tends to positively impact subjective thermal perception ▪ variety of microclimates enables physical adaptation (i.e., change location either to be in sun or shade)
	Subjective impacts: ▪ What is the impact of street greenery (street trees and front gardens) on momentary and long-term thermal perception? ▪ How does momentary thermal perception relate to the evaluation of green street design (aesthetic appreciation)?	▪ the amount of street greenery tends to be related to momentary thermal perception; not to long-term thermal perception ▪ no relationship between momentary thermal perception and aesthetic appreciation ▪ respondents were aware of diurnal and seasonal variations, especially solar exposure (sun/ shade)	

was rated more positively in those streets than in streets with trees. This finding could be explained by the more varied view of different types and heights of vegetation in streets with trees and front gardens than streets with trees only. Streets with front gardens offer views for example of arrangements of low vegetation beds, medium high hedges, small trees or climbing constructions.

The findings of Chapters 2, 3 and 4 allow for concluding remarks to answer research sub-question 1: Across all scale levels, UGI improves subjective thermal perception. People evaluate urban environments with UGI as more thermally comfortable and prefer them to non-green environments. A large portion of the variance of subjective thermal perception in cities can thus be explained by the spatial characteristics of the environment, in particular the presence of UGI spaces (large green spaces, parks) and elements (street greenery). Additionally, a more varied vegetation in the visual field of pedestrians probably leads to a better thermal perception.

The findings of Chapters 2, 3 and 4 regarding subjective thermal perception are in line with and can mostly be explained by the objective microclimate conditions. This correspondence between the subjective and objective reality was also found in the majority of studies examined in the literature review (Chapter 5). It indicates a close relation between subjective and objective reality. Concerning this research, one can say '*green is perceived to be cool*' and '*green is cool*'. It implies that people's subjective thermal perception (momentary and long-term), as well as objective microclimate conditions can be increased during warm summer periods by incorporating ample UGI spaces and elements in urban environments.

However, results of Chapter 4 (similarly to two other studies mentioned in Chapter 5) show that people's subjective thermal reality can deviate from the objective thermal reality; their momentary thermal perception can differ from the physical thermal conditions. Knowing that such mismatches may exist is important for studying thermal comfort. Studying either solely the subjective or solely the objective reality would be insufficient. Since urban design needs to respond to both realities, investigations and representations need to address both: the physical environment, and how people subjectively perceive this environment.

7.2.2 Spatially explicit evidence of climate-responsive UGI

This thesis provides a series of spatially explicit characteristics of UGI spaces and elements relevant for climate-responsive design. From the objective perspective, results of this research prove that upwind vegetation cover in urban environments, as well as size and leaf density of tree canopies enhance physical thermal conditions. From the subjective perspective, an enhanced ratio of street greenery in the visual field of pedestrians and conscious distribution of tree canopy cover in specific sites improve people's thermal perception. Furthermore, this thesis argues for creating diverse microclimates, in particular regarding solar exposure within urban environments. Such diverse microclimates are created through the conscious distribution of tree canopy covers and enable people to physically adapt to the perceived thermal conditions. In this section I elaborate on the spatially explicit evidence of UGI and discuss the important phenomenon of physical adaptation. Table 7.1. represents those findings in the right column 'Climate-regulating variables of UGI'.

With regard to the objective perspective, Chapter 2 showed that upwind vegetation cover in urban environments significantly influenced air temperature (T_a) in the parks investigated. The higher the amount of vegetation land cover in the upwind urban environments, the lower the T_a in the parks. This rather general variable suggests that all type of green surfaces, as in vegetated and permeable surfaces in gardens and parks, but also in parking lots, tram sections or streets, temper T_a in the neighbourhood located downwind. This evidence emphasises the positive accumulated effects that UGI spaces and elements can have on urban thermal conditions, and also the interdependencies of thermal influences of adjacent neighbourhoods. Climate-responsive design at city level thus exceeds the scale of parks or neighbourhoods.

Besides upwind vegetation cover, the objective thermal conditions are significantly determined by the size and leaf density of tree canopy covers. Chapters 2 and 4 show that the size of tree canopy cover is significantly linked to the thermal variances between different parks and between streetscapes. Tree canopy cover alleviates thermal discomfort by limiting solar short-wave radiation and providing shade to park visitors or pedestrians. The increase of tree canopy cover of 10% lowers the spatially average T_{mrt} about 3.2 K in a park (Chapter 2), and about 1 K in a residential street (Chapter 4). The results at street scale show that tree canopy cover within the public and private spaces impacts T_{mrt} levels within the middle of the street canyon. Chapter 4, furthermore, indicates that solely considering the size of tree canopy covers can over- or underestimate actual shading impacts regarding T_{mrt} (see Appendix R). A more realistic estimation of shading impacts can be reached by considering the leaf density additional to the size of tree canopy covers. The leaf density (or gap fraction) of tree crowns influences solar permeability and thus the actual amount of shade provided by trees.

From the subjective perspective, Chapter 4 suggests that the amount and varying heights of street greenery in public and private spaces improve thermal perception. Green front gardens with grasses, hedges, bushes, trees, climbing vegetation on facades or pergolas, combined with street trees, provide a spatially diverse vegetation structure of varying heights in streets. Pedestrians who experience such an enhanced ratio of street greenery in their visual field tend to have a more positive thermal perception than they do in streets without greenery.

As shown in Chapter 3, spatial distribution of tree canopies is another spatially explicit characteristic related to subjective thermal perception. Regardless of the ambient T_a, whether on warm or on tropical days, resting park visitors described their level of momentary thermal perception as 'comfortable' or 'very comfortable' (Table 7.1) because they had made their own choice to visit the park investigated on this warm summer day, and found their zones of preferred thermal comfort in the park. Chapter 3 revealed a significant relationship between ambient T_a and resting park visitors' solar exposure preferences. Resting park visitors preferred sun-exposed places when ambient T_a was lower than 26 °C, and tree-shaded places when ambient T_a was higher than 26 °C. The design of a park, in particular the distribution of tree canopy cover inside the park, thus determines park visitors' momentary thermal perception (by providing choices for resting locations). Designs that strategically distribute trees, for example, by allocating trees in small groups, rows or scattered boscages around open sun-exposed areas create broad varieties of microclimates. Results in Chapter 3 suggest optimal proportions of 40% shade, 40% sun and 20% half-shade for park design.

Together with the above-mentioned spatially explicit variables of climate-responsive UGI, physical adaptation was found to be crucial for climate-responsive design in general. All studies that investigated subjective thermal perception (Chapters 2, 3 and 4) showed that people are consciously or unconsciously aware of thermal conditions in their urban surroundings and can therefore choose a space with specific microclimate conditions in which to sojourn/recreate (city), rest (park) or walk (street). In particular, the results in Chapters 3 and 4 demonstrate that if people's momentary thermal perception is uncomfortable, they physically adapt by carrying out changes to the thermal circumstances they are exposed to (Nikolopoulou, 2011, Nikolopoulou et al., 2001, Thorsson et al., 2004). For instance, people move to the shaded side of a street if they feel uncomfortable because of high radiation on the sun-exposed side (Chapter 4). Similarly, in a park (Chapter 3), resting park visitors move their towel or blanket a few metres further if sitting in the shade of a tree makes them feel too cool on an early summer day. By contrast, they move to the shade, open umbrellas or even install sun canvasses when they cannot bear the sun any more on a hot summer day. A tipping point of 26 °C related to the ambient T_a was found for resting park visitors to move to either sun or shade (as described in the paragraph before).

This physical adaptation has implications for the design of climate-responsive UGI. Since people are aware of varying thermal conditions, in particular, solar exposure, and their subjective thermal preferences, they can choose places they feel are thermally comfortable to recreate, sit or walk at a specific moment. Therefore, urban outdoor spaces should provide a variety of microclimates, namely sun-exposed, half-shaded and sheltered places that enable people to physically adapt to varying diurnal and seasonal thermal conditions, and varying individual needs. Instead of urban green everywhere, climate-responsive UGI should be designed in a 'clever' way, to strategically provide a diversity of solar exposure conditions.

7.2.3 Development of evidence-based and useful design guidelines for climate-responsive UGI

This thesis set out to use the scientific evidence generated from empirical research in the field to develop design guidelines that are considered useful in design practice. After having completed a Research for Design study (Chapters 2, 3, 4) followed by a participatory RTD study (Chapter 6), this thesis provides nine evidence-based and useful design guidelines for climate-responsive UGI (see Figure 7.2 and description in Section 7.2.4). In this section I will elaborate on the process of knowledge generation to develop those guidelines.

In the beginning of my thesis (Section 1.6) I described the challenges for developing evidence-based and useful guidelines in a broader context. I presented a conceptual model that illustrates this context (Figure 1.3). It includes knowledge ranging from site-specific knowledge in a particular real life context to generally applicable knowledge needed to inform design guidelines (y-axis), and it includes scientific microclimate knowledge on one side and the practical design knowledge on the other side (x-axis). The challenges are (1) to develop spatially explicit, generally applicable evidence, i.e., guidelines, based on site-specific knowledge, (2) to ensure the usefulness of this scientific knowledge in design practice, and finally (3) to implement the evidence-based and useful guidelines, i.e., generally applicable knowledge, in site-specific real life contexts.

Having finalized this research enabled me to enrich the conceptual model through sequentially describing the steps taken to deal with the challenges mentioned above and develop the design guidelines for climate-responsive UGI. The three steps of knowledge generation taken in this research are (I.) observation and monitoring, (II.) generalisation, and (III.) transforming and refining. Related to the two phases of this research, (I.) observation and monitoring and (II.) generalisation are part of the Research for Design studies (Chapters 2, 3 and 4), whereas the (III.) transforming and refining was done in the participatory RTD study (Chapter 6). The fourth step of the framework, (IV.) specification and implementation, was not part of the thesis but is considered to support the employment of the guidelines in design practice. The methodological model in Figure 7.1 exemplarily represents findings of the field study at street scale (Chapter 4), that informed one of the street level guidelines in the participatory RTD study (Chapter 6). In the following I elaborate on the four steps of knowledge generation.

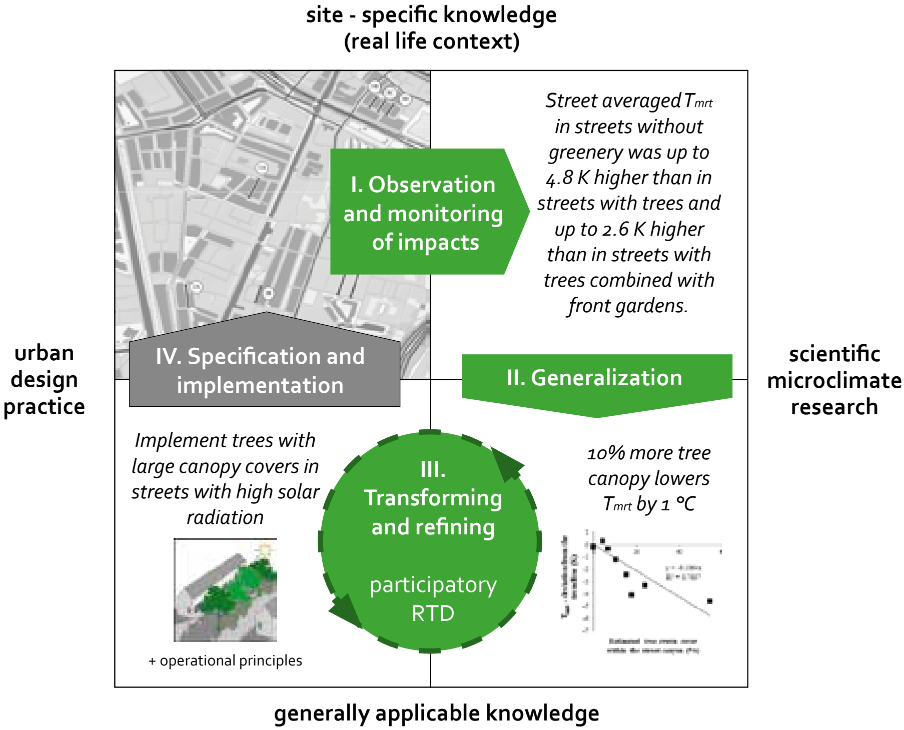


Figure 7.1: Methodological model, exemplarily illustrating the development of street level design guidelines for climate-responsive UGI (steps I. to III. are part of this thesis; step IV. is not part of this thesis)

The first step includes (I.) observing and monitoring UGI impacts in real life urban spaces. Empirical data that describe the impacts and thermo-spatial characteristics of UGI on thermal comfort were gathered by mixed methods. Since the urban microclimate is characterised by high spatial variability (e.g., Oke, 1989, Erell, 2008) and determined by built and green features, this phase involved cautious selection of samples. Since the focus is on impacts of UGI, in this thesis samples were needed that include independent variables related to the green features in the urban environment means and exclude independent variables related to the built features. The latter encompass UGI spaces and elements at the respective scale levels. Multiple samples were to increase the reliability of relationships found in individual, site-specific samples and to advance the broader generalisation of individual instances. In the case at street level, illustrated in Figure 7.1, the samples are nine streets with similar spatial characteristics of the built surrounding and varying amounts and types of street greenery, namely streets without greenery, streets with street trees and streets with street trees and front gardens. Micrometeorological results showed the T_{mrt} values in the three types of streets: '*Street averaged T_{mrt} in streets without greenery was up to 4.8 K higher than in streets with trees and up to 2.6 K higher than in streets with trees combined with front gardens*' (Chapter 4). The first step delivers empirical evidence, being situational knowledge of multiple individual samples.

The second step, (II.) generalisation, is the process of transforming situational knowledge into generally applicable knowledge. This step responds to the challenge of high variability in urban microclimates: significant relationships between variables found coherently in multiple samples underpin generalizable results. Data analysis thus focusses on significant relationships between UGI (independent variable) and objective thermal conditions or subjective thermal perception (both dependent variables) that are consistently found in various cases. In the example illustrated in Figure 7.1 this means that, micrometeorological measurements in nine site-specific street canyons prompt general results, such as '*10% more tree canopy cover lowers T_{mrt} by 1 °C*' (Chapter 4). This evidence describes a general impact of tree canopies (independent variable) on objective thermal conditions (dependent variable), which is valid and thus applicable in streets with the same built features as the streets under investigation. The second step delivers descriptive empirical evidence, which is generally applicable knowledge.

The third step, (III.) transforming and refining, links knowledge from scientific microclimate research with knowledge from urban design practice. In this study I applied a participatory RTD approach to transform scientific knowledge and test it on its usefulness in practical design settings (Chapter 6). A first transitional step appeared crucial in order to improve the comprehensibility of the scientific knowledge in design practice. It was necessary because participants of the design settings had severe difficulties understanding the descriptive nature of the scientific knowledge and its direct links to the design process. This transitional step therefore included the following aspects: transform the descriptive information into prescriptive information, i.e., shift the emphasis from the scientific understanding of '*how things are'* towards new possible solutions of '*how things can be*'. Link the scientific information to the spatial and functional context of urban design, replace scientific terminology, and provide visual information. In the example provided above, namely '*10% more tree canopy cover lovers* T_{mrt} *by 1 °C*' (Chapter 4), the translated guideline would be '*Implement trees with large canopy covers in streets with high solar radiation*' (Chapter 6). This prescriptive guideline provides an imperative or advice that encompasses possible design actions ('*implement trees with large canopy covers*') in a general spatial and functional context ('*in streets with high solar radiation*'). It is illustrated by an icon and reference image. This transitional step turns scientific microclimate knowledge into knowledge relevant for urban design practice.

To further enhance the usefulness of the design guidelines, the participatory RTD approach included a testing of the (preliminary) design guidelines by future end-users in practical design settings (Chapter 6). Professional landscape architects and landscape architecture students were asked to implement the general preliminary guidelines in site-specific design proposals comparable to design assignments in the real life context. Insights into the application of the guidelines in the design process and the design proposals as well as feedback from participants subsequently directed the refinement of the preliminary into revised guidelines. As such evidence-based knowledge was merged with practical design knowledge through using the activity of designing in the research process of knowledge generation. Since the testing of the preliminary guideline '*Implement trees with large canopy covers in streets with high solar radiation*' showed that it is considered comprehensible and easy to use, no refinement was needed. It was accompanied with visual information as icons and the reference image to respond to the participants demand for visual information. This third step of transforming and testing delivered design guidelines; that is, evidence-based knowledge, which is generally applicable and tested on its usefulness for design practitioners.

The fourth step, which explicitly is not part of this thesis, involves the (IV.) specification and implementation of the provided evidence-based design guidelines in urban design practice in the real life context. Landscape architects or urban designers can use the guidelines provided and propose site-specific climate-responsive design solutions in real life. However, through the testing of the preliminary design guidelines in a participatory RTD approach, that 'imitated' real life design assignments (III. transforming and refining, Chapter 6), insights into the implementation phase were gained ahead of it.

This phase includes specification, namely combining the generally applicable knowledge (design guidelines) to situational knowledge of the specific site under investigation. What the practical design settings (Chapter 6) already showed, is that a proper functional, spatial and microclimate (shadow, wind) analysis are needed to gain site-specific situational knowledge of the existing thermo-spatial conditions. Then the design guidelines provide possible, generally applicable solutions on how these thermo-spatial conditions can be improved. In the case described above, landscape architects could, for instance, use the guideline to improve thermal comfort in all streets of the neighbourhood under investigation. The provided operational principles then can guide the implementation of this generally applicable knowledge in site-specific situations: How should the trees be distributed? Where is sun or shade desired? Do trees create adverse effects, such as limiting daylight in buildings, or reducing the air quality on streets with heavy traffic? The additionally provided operational principles help answer those questions and support decisions on design (location, vegetation species, planting circumstances) and maintenance (irrigation, for example).

Once the design proposals are complete, climate-responsive UGI can be incorporated in real life urban development or retrofit projects: trees are planted, grass is sown. This implementation in urban environments delivers real life urban spaces with site-specific thermally comfortable conditions.

7.2.4 Climate-responsive UGI – not everywhere, but '*clever and cool*'

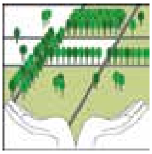
This section synthesises the findings above to answer the main research question and presents the revised design guidelines for climate-responsive UGI.

Scientific findings that form the starting point for the design guidelines demonstrate the general positive impacts of UGI on the urban microclimate and on people's thermal perception: '*green is cool*' and '*green is perceived to be cool*'. This implies that, to mitigate urban heat stress effectively, ample UGI spaces and elements should be incorporated in urban environments. Yet, this amplifying of UGI elements and spaces needs to be implemented in a '*clever*', namely, an effective and resourceful way. It is not clever and purposeful to plant trees and create shade everywhere. Similarly, there is no one-size-fits-all-solution. Besides providing a list of spatially explicit characteristics that can guide climate-responsive UGI design, this thesis emphasises the importance of creating diverse microclimate conditions, particularly in terms of solar exposure. The findings demonstrate that people physically adapt to thermal conditions and choose locations to recreate (city), rest (park) or walk (street) that fit their momentary individual thermal preferences. To satisfy various individual needs simultaneously and under changing diurnal and seasonal thermal conditions, urban outdoor environments should provide adequate sunny, shaded and half-shaded places. Therefore, designing climate-responsive UGI requires considering solar radiation and other thermo-spatial and functional characteristics of the respective urban environment. Besides solar radiation also wind circulation requires attention. This includes, for instance, keeping wind corridors open at city scale, or avoiding the 'tunnel effect' of tree crowns that hinders wind circulation in streets.

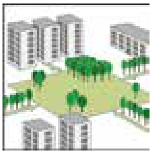
To further guide the process of giving form to '*clever and cool*' climate-responsive UGI, this thesis developed evidence-based design guidelines at the scale levels of city, park and street (Figure 7.2). The guidelines encompass generally applicable, prescriptive knowledge, which is connected to spatial and functional information relevant for

Figure 7.2: Revised design guidelines for climate-responsive UGI at city, park and street level

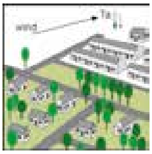
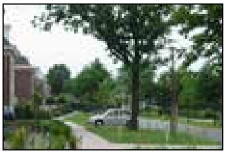
CITY 1.1 Maintain and improve a network of interconnected green spaces in cities, including all types of urban vegetation (green elements and green spaces in private and public realm).




CITY 2.1 Guarantee the presence and/or accessibility of public green spaces in neighbourhoods without or with minimal private outdoor spaces.

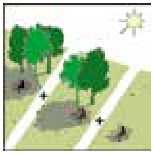



CITY 3.1 Increase the green fraction in cities (including private and public green elements and green spaces) on the windward side of the prevailing summer wind direction and keep cold air corridors open.

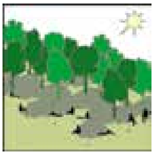
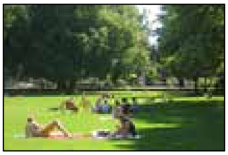
Operational principles:
Check operational principles on park and street level for site designing

PARK 4.1 Create diversity of microclimates (sun, half shade, shade) through diverse tree plantings (e.g. open lawn, single/solitary tree, group of trees or boscage) and combine them with park furniture, i.e. sitting elements.



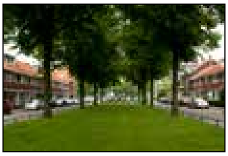

PARK 5.1 Create flexible and multi-functional spaces in parks to facilitate individual thermal adaptation.


PARK 6.1 Create gradients/borders of open areas and shading elements where sun and shade are provided in close vicinity and alternation.

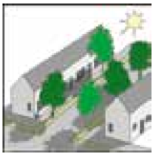



Operational principles:
- Shadow needed the most during periods with highest radiation (12:00 - 16:00)
- Use species resistant against heat, drought, cold and salt (for icy roads)
- Appropriate planting circumstances and effective maintenance (incl. sufficient space for the root system, high quality ground, sufficient irrigation during summertime)

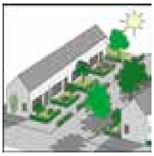
STREET 7.1 Implement trees with large canopy covers in streets with high solar radiation.

STREET 8.1 Create diversities of microclimates (sun/shade) in street canyons to enhance people's choice in which places they would like to walk.




STREET 9.1 Implement green elements in street canyons at various heights (including public and private spaces) to improve thermal perception of pedestrians.




Operational principles:
- Effective implementation of street trees (instead of trees everywhere) depending on specific site characteristics (Height to Width ratio, orientation towards the sun)
- Shadow needed the most during periods with highest radiation (12:00 - 16:00)
- Deciduous trees are preferred (shade during summer/ radiation during winter)
- In streets with heavy traffic: avoid disturbing traffic flows for safety reasons and avoid 'tunnel effect' by creating space for wind circulation between the tree canopies
- Use species resistant against heat, drought, cold and salt (for icy roads)
- Appropriate planting circumstances and effective maintenance (incl. sufficient space for the root system, high quality ground, sufficient irrigation during summertime)

design. To enhance their explicitness, these guidelines were visualized by icons and reference images. They were also accompanied by operational principles for implementation in design practice. Together with the operational principles provided and a basic understanding of microclimate processes, these nine design guidelines can support resourceful and efficient design of climate-responsive UGI. Instead of ubiquity of UGI, following the adage '*the more green, the better (adapted to urban heat issues)*', this thesis argues for urban green that is '*clever and cool*': climate-responsive UGI that is designed resourcefully and is efficiently based on site-specific microclimate analysis and that considers spatial conditions as well as the behavioural demands of urban dwellers.

Testing (a preliminary version of) the guidelines in practical design settings showed that architecture professionals and students appreciated the guidelines. They understood the preliminary guidelines and were able to apply them in various urban design contexts for different scales (city, park, street), urban surroundings (business, recreational, or residential environments) and urban contexts (new developments or retrofit). Furthermore, the design proposals revealed creative, multifunctional solutions that coped adequately with the urban microclimate challenges.

7.3 Discussion

In the previous section I answered the research questions; in this section I discuss the findings of this thesis in light of the academic debate. The discussion is structured on three topics, the type, the usefulness and the development process of knowledge presented in this thesis, that emerge from the answers provided to the three research sub-questions (RSQs 1 to 3). The topics discussed in this section transect the findings of the research sub-questions as illustrated in Figure 7.3. The first topic, the type of scientific evidence, encloses the evidence of UGI impacts on the subjective and objective thermal reality and the spatially explicit evidence, that together form the foundation of the evidence-based design guidelines (7.3.1). The second aspect, the usefulness of scientific evidence, covers the discussion on enhancing the comprehensibility, applicability and feasibility of scientific knowledge in design practice (7.3.2). The final aspect, the development process, discusses the

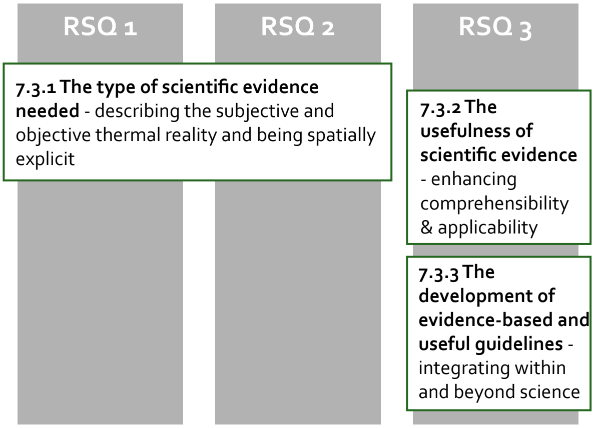


Figure 7.3: Topics discussed in relation to the research sub-questions 1 to 3 (RSQ)

importance of integrating within science (micrometeorology and landscape architectural design) and beyond science (science and practice) to develop evidence-based and useful design guidelines for climate-responsive UGI (7.3.3).

7.3.1 The type of scientific evidence needed

To inform evidence-based design of climate-responsive UGI (Brown and Corry, 2011, Brown and Gillespie, 2017), scientific evidence is needed that describes UGI impacts on the objective and subjective thermal reality. Both realities need to be included to gather a comprehensive understanding of outdoor thermal comfort (Chen and Ng, 2012, Nikolopoulou and Steemers, 2003) and to inform landscape architectural design. The latter needs to respond to both dimensions: to people's surroundings, that is, the physical environment and to people's subjective perception of this environment (Deming and Swaffield, 2011, Van den Brink et al., 2017, ECLAS, 2017, Evert et al., 2010). Therefore, this thesis gathered evidence both on objective thermal conditions and on individual, subjective thermal perception of the urban environment. Furthermore, evidence needs to be spatially explicit in order to be relevant for design (Fryd et al., 2011, Mathey et al., 2011). In the following I discuss the findings related to those aspects in the light of the academic debate.

The evidence regarding UGI impacts on objective thermal conditions is in line with earlier studies in moderate climates outside the Netherlands (e.g., Armson et al., 2013, Bowler et al., 2010). The extensive data source of this thesis offers novel quantitative evidence that describes the heat-mitigating effects of UGI in the temperate climate of the Netherlands. Effects are shown for the parameters air temperature (T_a) and mean radiant temperature (T_{mrt}) in Chapters 2 and 4. At city scale, the parks investigated proved to be 0.8 K cooler on average than the city centre on warm summer days. This is in line with the cooling effect of 0.9 K for T_a, as described in the meta-analysis of 16 micrometeorological studies by Bowler et al. (2010). With regard to T_{mrt}, parks are on average 1.7 K cooler than the built city centre. Furthermore, there are considerable differences in individual parks (up to 10 K warmer and cooler related to T_{mrt} than the city centre) depending on the spatial set-up, in particular in the solar exposure conditions. At street scale, UGI proved to reduce T_{mrt} significantly, while the reduction in T_a was small. These results are in line with those of studies in Great Britain (Armson et al., 2013) and in the Netherlands (Wang et al., 2015b). T_{mrt} in streets without greenery was up to 4.8 K higher than in streets with street trees and up to 2.6 K higher than in streets with street trees combined with front gardens.

The findings regarding UGI impacts on objective thermal conditions confirm that upwind vegetation cover (Chapter 2) and tree canopy cover (Chapters 2 and 4) are spatially explicit parameters physical. In line with an earlier study (Heusinkveld et al., 2014), the findings of Chapter 2 indicate that the amount of UGI in an upwind urban area significantly influences T_a at city scale. This thesis further confirms that the size (e.g., Lee et al., 2013, Streiling and Matzarakis, 2003) and leaf density (Wang et al., 2015b, Abreu-Harbich et al., 2015) of tree canopy cover directs T_{mrt}, both in parks (Chapter 3) and at street level (Chapter 4). The latter supports the premise that intercepting solar radiation, for example, by tree canopy cover, is the most important parameter influencing thermal comfort conditions in summertime (Brown et al., 2015), in particular in the moderate climates of Central Europe (e.g., Lee et al., 2013, Holst and Mayer, 2011). Unlike other studies, no significant relationship between thermal conditions and park size was found (Bowler et al., 2010).

The evidence regarding subjective thermal perception showed that UGI spaces and elements explain a large portion of the variance of subjective thermal perception in cities. Results obtained both at city and street level indicate that during warm summer periods, people prefer green to non-green environments (Chapters 2 and 4). The insights at city scale (Chapter 2) confirm the perceived thermal benefits and preferences of UGI on warm summer days in the Netherlands, as described for Italy and the UK (Lafortezza et al., 2009). Moreover, Chapter 4 shows that an enhanced ratio of street greenery in the visual field of pedestrians tends to positively affect subjective thermal perception. This supports earlier studies in the Netherlands which suggest that thermal perception is likely to be improved through UGI elements (Lenzholzer and Van der Wulp, 2010) and natural views (Wang et al., 2017). Chapter 2 and 4 indicate that UGI is not only preferred by people related to their aesthetic perception (Smardon, 1988, Ulrich, 1986), but also to their thermal perception.

Related to subjective thermal perception, this thesis also highlights the importance of physical adaptation and the consequent need for diverse microclimates in urban environments (Nikolopoulou et al., 2001, Nikolopoulou and Steemers, 2003). Chapter 4 indicates that residents' thermal preferences for walking on a specific side of the street vary depending on their activity and diurnal and seasonal variations. They are aware of microclimate, in particular solar expose conditions, and change sides, if they feel uncomfortable. Moreover, Chapter 3 demonstrates a significant relationship between T_a and solar exposure responses. Park visitors found their preferred places of thermal perception in sun-exposed places when T_a was lower than 26 °C, and in shady places when T_a was higher than 26 °C. An ambient T_a of 26 °C thus can be considered a tipping point for changes in subjective thermal preferences related to solar exposure in the moderate climate of the Netherlands.

Results confirm that seeking shade under trees is a popular response to extreme summer temperatures in the moderate climate of the Netherlands (Wang et al., 2017), and in other moderate climates (Kántor and Unger, 2010, Katzschner, 2004, Thorsson et al., 2004). Unlike studies in the Mediterranean or Subtropical climates that in particular highlight the need of shading (e.g., Martinelli et al., 2015b, Cohen et al., 2012, Fintikakis et al., 2011, Huang et al., 2015), this thesis supports studies from moderate climates, that call for diverse microclimates, i.e., sunny and shaded spaces (Katzschner, 2004, Thorsson et al., 2004). Findings of Chapter 3 clearly show that solar exposure preference is even more nuanced: parks which provide a range of sunny, half-shaded and shaded places can facilitate various user preferences under normal and extreme thermal summer conditions ($T_{a\ max}$ > 25 °C and > 30 °C, respectively).

Therefore, this thesis recommends to consider solar exposure and create microclimatic variance including sunny, half-shaded and shaded spaces for various times of the day; the ratio of 40% sun, 20% half-shaded and 40% shade can provide direction.

Furthermore, the findings reading UGI impacts on subjective thermal perception may offer a more comprehensive understanding of the term 'naturalness', that was linked to the greening of an area or natural, vegetated views before (Nikolopoulou, 2011, Nikolopoulou and Steemers, 2003). Linked to psychological aspects regarding subjective thermal perception, naturalness original was defined as 'the degree of artificiality' by Griffiths (1987). Later it was described as the level of 'greenness' of an urban environment (Nikolopoulou and Steemers, 2003). However, little has been written about 'naturalness', and what it can imply for climate-responsive urban design. The findings of this thesis indicate that UGI spaces (large green spaces, forests, parks, gardens) and elements (street trees, and green front gardens) enhance people's thermal perception during summertime in urban environments. Subjective thermal perception is enhanced by the following spatially explicit parameters: the presence of UGI spaces and elements on various urban scales (see also Lafortezza et al., 2009), the conscious distribution of tree canopies to create diverse solar exposure conditions, and the enhanced ratio of vegetation in the visual field of pedestrians (see also Lenzholzer and Van der Wulp, 2010, Wang et al., 2017). Sharpening the term 'naturalness' by adding spatially explicit parameters of UGI can increase its relevance for climate-responsive design and contribute to the scientific knowledge base.

7.3.2 The usefulness of scientific evidence

Besides addressing the objective and subjective reality and being spatially explicit, scientific microclimate knowledge needs to be useful for design practitioners in order to warrant its implementation in urban design practice. Usefulness of knowledge, and in particular, of design guidelines, in this thesis was conceptualised as the composition of comprehensibility for designers, applicability in design processes, and feasibility in design practice (Klemm et al., 2017a). This consistent set of criteria was developed from earlier studies that indicated obstacles between scientific microclimate evidence and the needs of design practitioners (e.g., Brown and Corry, 2011, De Schiller and Evans, 1990, Eliasson, 2000, Lenzholzer, 2010a, Norton et al., 2015, Pijpers-van Esch, 2015). This set of criteria was employed in testing the preliminary design guidelines in the practical design settings in Chapter 6. The following discussion outlines the findings and experience of developing 'useful' guidelines, particularly regarding comprehensibility and applicability of knowledge.

To guarantee the comprehensibility of scientific microclimate knowledge for design practitioners, a 'transitional step' proved crucial in the development of guidelines. During the practical design settings, it appeared that the participants had severe difficulty in understanding the scientific microclimate evidence and its direct links to the design assignments. Similar difficulties of practitioners in understanding the descriptive nature of microclimate evidence was described earlier (De Schiller and Evans, 1990, Eliasson, 2000). It was mentioned before that a 'transitional' or 'pre-processing' step (Lenzholzer, 2010a, p.120) can improve the comprehensibility and usefulness of scientific knowledge for design practice, yet it was unclear how this pre-processing should take place. Transitional steps that transfer (Nassauer and Opdam, 2008) or translate (Lenzholzer, 2010a) specialist knowledge are needed in order to make the knowledge ready for application in practice. In particular, if design guidelines are founded upon fundamental knowledge gathered through other disciplines than landscape architectural and urban designers. Chapter 6 depicts the following 'transitional' step, which proved valuable in the practical design setting to improve the comprehensibility of microclimate knowledge for practitioners. It encompasses transforming the descriptive knowledge into prescriptive, normative knowledge; it changes the focus from 'how things are' into 'how things can be'. This step also replaces scientific microclimate terminology and adds explanatory spatial and functional information, as argued by Fryd et al. (2011), Lenzholzer (2010a), Norton et al. (2015) as well as a visual representation, as argued by De Schiller and Evans (1996), Eliasson (2000), Pijpers-van Esch (2015). The latter can include icons and reference images.

Furthermore, Chapter 6 showed that simply providing evidence-based design guidelines does not guarantee their proper application in design processes. The practical design settings showed that additional microclimate knowledge on how to apply the design guidelines in site-specific situations is necessary to ensure proper implementation. Referring to general design guidelines, Prominski (2017, p.207) aptly writes: “Design is always specific and guidelines can only support it. In practice, they [the guidelines] have to be adapted to the specific situation of the site”. He also acknowledges the need for additional knowledge and skills in landscape architects, which are required to adapt the general guidelines to specific sites. This also applies in the case of climate-responsive UGI design. Here, an understanding of site-specific microclimate situations is a basic necessity for proper climate-responsive design (e.g., Brown, 2011, Eliasson, 2000). Such proper designs depend on an appropriate microclimate analysis of the situation, including shadow and wind patterns (Lenzholzer and Brown, 2012). In order to conduct such site- and scale-specific analysis, design practitioners need a basic understanding of microclimate processes, for example of solar exposure and wind circulation in urban environments, and the skills to conduct such analysis. Such microclimate analyses uncover thermo-spatial conditions of existing urban environments, for example, exaggerated sunny or shaded sites, that call for climate-responsive design investigations. Because site-specific micrometeorological conditions are so important complementary to the provided generally applicable design guidelines, microclimate analysis should become a standard part of the collection of situational information and data that inform the design process. In the landscape architecture context, this phase is referred to as Research for Design (Van den Brink and Bruns, 2012), Research before Design (Milburn and Brown, 2003) or Plan Analysis (Nijhuis and Bobbink, 2012).

Additionally, operational principles are provided to further support and ensure proper application of the general guidelines to site-specific conditions (Figure 7.2, right column). These principles can guide decisions on design (vegetation species and planting circumstances) and on maintenance (irrigation, for example) in the specific circumstances and at the respective scale levels. Thereby the design guidelines and accompanying operational principles not only provide general design solutions, but also support the process of specification and implementation, being the fourth step in the methodological model to develop design guidelines (Figure 7.1). In this aspect, the guidelines of this thesis differ from other tools that provide overviews of possible design interventions (e.g., Kennisportal Ruimtelijke Adaptatie, 2017, Kleerekoper, 2016, Lenzholzer, 2015). The tools mentioned list and explain generally applicable green design interventions textually and graphically, for example 'Plant trees in city lanes or streets'. But these tools provide limited guidance about how the tools should be applied in specific sites, that is, 'how to plant the trees in a clever way'. This thesis, however, provides design guidelines, together with operational principles that support site-specific application, as suggested by Prominski (2017). More than solely providing generic transferable knowledge (design guidelines) to solve complex problems like urban climate change adaptation guidelines, it offers guidance how this general knowledge can be combined with situational (specific/embodied) knowledge, which is essential in landscape architecture (Brown and Corry, 2011, Bruns et al., 2017, Nassauer, 2012, Nassauer and Opdam, 2008, Nijhuis and Bobbink, 2012).

Concluding, the applicability of the guidelines is enhanced if site-specific microclimate functioning is investigated, and if this situational knowledge together with the operational principles are used to direct the application of the general design guidelines to specific sites. In this way, landscape architects and other urban designers can bringing about '*clever and cool*' site-specific design solutions with optimal shape, structure and distribution of climate-responsive UGI.

7.3.3 The development process of evidence-based and useful design guidelines

In order to generate evidence-based guidelines that are considered useful by design practitioners, the knowledge gap between microclimate science and urban design practice (e.g., Eliasson, 2000, Lenzholzer, 2010a) needs to be narrowed or bridged. To do so, scholars have repeatedly called for collaborative, transdisciplinary approaches by scientists and practitioners (Fryd et al., 2011, Nassauer and Opdam, 2008, James et al., 2009), and for designing as being a part of innovative knowledge generation (Nassauer and Opdam, 2008, Lenzholzer et al., 2017, Lenzholzer et al., 2013). Yet, in the field of climate change adaptation, particularly related to heat mitigation, such integrative processes between scientists and stakeholders are limited and remain at the academic margins (Groot et al., 2015).

In this research I took a pragmatic perspective (Creswell, 2014) that enabled me to bring together different types of knowledge to develop evidence-based and useful design guidelines for climate-responsive UGI. The guidelines are founded upon fundamental scientific knowledge from the disciplines of micrometeorology and landscape architecture as is the practical knowledge from landscape architectural professionals. Using the terminology of van Kerkhoff (2005), this section discusses the importance of *integrating within science* and *integrating beyond science* to develop evidence-based and useful design guidelines. *Integrating within science* relates to the combination of micrometeorology and landscape architecture knowledge in the phases of (I.) observing and monitoring of impacts, and (II.) generalisation, whereas *integrating beyond science* relates to the combination of scientific and practical knowledge in landscape architecture and related disciplines in the phase of (III.) transforming and refining, and (IV.) specification and implementation (Figure 7.4).

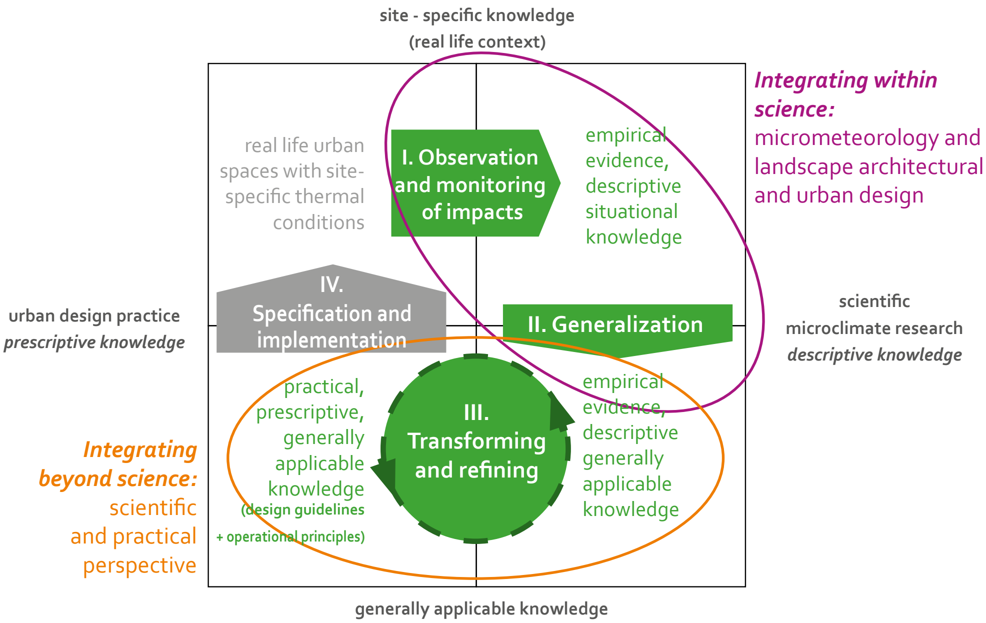


Figure 7.4: Generating evidence-based and useful design guidelines though integrating within and beyond science

Integrating within science

The Research for Design phase complementarily focussed on two realities: the objective, physical reality of the urban environment, and the subjective reality of people's experience. Therefore, it was crucial to combine methods from different disciplines, such as landscape architecture, micrometeorology and social geography in the field studies. The objective reality was studied through quantitative methods from the field of micrometeorology (Heusinkveld et al., 2010), while the subjective reality was studied through methods that origin from the fields of social sciences and environmental psychology (e.g., Eliasson et al., 2007, Thorsson et al., 2004). The latter are used torepresent people's multisensory experience of and behaviour in urban environments. Besides applying mixed methods, I collaborated closely with micrometeorologists in this phase to set up and conduct the field work, and to collect and analyse the data. This collaboration and the mixed methods approach made possible the combination of post-positivist and the social-constructivist research perspectives (Creswell, 2014) to gather a comprehensive understanding of UGI related to thermal comfort. Such an integration across disciplines, methods, models and data is referred to as *integrating within science* (Groot et al., 2015, Van Kerkhoff, 2005).

Looking back at this first phase of the research, including (I.) observing and monitoring of impacts and (II.) generalisation (Figure 7.3), I recognise the importance of integrative approaches, in particular between the disciplines of micrometeorology and landscape architectural and urban design. The common aim, as Nikoloupoulou (2011, p.1552) appropriately describes, is "to improve the fit between organism and the immediate environment". To enhance climate-responsive design in real life, both is needed, an understanding of '*how things are*' related to atmospheric processes in and around cities, and an understanding of '*how things can be*' addressing urban heat and thermal discomfort through landscape design. To reach the common aim of thermally comfortable living environments I agree with other scholars that argue for collaborations between micrometeorologists and landscape architects (Brown, 2011, Eliasson, 2000, Lenzholzer et al., 2013, Nikolopoulou, 2011).

Moreover, I endorse collaborations that start from the very beginning of the (I.) observing and monitoring phase. This includes the set-up of study designs, including the definition of variables and the selection of cases, in order to ensure the relevance of the evidence to be found for design. Knowledge from both disciplines also is needed for the 'transitional step' of the (III.) transforming and refining phase to appropriately translate scientific descriptive knowledge into practical prescriptive knowledge, while including spatial and functional information relevant for design. Other scholars divide tasks and link the generation of scientific evidence suitable for design to a single discipline (Nassauer and Opdam, 2008, Bruns et al., 2017). The climatologist Eliasson (2000, p.42), for example, encourages climatologists to

“Develop tools and courses suitable for urban planners”, whereas landscape architects, e.g., Lenzholzer et al., (2013, p.121) state that Research for Design “can also be conducted by other disciplines than landscape architecture [...] the knowledge is then translated by the designer to substantiate the design...”. The latter may work in the case of a Research for Design study that substantiates a specific design proposal. However, in the context of this thesis, where a Research for Design study substantiates the development of evidence-based design guidelines, this does not seem realistic. Here fundamental microclimate knowledge lacks comprehensibility for landscape architecture design practitioners, as evidenced in Chapter 6, and by other scholars (De Schiller and Evans, 1990, Pijpers-van Esch, 2015). In opposition to Nassauer and Opdam (2008), Eliassion (2000) and Lenzholzer (2013), I therefore argue for interdisciplinary approaches from the very beginning of studies that develop fundamental knowledge to create evidence-based design guidelines. Such *integrating within science* is essential in the context of microclimatic design to investigate microclimate phenomena in urban environments and guarantee the relevance of novel evidence for urban design.

Integrating beyond science

In the participatory Research through Designing approach with landscape architectural design practitioners, the preliminary guidelines were tested and revised into evidence-based and useful design guidelines. A general testing phase of novel knowledge is well acknowledged in the discipline of landscape architecture (Prominski, 2017, Lenzholzer et al., 2013, Nijhuis and Bobbink, 2012, Nassauer and Opdam, 2008). For example, in the field of microclimatic design, simulation models are used to test efficiency, thus objective impacts on thermal conditions, in post-positive Research through Design approaches (Lenzholzer and Brown, 2016). Yet, in scientific literature, studies that focus on the criterion of usefulness for end-users are limited.

In the (III.) transforming and refining phase of this research (Figure 7.4), the expertise and experience of practising landscape architects was involved to improve the usefulness of evidence-based design guidelines, as suggested by Nassauer and Opdam (2008). Landscape architects were asked to apply the novel guidelines in site-specific design proposals during practical design settings, simulating real life design assignments. By observing their design processes, analysing their design results and listening to their evaluation of the guidelines, the practitioner's perspective – their expertise and experience – became part of the development process of the guidelines. This iterative testing process, in which acquired knowledge is tested and refined continuously through the activity of designing (Lenzholzer et al., 2013, Nijhuis and Bobbink, 2012), is represented through the circle and arrows in Figure 7.4., it produces insights into the usefulness of the guidelines and allows for refinements before the guidelines are actually presented to outside academia. Here *integrating beyond science*, with practitioners and stakeholders was essential to improve the knowledge in terms of usefulness in practice.

Integrating beyond science in the course of this research also took place independently from the studies described in the previous chapters, in particular Chapter 6. The knowledge developed in this thesis, both design guidelines and operational principles, was continuously advanced from the academic and professional perspective. This was possible through testing of intermediate research results in MSc thesis projects, that I supervised, or specific design projects, in which I contributed. First, as supervisor of multiple MSc thesis projects on climate-responsive designing I was able to test and advance microclimate analysis techniques and intermediate results in site-specific design projects with the help of students (for example, see Tang et al., 2016, Chang and Ji, 2012, Hotkevica, 2012, Lensink, 2015). The intermediate testing of results also included my contributions to the winning design proposal 'One step beyond' in the international design competition Re-Think Athens. Together with landscape architectural and urban design practitioners and microclimate scientists, a design was developed for a thermally comfortable and attractive city centre of Athens (Altinisik et al., 2014). Most of all, the link between science and practice in this thesis was enabled through the transdisciplinary character of the Climate Proof Cities consortium (Albers et al., 2014), that this PhD research project was part of. In this context I contributed to various sessions to present and discuss intermediate results with stakeholders from Dutch municipalities (Utrecht, Arnhem, The Hague). For example, intermediate results were used in design studios with landscape architects, urban planners, urban green maintainers in the specific site Berg-Polder Zuid in the city of Rotterdam (Groot et al., 2015). And, last but not least, *integrating beyond* *science* in this research was possible through my own work expertise and experience, both in practice and academia, that enabled me to link perspectives (Van Kerkhoff, 2006).

Integrating beyond science is essential for climate-responsive design since it requires academic and practical knowledge to generate real life solutions. Through linking scientific knowledge with knowledge acquired in urban design practice (both in the study described in Chapter 6 and in the examples described above), the guidelines for climate-responsive UGI are not only scientifically consistent, but are also tested and applicable in real life contexts.

Concluding the discussion, recommendations made for the three aspects, the type of scientific evidence (7.3.1), the usefulness of scientific evidence (7.3.2), and the development of evidence-based and useful design guidelines (7.7.3) can contribute to bridging the application gap between microclimate science and urban design practice (e.g., Eliasson, 2000, Lenzholzer, 2010a). Knowledge developed in this thesis contributes to extend the scientific knowledge base on design guidelines (Lenzholzer, 2010a, Prominski, 2017) and how to develop them based on fundamental knowledge (Brown and Corry, 2011, Nassauer and Opdam, 2008). In particular, the novel scientific evidence, design guidelines for climate-responsive UGI design and operational principles can advance the scientific knowledge base and design practice related to '*clever and cool*' climate-responsive UGI.

7.4 Methodological reflections

In this thesis I applied a multiphase, mixed methods approach (Creswell and Plano Clark, 2011). In the Research for Design phase, I studied the impacts of UGI on people's subjective perception and on the objective urban environment. In the subsequent participatory Research through Designing phase, I used the evidence gathered before to generate useful design guidelines for climate-responsive UGI.

In the first Research for Design phase (Lenzholzer et al., 2013) I applied mixed methods to comprehensively investigate subjective and objective aspects related to thermal comfort (Chen and Ng, 2012, Nikolopoulou, 2011). I used novel qualitative methods and descriptive research strategies to generate new knowledge on people's thermo-spatial perception.

The methods, such as interviews and unobtrusive observations, originate from the field of social sciences and environmental psychology and were applied in earlier studies (e.g., Eliasson et al., 2007, Lenzholzer and Van der Wulp, 2010, Thorsson et al., 2004). Those studies chiefly investigated thermal perception per se (see also Chapter 5). The empirical studies of this thesis (Chapters 2, 3 and 4) investigated subjective thermal perception related to UGI and examined thermo-spatial evidence of climate-responsive UGI. Likewise to other studies that investigated thermal perception, the scale and context (city, park, street), and the time scales of perception (momentary and long-term thermal perception), and the kinetic state (here stationary) are important dimensions for qualitative methods (Chapter 5).

The qualitative methods applied do, however, still have some limitations. In the study at street scale (Chapter 4) the number of participants was limited since there were only few passers-by in the living environments under investigation. Also, the studies that investigated people's momentary thermal perception related to UGI (Chapters 3 and 4) were conducted independently of investigating physiological effects of UGI on the energy balance of the human body (metabolic rate, actual sensation vote). Unlike quantitative studies with more experimental settings including micrometeorological measurements of human physiological responses, the qualitative methods applied in this research were conducted in real (natural) urban sites with randomly approached pedestrians. This approach may create less biased, more natural, and socially desirable answers regarding subjective thermal perception.

The studies that investigated objective thermal conditions clearly focused on warm summer days, in particular, on daytime conditions. The use of mobile measurement devices (Heusinkveld et al., 2010) enabled the gathering of continuous, accurate and GIS-based datasets of various urban sites with UGI. As a result, I was able to compare objective thermal conditions in 13 parks, the city centre, the rural grassland outside the city (Chapter 2) and in nine streets (Chapter 4). All mobile measurements were conducted in the city of Utrecht in July and August 2012. Only one city was chosen because of the high demand in human resources and preparation time to guarantee the mobile measurements. The number of observation days for the investigations in (natural) urban sites was limited on account of the actual weather conditions. In the study at park scale (Chapter 3), I used ambient thermal conditions measured in nearby weather stations as references, since on-site measuring devices and human resources were unavailable.

In Chapter 6, I developed evidence-based and useful design guidelines by applying and testing a novel participatory Research through Designing approach (Lenzholzer et al., 2013). As such, this thesis made a major attempt to describe step-by-step the development process of design guidelines that are founded on fundamental knowledge. In addition, it contributed to the conceptualisation of design guidelines by setting up criteria related to usefulness in design practice. However, this explorative study has some limitations: the number of participants was limited, and findings regarding the design processes might be biased due to the experimenter effect with students of our own department. Even though the sample size of participants is not representative of the large population active in landscape architectural design practice, this explorative study has determined and deliberately described a participatory RTD approach. This approach, earlier described by Lenzholzer et al. (2013, 2017), indeed appeared valuable to merge scientific microclimate and practical design knowledge through the active employment of designing in the process of knowledge generation. Through involving future-end users, being landscape architecture professionals and students, in the testing and development phase of the guidelines in practical design settings, the usefulness of the guidelines in real life design practice is confirmed. The participatory RTD approach, determined in the present study, may be repeated and advanced for the development of evidence-based and useful design guidelines.

7.5 Future research

The evidence on objective thermal impacts of UGI provided in this thesis contributes to the knowledge base on heat-mitigating effects of UGI during daytime found in other studies in the moderate climates. It also approves and advances spatially explicit characteristics of UGI, for example green fraction, size and leaf density of tree canopy cover. Future research should investigate diurnal and seasonal impacts of UGI on thermal conditions to more comprehensively consider positive and adverse effects of UGI. Negative effects may include a general decrease in wind circulation, and consequently, the limitation of heat loss of hard surfaces and facades through radiation at night time. For example, it would be interesting to know at the scale of a street canyon, how the size and leaf density of tree canopies lower thermal comfort parameters during the day compared to the night. Also, longitudinal studies investigating UGI impacts on thermal conditions could create a better understanding of impacts in all-year-round: which type or combination of vegetation can create shade in summertime to mitigate heat and also block cold winter winds to create thermally comfortable spaces in all seasons? Such insights are needed to guide even more '*clever and cool*' climate-responsive UGI design decisions. They allow for better balancing between day- and night-, and summer- and wintertime effects and choosing the appropriate UGI design according to the functions of the adjacent environment.

This research shed light on the positive psychological and behavioural impacts of UGI on subjective thermal perception. It demonstrated strong relationships between UGI and long-term thermal perception at city scale (Chapter 2) and marginally significant relationships between street greenery and momentary thermal perception (Chapter 4). Future research is needed to further unravel the impact of different types of UGI at park or street scale on momentary thermal perception as well as on aesthetic appreciation. Here attention should be paid to all three-dimensional spatial characteristics of UGI, so that more different types of UGI spaces and elements can be included. Besides street trees and green front gardens, such elements may encompass green facades, pergolas, other constructions for climbing vegetation, or flower boxes, that are valuable in urban environments with limited spaces available. Such empirical evidence would not only be very valuable to further enhance the scientific knowledge base related to subjective thermal perception and the conceptualisation of 'naturalness' (Griffiths et al., 1987, Nikolopoulou and Steemers, 2003), but also for the climate-responsive design practice.

Based the scientific evidence, I developed evidence-based and useful design guidelines for climate-responsive UGI in the context of the moderate climate of the Netherlands. To do so I applied an exploratory study testing the participatory Research through Designing approach (Lenzholzer et al., 2013). In this study the approach appeared valuable. Yet further testing and advancing this participatory RTD approach with larger numbers of (professional) participants and more exhaustive datasets is needed to enhance the reliability and robustness of results.

Besides the approach on how to develop the guidelines, also the design guidelines themselves should be the focus of further research. It is yet unclear how the provided design guidelines are received in the real life design practice, and how effective they are in terms of urban heat mitigation. It would be valuable to know which factors in the course of the design and implementation process support or hamper the application of the design guidelines in order to advance climate-responsive design practice. Also, post-implementation monitoring should investigate the real effect on urban heat mitigation, once the guidelines are implemented in real urban sites. Studies that longitudinal monitor design interventions in urban spaces and compare pre- and post-implementation conditions at the site are valuable. Such monitoring closes the learning gap, as illustrated in Figure 7.3, and provides continuous feedback to further improve the scientific knowledge base and subsequently, the urban design practice (Ahern, 2013, Chen and Ng, 2012). Closing the learning gap between scientific microclimate knowledge and landscape architectural and urban design practice enables systematic and conscious evidence-based climate-responsive landscape architecture (Brown and Corry, 2011, Brown and Gillespie, 2017).

7.6 Relevance for society and professional practice

The motivation for me, a professional landscape architect, to start this research was to learn about the actual 'cooling' impacts of UGI and to provide guidance for climate-responsive UGI design. Through this research I became acquainted with urban micrometeorology and learned about the various impacts of UGI on thermal comfort: besides the objective 'cooling' impacts, there are subjective impacts on people's thermal perception and behavioural response. I was able to provide evidence that demonstrates that '*green is perceived to be cool*' and also evidence that underpins the general belief that '*green is cool*'. This latter belief is ubiquitous nowadays. I am delighted to see more awareness and a sense of urgency for urban adaptation strategies at all policy levels and in the wider society than was evident a couple of years ago. Municipalities are starting to include climate adaptation strategies for storm water management and urban heat mitigation in their policymaking. The city of Amsterdam, for example, set out to combine rainwater and green design to make the city climate-proof (City of Amsterdam, 2015), and the Rotterdam Climate Initiative (2017) pleads for 'Greenification' to enhance urban resilience. A question that is still current is, what are effective heat-related adaptation strategies for the design of climate-responsive outdoor spaces?

The evidence of microclimate UGI impacts and the design guidelines for climate-responsive UGI generated in this research, can contribute an answer to that question. The quantitative measures of UGI impacts, both on objective thermal conditions and on subjective thermal perception, and the guidelines at city scale are valuable for those involved in generating heat mitigation strategies for cities. For instance, they can inform local spatial legislation plans, like the spatial development strategy ('structuurvisie') or the zoning plan ('bestemmingsplan'). The design guidelines and respective operational principles at park and street scale, in particular, are valuable for those involved in site-specific design, like landscape architectural and urban designers. They can be included into and update municipalities' manuals for public spaces ('Handboek openbare ruimte') in terms of climate-responsive UGI design. In the longer term, Dutch local governments could include the knowledge developed in this thesis in drawing up the new Environment and Planning Act ('Omgevingswet'). This legislation, which is expected to come into force in 2021, obliges municipalities to develop integral environmental visions and plans that describe the quality of the physical environment at various scale levels. I see an opportunity for the subject of climate-responsive UGI to be reflected in these visions and plans. The knowledge developed in this thesis, additionally may be of interest for public and private parties involved in the realisation and maintenance of climate-responsive UGI, like tree nurseries, garden and landscaping firms.

Indicating the relevance for society, the knowledge developed in this research has been the focus of a number of publications for the wider public in the course of the research (e.g., Van Limpt, 2014, Klemm and Bruinenberg, 2014, Maandag, 2014). For instance, the design guidelines were recently presented at a website that disseminated scientific results to a wider audience (Klemm, 2018), and they were published in a German popular scientific journal of landscape architecture (Fahrenhorst, 2018). Also, they will be presented, as part of heat-related adaptation strategies, at the 'heat stress' congress on June 25th 2018, that the Dutch government has initiated to give wide attention to urban heat issues. Publications in newspapers, popular scientific journals or events contribute to disseminate the knowledge developed in this thesis: The first set of guidelines for climate-responsive UGI is ready for application; now it would be encouraging to see public and private actors to implement them.

More than the provision of the evidence, the guidelines and the operational principles, this thesis raises the general questions about which type of knowledge should inform climate-responsive designs in practice. When talking about climate-responsive, and in particular, heat-mitigating design proposals, I recognise that the main concern often is: How much cooling does it provide? I understand that precise predictions or targets on aspired future objective thermal conditions, for example a decrease of 1.5 °C related to T_a, are needed in specific situations. This might be the case when policymakers need to substantiate long-term financial and spatial decisions, or in the case of extraordinary design projects or competitions (e.g., Altinisik et al., 2014). The latter may function as role models for climate-responsive design for the wider professional discipline of landscape architecture. Nevertheless, I wonder whether such precise predictions or targets are needed as decision-making tools for each and every specific site-design in order to be 'climate-responsive'.

The urban microclimate is too complex and spatially variable to easily predict *the* 'cooling' impact of proposed UGI interventions. The large spatial variability in urban microclimate figures on UGI impacts are not simply transferrable to any other urban site. Every urban location is specific in terms of spatial, functional, and thus microclimatic, characteristics. Specialist and resource-demanding micrometeorological observation methods and/or simulation models, e.g., EnviMet, are needed to predict site-specific impacts of possible design interventions. However, landscape architectural and urban designers often are not familiar with such methods or models.

Rather than using precise targets as decision-making tools for heat-mitigating design proposals, I recommend using thermo-spatial knowledge to design thermally comfortable outdoor places. In this thesis I emphasise that the microclimate impacts of UGI go beyond the objective impacts and improve subjective thermal perception and behaviour. This thermo-spatial knowledge describes the interrelationship between people's subjective thermal perception and behavioural response *and* the environment's objective thermal conditions. Such knowledge should inform climate-responsive UGI design.

Concerning the relevance for professional practice, this thesis revealed that understanding and analysing microclimatic processes is a critical skill for efficient and resourceful climate-responsive UGI designing. Those processes, for example, include solar exposure as well as people's physical adaptation in urban environments. Analysis of such processes should become a standard in the general analysis phase of design projects. In special cases, like the role model projects described earlier, such analysis could be outsourced to experts in the field of microclimate simulations. For the greater part, landscape architects should be able to use their accustomed tools and programmes, like SketchUp, AutoCAD or GIS, to conduct shadow pattern analysis themselves. Additionally, they may observe user patterns in the respective sites to understand the sites' thermo-spatial and functional characteristics. Subsequently they can efficiently apply general design guidelines, as provided in this thesis, to generate '*clever and cool*' climate-responsive UGI design proposals. My recommendation is to systematically include integrated courses of urban micrometeorology and climate-responsive design into academic and practice-oriented education in landscape architecture and related disciplines. Other courses should address professionals in this field. Such courses provide a basic microclimate knowledge base and available design guidelines, and furthermore train skills to conduct microclimate analysis and apply design guidelines.

Last but not least: enhancing the adaptive capacity of the outdoor environments in existing cities needs long-term and multifunctional strategies. Urban climate change adaptation is not a stand-alone reason for rebuilding urban areas. Instead, urban climate change adaptation strategies should be incorporated in urban developments that need to be realised anyhow. Those may include regular replacement of underground infrastructure in streets, regular maintenance of parks or urban squares, or any new or retrofit urban development. A long-term urban climate adaptation plan or vision, possibly integrated in the new legislation as mentioned above, can provide a spatial and temporal overview of such windows-of-opportunity in cities.

At the same time, urban climate change adaptation is just one of the environmental challenges confronting cities nowadays. Others include the quality of air, soil and water, or the provision of space for recreation, biodiversity and food production. Due to the limited space available in cities, the multi-functionality of UGI is a key to guarantee healthy and liveable environments (e.g., Demuzere et al., 2014). This means that UGI should be designed in a way that is climate-responsive and provides other benefits, e.g., environmental, visual or social benefits.

To reach this goal in a resourceful and cost-efficient way, strong collaboration is needed: between scientists from different disciplines; between scientists and public and private actors, between those involved in the design, implementation or maintenance of UGI. Moreover, inhabitants of cities want to be involved in design and decision-making processes in the urban environment in which they live, work and recreate. Such participatory processes gain more and more in importance in the Dutch context, partly due to the new legislation. The result of such collaborative processes are cities with a high quality of urban environment and, as a consequence, cities with a high quality of life.

To conclude, based on the findings of this thesis I recommend that those working on the quality of urban environments keep an eye on the positive impacts of UGI on the urban microclimate, both on thermal conditions and inhabitants' thermal perception. Be aware of windows-of-opportunity and take chances to enhance '*clever and cool*' climate-responsive UGI to create more thermally comfortable and liveable cities right now and in the future.

"The best time to plant a tree is twenty years ago.
The second-best time is now."
(Chinese proverb)

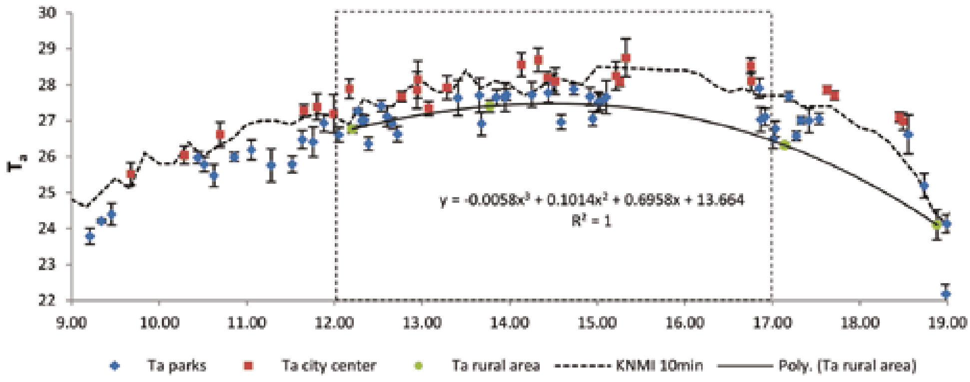
Appendices

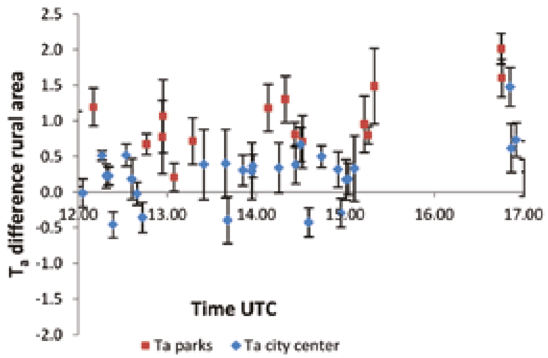
Appendix A

Construct Item	Cronbach's α	Item-total correlation
Evaluation thermal comfort effect of green environment	.81	
Nice		.62
Important		.75
Essential		.60
Convenient		.64
Experienced thermal comfort green environment	.67	
Garden		.34
Wood		.47
Park		.46
Rural area		.53
Experienced thermal comfort built environment	.74	
Shopping street		.59
Square		.59
Parking lot		.47
Terrace		.46
Experienced thermal comfort water environment	.72	
Swimming pool		.54
Beach		.50
Lake		.55
Canal		.48

Appendix A: Reliability analyses of interview results (559 questionnaires in the Dutch cities of Arnhem, Rotterdam and Utrecht, 2011/2012)

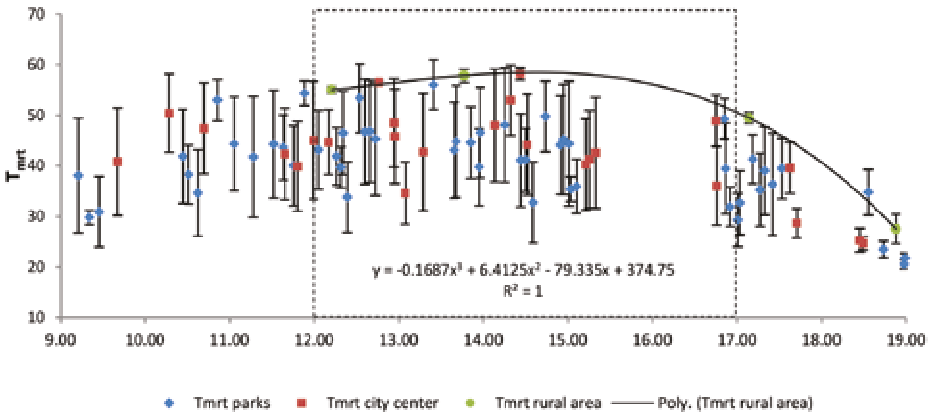
Appendix B

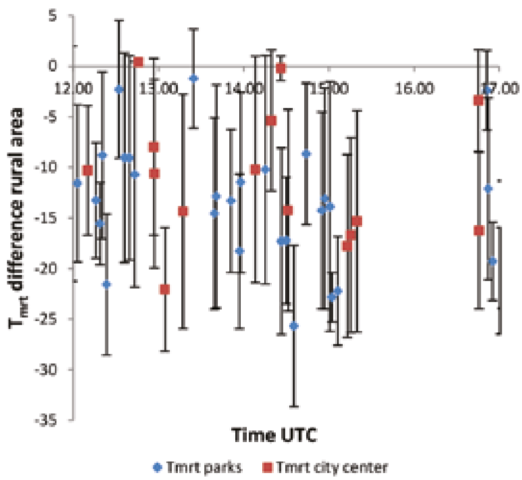




Appendix B: Air temperature (T_a) in 13 parks, city centre and open grassland outside the city on July 24th 2012 in Utrecht, the Netherlands. Top panel: Actual measurements and fit function based on measurements in the open grassland outside the city in relation to T_a of the KNMI weather station in De Bilt. Dashed lines illustrate the period of 12:00-17:00 UTC in which thermal performances were compared. Lower panel: Temperature deviation in relation to the open grassland outside the city.

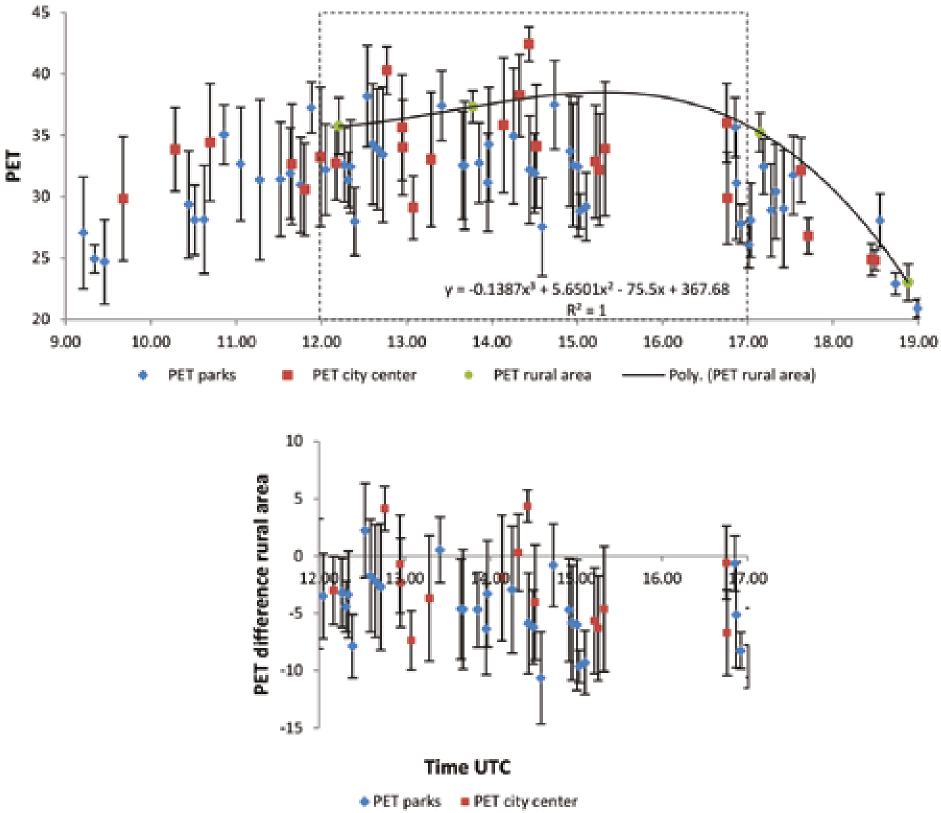
Appendix C





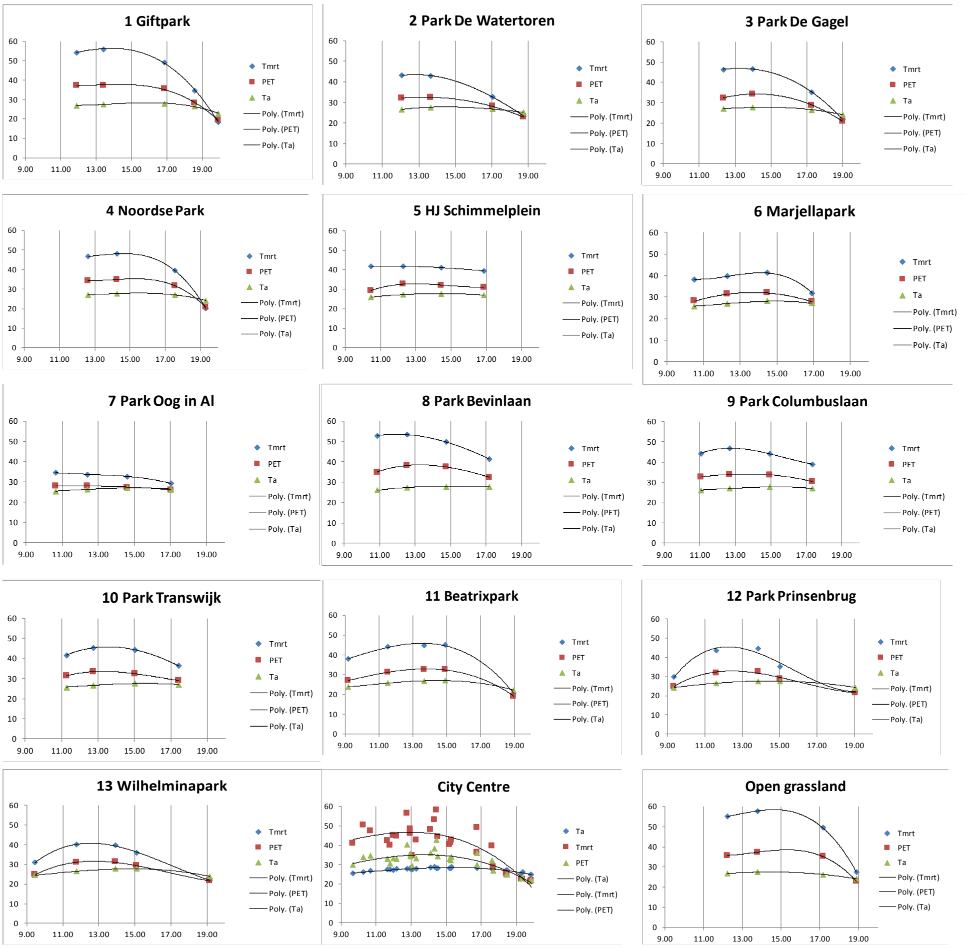
Appendix C: Mean radiant temperature (T_{mrt}) in 13 parks, city centre and open grassland outside the city on July 24th 2012 in Utrecht, the Netherlands. Top panel: Actual measurements and fit function based on measurements in the open grassland outside the city in relation to T_a of the KNMI weather station in De Bilt. Dashed lines illustrate the period of 12:00-17:00 UTC in which thermal performances were compared. Lower panel: Temperature deviation in relation to the open grassland outside the city.

Appendix D



Appendix D: Physiological Equivalent Temperature (PET) in 13 parks, city centre and open grassland outside the city on July 24th 2012 in Utrecht, the Netherlands. Top panel: Actual measurements and fit function based on measurements in the open grassland outside the city in relation to T_a of the KNMI weather station in De Bilt. Dashed lines illustrate the period of 12:00-17:00 UTC in which thermal performances were compared. Lower panel: Temperature deviation in relation to the open grassland outside the city.

Appendix E



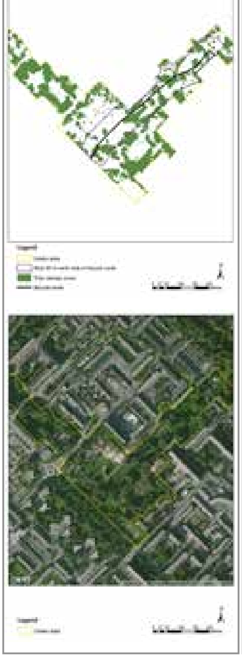
Appendix E: Daily temperature cycles of T_a, T_{mrt} and PET for each of the 13 investigated parks, the city centre and the open grassland outside the city based on third order polynomial fit function of all measurement points between 9:00-19:00 UTC, on July 24^{th} 2012 in Utrecht, the Netherlands.

Appendix F

1 Griftpark

2 Park de Watertoren

3 Park de Gagel



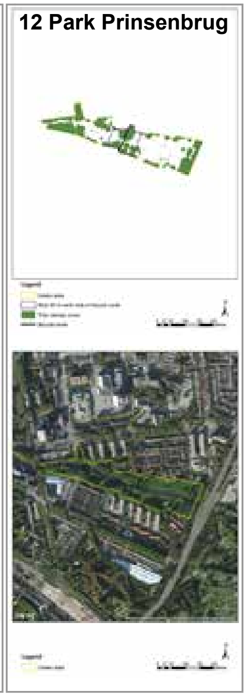
4 Noordse Park

5 HJ Schimmelplein

6 Marjellapark

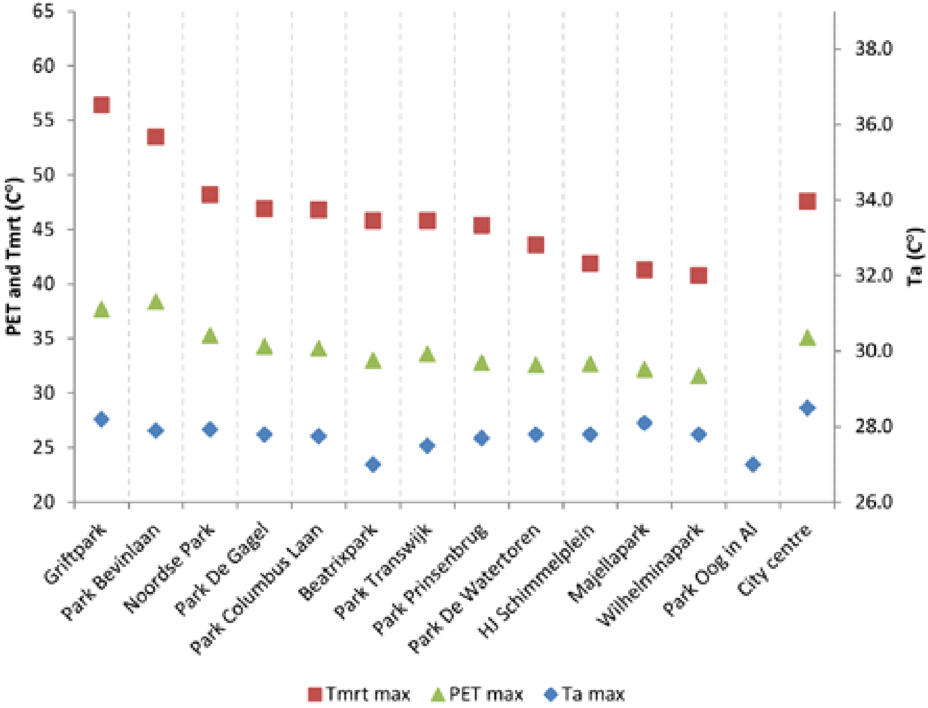
7 Park Oog in Al

8 Park Bevinlaan



Appendix F: Analysis of spatial variables of 13 investigated parks in Utrecht, the Netherlands.

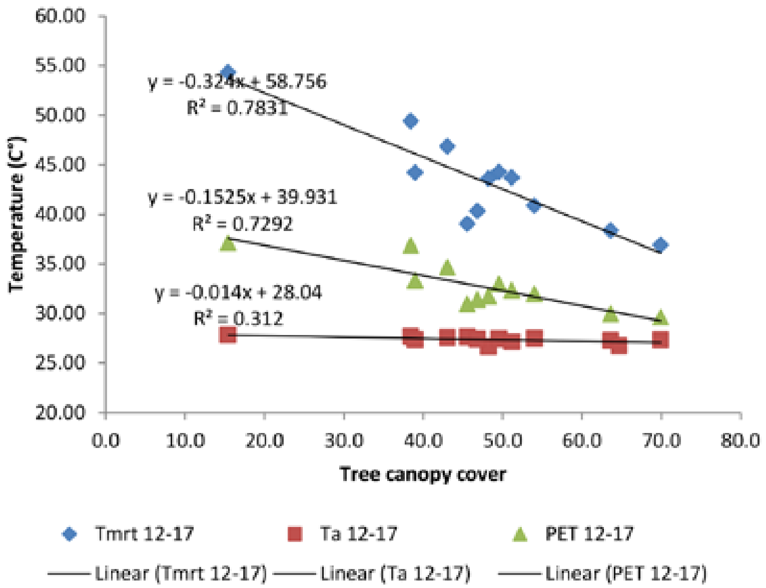
Appendix G



Appendix G: Maximum T_a, T_{mrt} and PET values of 13 parks and the city centre compared to the open grassland outside the city based on third order polynomial fit functions of all measurement points between 9:00-19:00 UTC, on July 24th 2012 in Utrecht, the Netherlands.

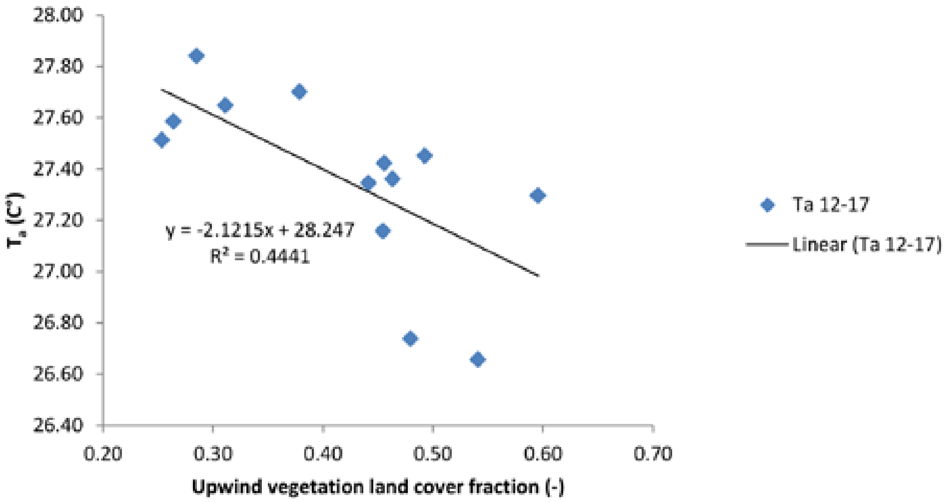
A

Appendix H



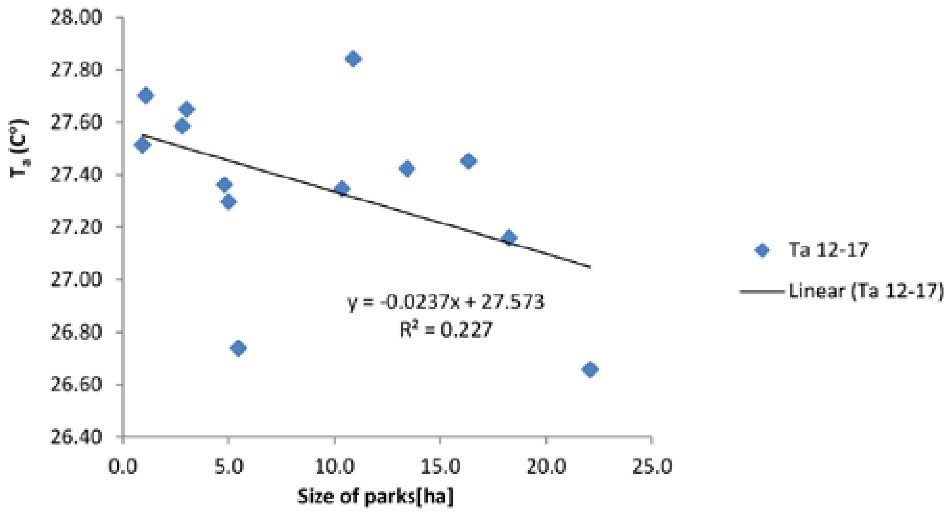
Appendix H: Averages air temperature (T_a), mean radiant temperature (T_{mrt}) and physiological equivalent temperature (PET) as a function of tree canopy cover in 13 investigated parks on July 24th 2012 (12:00-17:00 UTC), in Utrecht, the Netherlands.

Appendix I



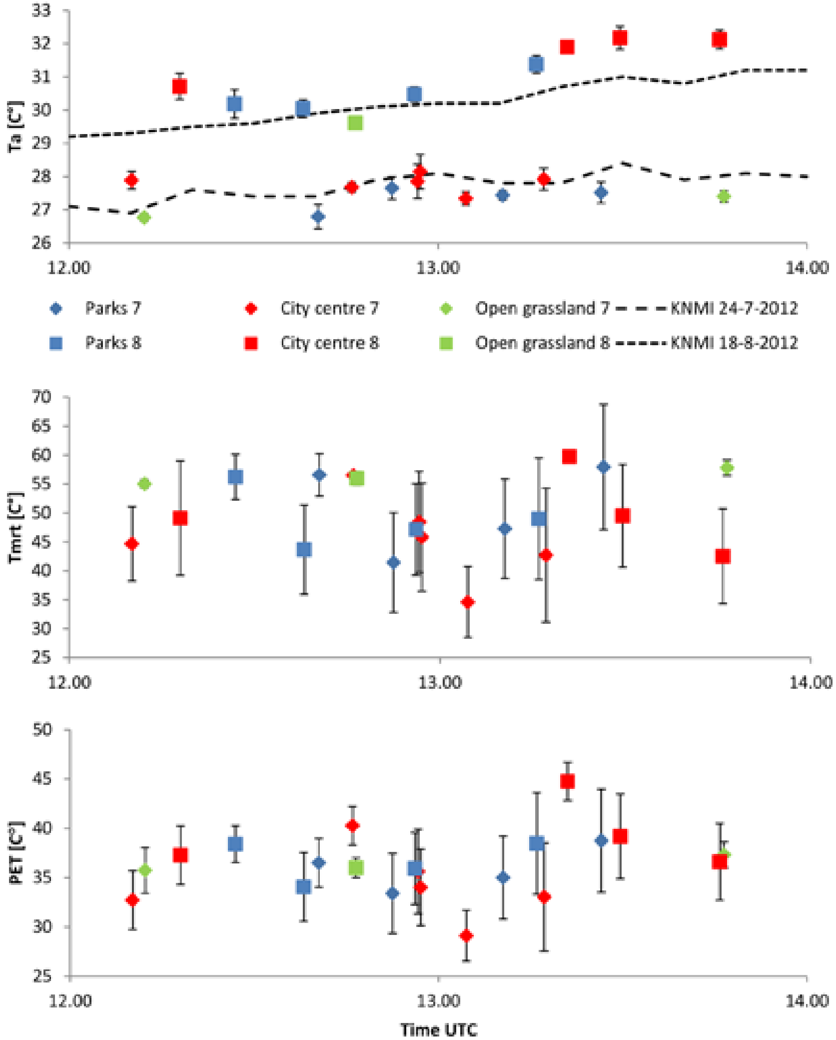
Appendix I: Average air temperature (T_a) of 13 investigated parks as a function of upwind vegetation land cover fraction measured on July 24th 2012 (9:00-18:00 UTC), in Utrecht, the Netherlands.

Appendix J



Appendix J: Averages air temperature (T_a) as a function of size [ha] in 13 investigated parks on July 24th 2012 (12:00-17:00 UTC), in Utrecht, the Netherlands.

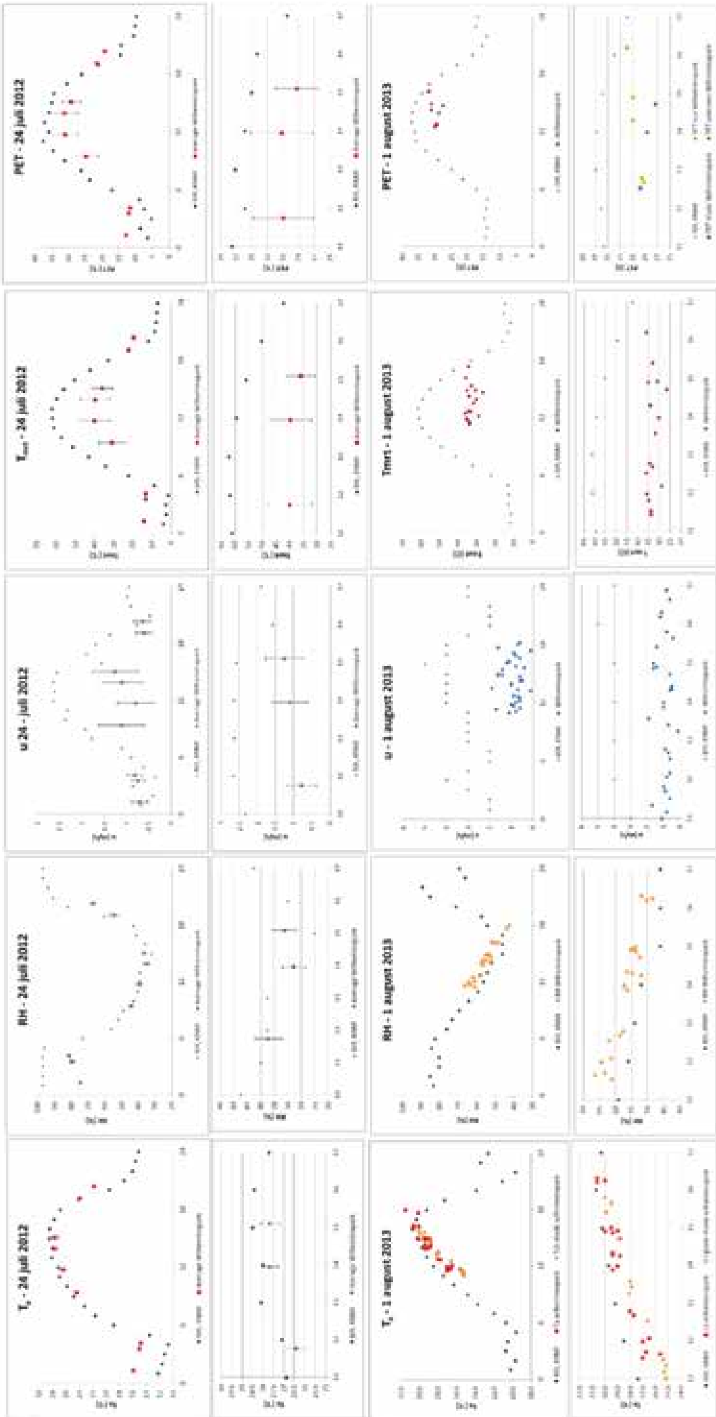
Appendix K



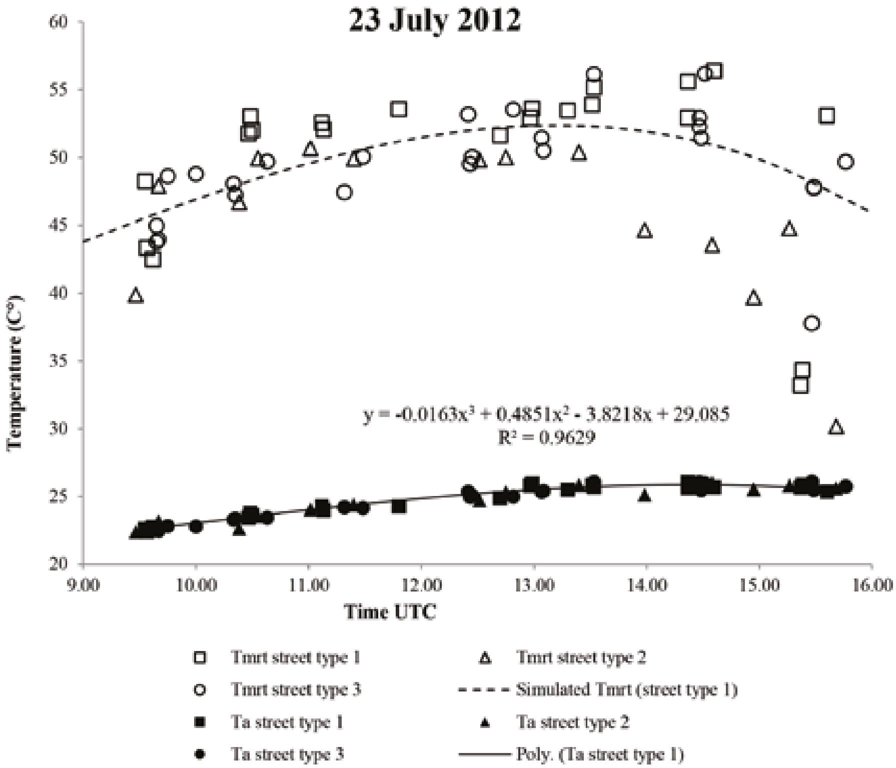
Appendix K: Air temperature (T_a), mean radiant temperature (T_{mrt}) and physiological equivalent temperature (PET) in parks, city centre and open grassland outside the city on July 24th 2012 and August 18th 2012 (12:00-14:00 UTC) in Utrecht, the Netherlands. (Top panel: T_a in relation to T_a of the KNMI rural weather station, Mid panel: T_{mrt}, Lower panel: PET)

Appendix L

Appendix L: Comparison of datasets from the rural station The Bilt with measurements in the Wilhelminapark, Utrecht, the Netherlands (July 24th 2012, August 1st and 2nd 2013)



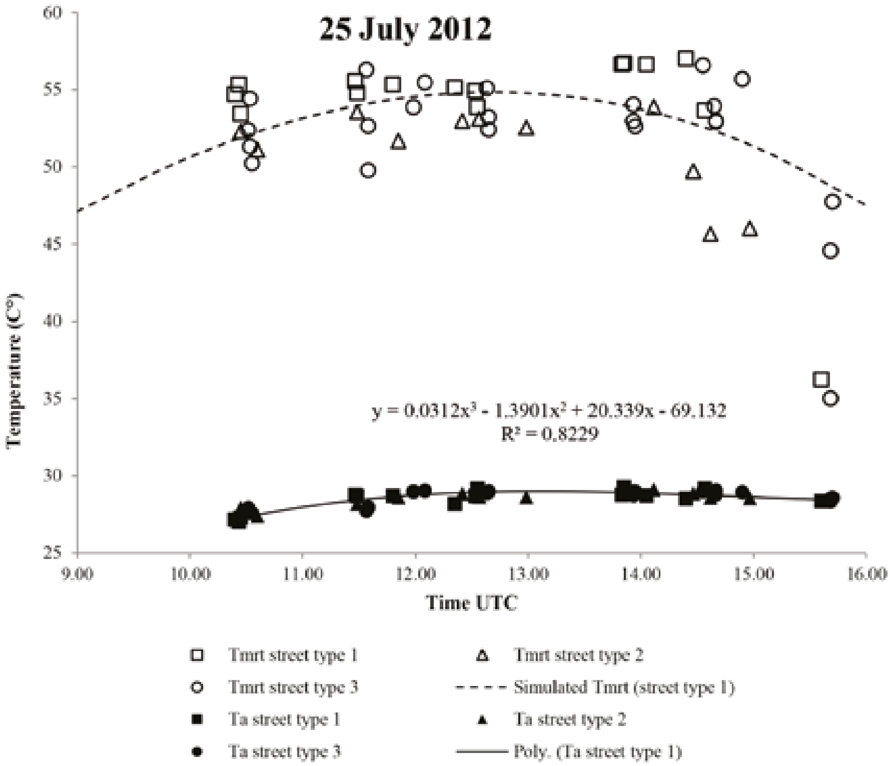
Appendix M



*Tmrt trendline is based the reference street canyon (street type 1) simulated in Rayman (Matzarakis et al., 2007) using the actual daily global radiation data from a nearby weather station (KNMI, 2013).

Appendix M: Air temperature (T_a) and Mean radiant temperature (T_{mrt}) in the three street types: 1. no greenery, 2. street trees, 3. street trees combined with front garden. In Utrecht, the Netherlands on July 23rd 2012 (9:00-16:00 UTC).

Appendix N



*Tmrt trendline is based the reference street canyon (street type 1) simulated in Rayman (Matzarakis et al., 2007) using the actual daily global radiation data from a nearby weather station (KNMI, 2013).

Appendix N: Air temperature (T_a) and Mean radiant temperature (T_{mrt}) in the three street types: 1. no greenery, 2. street trees, 3. street trees combined with front garden. In Utrecht, the Netherlands on July 25th 2012 (9:00-16:00 UTC).

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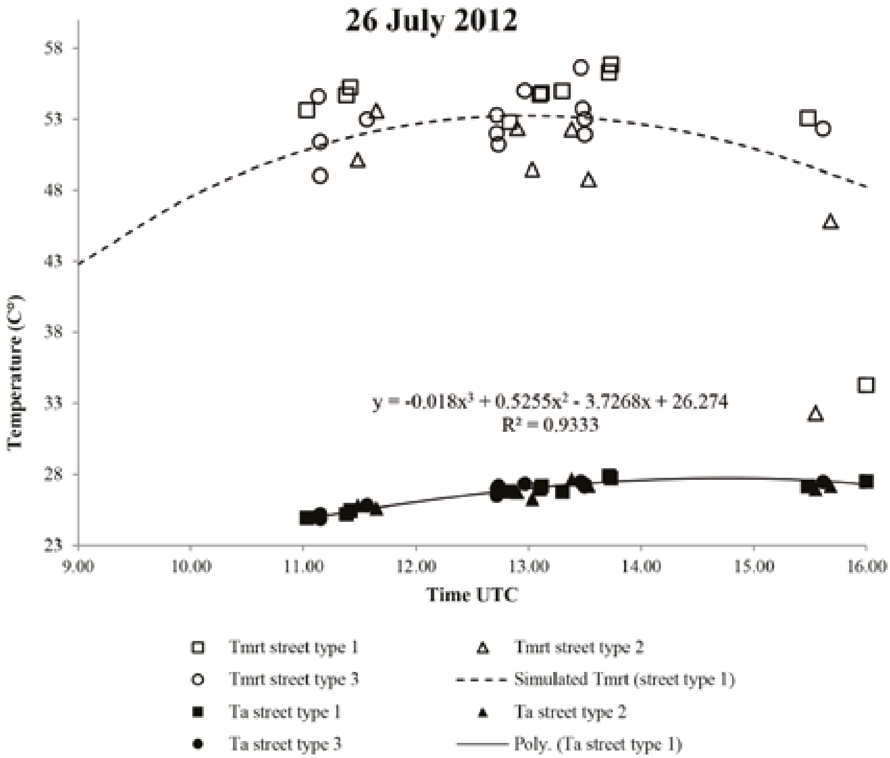
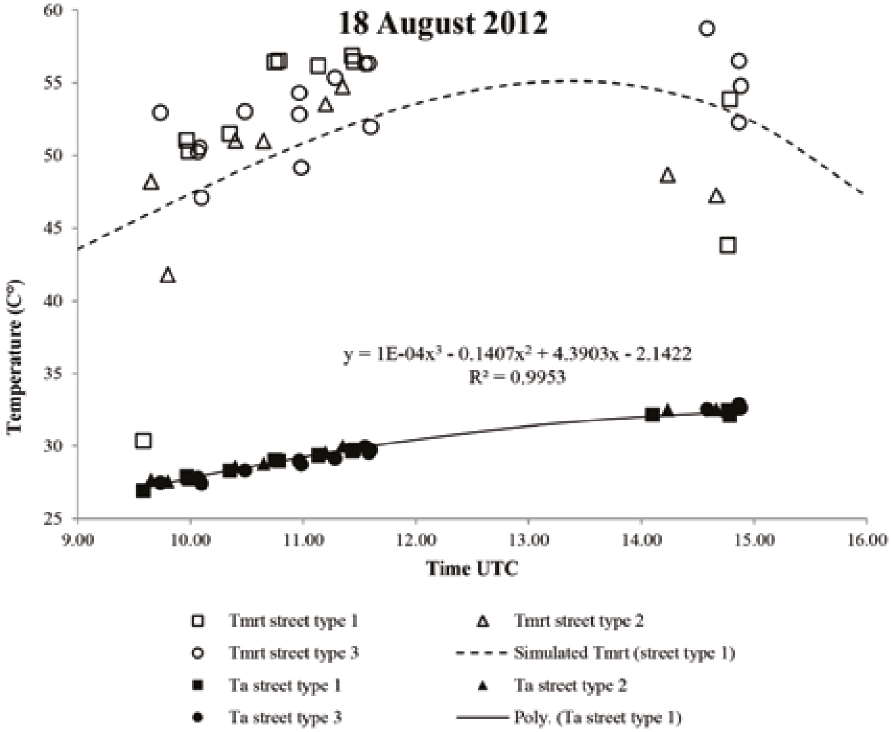
Appendix O



*Tmrt trendline is based the reference street canyon (street type 1) simulated in Rayman (Matzarakis et al., 2007) using the actual daily global radiation data from a nearby weather station (KNMI, 2013).

Appendix O: Air temperature (T_a) and Mean radiant temperature (T_{mrt}) in the three street types: 1. no greenery, 2. street trees, 3. street trees combined with front garden. In Utrecht, the Netherlands on July 26th 2012 (9:00-16:00 UTC).

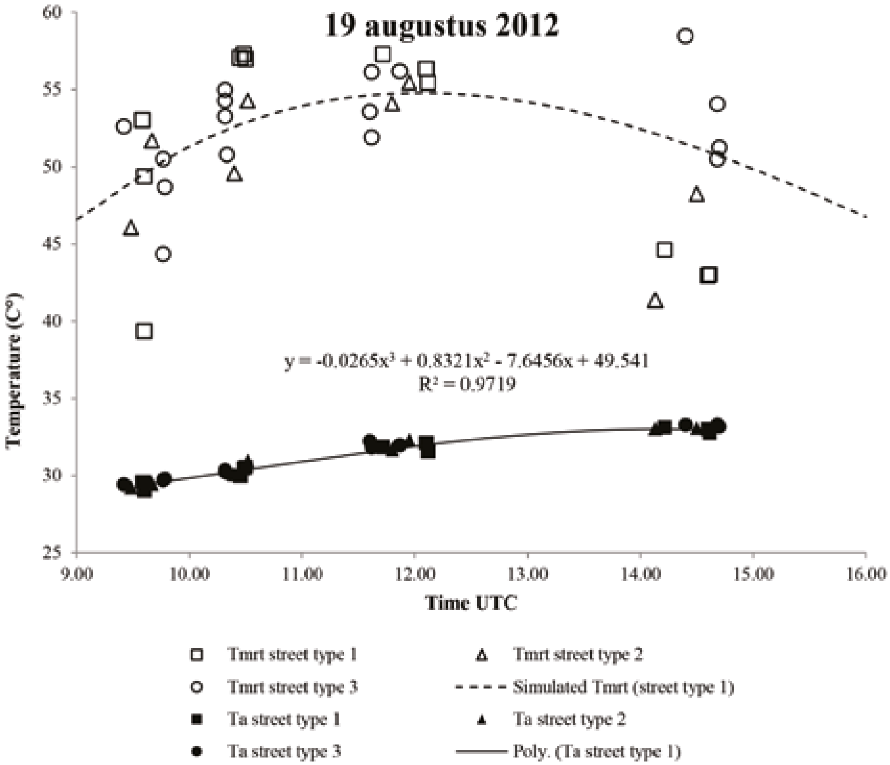
Appendix P



*Tmrt trendline is based the reference street canyon (street type 1) simulated in Rayman (Matzarakis et al., 2007) using the actual daily global radiation data from a nearby weather station (KNMI, 2013).

Appendix P: Air temperature (T_a) and Mean radiant temperature (T_{mrt}) in the three street types: 1. no greenery, 2. street trees, 3. street trees combined with front garden. In Utrecht, the Netherlands on August 18th 2012 (9:00-16:00 UTC).

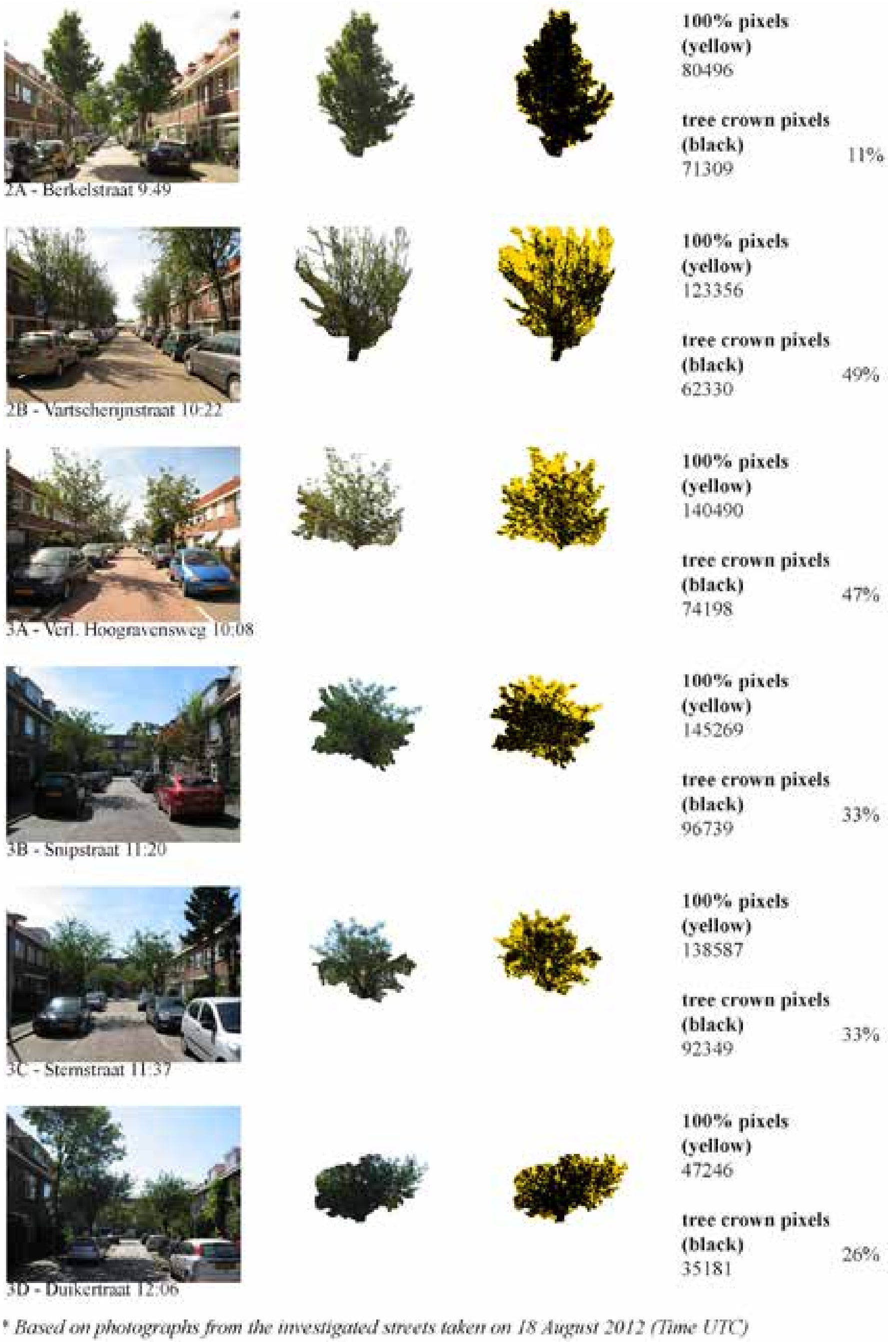
Appendix Q



*Tmrt trendline is based the reference street canyon (street type 1) simulated in Rayman (Matzarakis et al., 2007) using the actual daily global radiation data from a nearby weather station (KNMI, 2013).

Appendix Q: Air temperature (T_a) and Mean radiant temperature (T_{mrt}) in the three street types: 1. no greenery, 2. street trees, 3. street trees combined with front garden. In Utrecht, the Netherlands on August 19th 2012 (9:00-16:00 UTC).

Appendix R



Appendix R: Analysis on the gap fraction of tree crowns.

Appendix S

		CITY						PARK						STREET					
Professionals	Guidelines	**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**		**9**	
(n=5)	Survey statements*	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD
	** statements appear in the same order as in survey*																		
Appreciation	*a) I appreciate the availability of this design guideline.*	**1.00**	0.63	**0.80**	0.40	**1.00**	0.89	**1.40**	0.49	**0.80**	0.40	**1.20**	0.75	**1.40**	0.49	**0.80**	0.40	**0.60**	0.49
Comprehensibility	*b) I understand the meaning and content of this design guideline.*	**1.00**	0.00	**0.80**	0.40	**1.00**	0.63	**1.40**	0.49	**1.00**	0.00	**1.20**	0.75	**1.60**	0.49	**0.80**	0.40	**1.00**	0.00
	c) I understand the aspects of special attention related to this design guideline.	**0.80**	0.98	**0.60**	0.80	**0.80**	0.75	**1.60**	0.49	**0.80**	0.98	**1.40**	0.49	**1.60**	0.49	**1.00**	0.63	**1.20**	0.40
	d) I know when and where to apply this design guideline in order to improve microclimatic conditions.	**0.60**	0.80	**0.60**	0.80	**0.40**	0.80	**1.40**	0.49	**0.80**	0.98	**1.40**	0.49	**1.40**	0.49	**0.80**	0.40	**0.80**	0.40
		0.80	0.59	**0.67**	0.67	**0.73**	0.73	**1.47**	0.49	**0.87**	0.65	**1.33**	0.58	**1.53**	0.49	**0.87**	0.48	**1.00**	0.27
Applicability	*e) This design guideline is easily applicable in design- and planning processes.*	**0.80**	1.17	**-0.20**	0.40	**0.00**	1.10	**1.40**	0.49	**1.20**	0.40	**1.40**	0.49	**-0.20**	0.75	**0.20**	0.40	**0.20**	0.75
	f) This design guideline can flexibly be applied in different spatial conditions.	**1.00**	0.00	**0.40**	0.49	**-0.20**	0.75	**1.20**	0.75	**1.00**	0.00	**1.40**	0.49	**-0.40**	0.49	**0.40**	0.49	**0.80**	0.40
	g) This design guideline can be integrated in on-going urban renewal and construction processes.	**1.00**	0.63	**0.60**	0.80	**0.20**	0.75	**1.20**	0.75	**0.80**	0.40	**1.20**	0.75	**0.00**	0.63	**0.80**	0.40	**0.60**	0.49
		0.93	0.60	**0.27**	0.56	**0.00**	0.87	**1.27**	0.66	**1.00**	0.27	**1.33**	0.58	**-0.20**	0.62	**0.47**	0.43	**0.53**	0.55
Feasibility	*h) The availability of space above and below ground hinders the implementation of this design guideline is.*	**-0.80**	1.17	**-1.20**	0.75	**-0.60**	0.80	**0.60**	0.80	**0.60**	0.80	**-0.20**	0.98	**-1.20**	0.40	**-0.80**	0.40	**0.00**	1.10
	i) The construction and maintenance costs hinder the implementation of this design guideline is.	**-0.40**	0.80	**-0.40**	0.80	**-0.20**	0.75	**0.40**	0.49	**0.20**	0.98	**0.60**	0.80	**-0.80**	0.98	**-0.20**	0.75	**-0.80**	1.17
	j) The ground property situation hinder the implementation of this design guideline is.	**-0.60**	1.02	**-1.00**	0.63	**-0.60**	0.49	**0.60**	0.80	**0.20**	0.98	**0.60**	0.80	**-1.00**	0.89	**-0.60**	0.49	**-0.60**	1.10
		-0.60	1.00	**-0.87**	0.73	**-0.47**	0.68	**0.53**	0.70	0.33	**0.92**	0.33	**0.86**	-1.00	0.76	**-0.53**	0.55	**-0.47**	1.12
										strongly disagree	disagree			neutral		agree		strongly agree	
										-1.5	-1.5	-0.5	-0.5	0	0.5	0.5	1.5	1.5	

Appendix S: Survey results per item per group: professionals

Students	Guidelines	CITY						PARK						STREET					
		1		2		3		4		5		6		7		8		9	
(n=24)	Survey statements*	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
	*statements appear in the same order as in survey																		
Appreciation	a) I appreciate the availability of this design guideline.	**1.04**	0.61	**0.92**	0.64	**1.04**	0.68	**1.29**	0.61	**1.00**	0.76	**1.33**	0.55	**1.25**	0.60	**1.04**	0.61	**1.08**	0.49
Comprehensibility	b) I understand the meaning and content of this design guideline.	**1.13**	0.60	**1.00**	0.58	**1.08**	0.70	**1.46**	0.50	**1.08**	0.76	**1.33**	0.62	**1.21**	0.76	**1.25**	0.72	**1.04**	0.79
	c) I understand the aspects of special attention related to this design guideline.	**0.58**	0.81	**1.04**	0.73	**1.00**	0.71	**1.29**	0.68	**0.83**	0.90	**1.13**	0.60	**1.21**	0.58	**0.92**	0.72	**1.08**	0.81
	d) I know when and where to apply this design guideline in order to improve microclimatic conditions.	**0.54**	0.82	**0.83**	0.55	**0.88**	0.83	**1.33**	0.62	**1.08**	0.76	**1.13**	0.60	**1.13**	0.78	**0.83**	0.80	**0.92**	0.95
		0.75	0.74	**0.96**	0.62	**0.99**	0.75	**1.36**	0.60	**1.00**	0.81	**1.20**	0.61	**1.18**	0.71	**1.00**	0.75	**1.01**	0.85
Applicability	e) This design guideline is easily applicable in design- and planning processes.	**0.83**	0.69	**0.67**	0.80	**0.46**	0.91	**1.17**	0.75	**0.79**	0.91	**1.13**	0.60	**0.88**	1.01	**0.67**	0.75	**0.71**	0.93
	f) This design guideline can flexibly be applied in different spatial conditions.	**0.75**	0.66	**0.67**	0.69	**0.63**	0.81	**1.33**	0.75	**1.17**	0.75	**0.83**	0.75	**0.54**	0.87	**0.71**	0.84	**0.96**	0.79
	g) This design guideline can be integrated in on-going urban renewal and construction processes.	**1.04**	0.68	**0.75**	0.72	**0.71**	0.84	**1.21**	0.71	**0.96**	0.89	**0.83**	0.80	**0.63**	0.86	**0.79**	0.87	**1.04**	0.85
		0.87	0.68	**0.70**	0.74	**0.60**	0.85	**1.24**	0.74	**0.97**	0.85	**0.93**	0.72	**0.68**	0.91	**0.72**	0.82	**0.90**	0.86
Feasibility	h) The availability of space above and below ground hinders the implementation of this design guideline is.	**-0.38**	0.75	**-0.33**	0.75	**-0.38**	0.75	**0.29**	0.98	**0.25**	0.83	**-0.17**	0.99	**-0.92**	0.91	**-0.67**	0.85	**-0.29**	0.93
	i) The construction and maintenance costs hinder the implementation of this design guideline is.	**0.00**	0.82	**-0.21**	0.64	**-0.42**	0.86	**0.08**	0.91	**0.21**	1.00	**0.00**	0.82	**-0.63**	0.81	**-0.42**	1.00	**-0.38**	1.03
	j) The ground property situation hinder the implementation of this design guideline is.	**-0.38**	0.70	**-0.17**	0.75	**-0.21**	0.82	**0.25**	0.92	**0.13**	0.88	**-0.17**	0.80	**-0.33**	1.03	**-0.33**	0.80	**-0.26**	0.85
		-0.25	0.76	**-0.24**	0.71	**-0.34**	0.81	**0.21**	0.94	**0.20**	0.90	**-0.11**	0.87	**-0.63**	0.92	**-0.47**	0.88	**-0.31**	0.94
									strongly disagree		disagree			neutral		agree		strongly agree	
										-1,5	-1,5	-0,5	-0,5	0	0,5	0,5	1,5	1,5	

Appendix S: Survey results per item per group: students

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Summary
Samenvatting
Zusammenfassung

Summary

In the context of global climate change and urban heat problems, climate-responsive design of urban areas can create healthy and thermally comfortable living environments. This thesis was motivated by the need to provide landscape architects and other urban design professionals with specialised knowledge on how to shape urban green (i.e., vegetated) spaces and elements, such as parks, gardens and street trees, referred to as urban green infrastructure or UGI. Evidence-based knowledge, rather than popular general beliefs like '*green is good*' or '*the more green*, *the better*', should inform climate-responsive design of outdoor urban spaces to mitigate heat stress and to create thermally comfortable environments.

Urban green infrastructure moderates urban climate conditions on various scale levels. To date, research has predominately investigated the impacts on objective thermal conditions, like the positive effect of tree canopies on microclimate parameters such as air temperature (T_a) or mean radiant temperature (T_{mrt}). Such micrometeorological studies are limited in the moderate climate of the Netherlands, and the knowledge available does not match the demand of spatially explicit information by urban designers. Besides moderating objective thermal conditions, UGI impacts peoples' subjective thermal perception, that is how a person senses and experiences physical thermal conditions in a vegetated as compared to a non-vegetated environment. Research on subjective perception of thermal conditions linked to the spatial characteristics of the environment provides thermo-spatial knowledge, that can guide the design of climate-responsive UGI. Yet, studies on subjective thermal perception have been underrepresented in urban microclimate research. Consequently, the scholarly knowledge on UGI available has hardly impacted current design practice. To enhance the impact of scientific microclimate knowledge in urban design practice, it needs to be more spatially-explicit to be relevant for design. In addition, the knowledge should be communicated and presented in a way that it is regarded as useful by urban design practitioners.

Design guidelines can be considered as a tool supporting the design practice. But there only a few studies that have addressed the question how to develop useful design guidelines. This thesis considers design guidelines as evidence-based, generally applicable knowledge that guides urban design actions in a variety of site-specific spatial and

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functional circumstances, and that design professionals consider to be useful. Usefulness in this thesis is defined by a set of three criteria: comprehensibility for designers, applicability in design, and feasibility in practice. Concerning the development of evidence-based and useful design guidelines, models are described that use fundamental knowledge to generate evidence-based design in landscape architecture, and that assess and assure the usefulness of guidelines in design practice. Yet, the practicality of these models needs to be confirmed.

This research set out to generate evidence-based and useful design guidelines for climate-responsive UGI. It answered the main research question: *What are useful, evidence-based design guidelines for climate-responsive urban green infrastructure (UGI)?* This research question is divided into the following sub-questions:

- *What is the impact of UGI on peoples' subjective thermal perception in relation to objective microclimate conditions?*
- *What is spatially explicit evidence regarding effects of UGI on thermal perception?*
- *What are evidence-based and useful design guidelines for climate-responsive UGI and how can they be developed from the empirical evidence generated in this thesis?*

To answer the research questions, a multiphase, mixed methods approach consisting of a series of independent studies was chosen. The first phase contains a 'Research for Design' study including fieldwork at city, park and street levels (Chapters 2, 3 and 4) and a methodological literature review (Chapter 5), and the second phase involves a participatory 'Research through Designing' study (Chapter 6).

Chapter 2 presents a study in which the impacts of large urban green spaces on subjective thermal perception and on objective thermal conditions has been studied. Likewise to al fieldwork, the investigations focussed on warm summer periods in the moderate climate of the Netherlands. Inhabitants' long-term thermal perception was studied in three Dutch cities by means of questionnaires with pedestrians. Moreover, daytime thermal conditions of green spaces in the city of Utrecht were examined to find objective evidence to verify subjective thermal perception. To this end bicycles, equipped with micrometeorological sensors, were used to collect in situ data in 13 parks, the city centre and in the open grassland outside the city. Analyses focused on dependences between thermal conditions and spatial variables of parks (size, tree canopy, upwind vegetation cover). Results demonstrate consistently across the three cities that people generally perceive urban green spaces as thermally comfortable. People evaluate green urban spaces as more thermally comfortable than urban spaces with water or built features. The positive impact of urban green spaces on people's subjective thermal perception corresponds with the objective thermal investigations. Mean radiant temperature (T_{mrt}) in parks on average was 1.7 K lower than in the city centre and 13.6 K lower than in the surrounding grasslands during the hottest period of the day. Thermal variance between parks was significantly influenced by the spatial characteristics upwind vegetation cover in adjacent neighbourhoods and tree canopy cover inside the park.

Chapter 3 presents a study in which resting parks visitors momentary thermal perception and behavioural response in parks has been investigated. The field work took place during summer and tropical days ($T_{a\ max}$ > 25 °C and > 30 °C, respectively), the latter representing future climate conditions. Unobtrusive observations and surveys were conducted simultaneously in two parks in the Netherlands. Findings on park attendance and solar exposure preferences were related to air temperature (T_a) of meteorological reference stations and to spatial data on the vegetation structures of the parks. Results show that resting park visitors perceived a high level of thermal comfort during all investigated days. Park visitors chose resting locations predominantly based on solar exposure conditions. Those solar exposure preferences were significantly related to T_a: with increased T_a the number of park visitors in the shade increased and decreased in the sun with a tipping point of 26 °C, demonstrating physical adaptation of resting park visitors. Parks in moderate climates thus may guarantee a high level of thermal comfort, even on tropical days, if a variety of solar exposure conditions is guaranteed. A ratio of 40% sun, 20% half-shade and 40% shade appeared to accommodate preferences of resting park visitors under various thermal conditions (summer and tropical) and on various times of the day. These results and a spatial typology of tree configurations can inform climate-responsive design: urban parks need to offer a range of sun-exposed, half-shaded and shaded places to accommodate for different user needs and future climate conditions.

Chapter 4 reports on a studies that investigated the impact of street greenery on subjective thermal perception and on objective thermal conditions. Nine streets with comparable geometric configurations, but varying amount of street greenery (street trees, front gardens) were examined in the city of Utrecht, the Netherlands. Fieldwork included semi-structured interviews with pedestrians and mobile micrometeorological measurements. Results of the latter show that 10% tree crown cover within a street canyon lowered street averaged mean radiant temperature (T_{mrt}) about 1 K. In accordance with objective results, interview results indicate that streets with streets greenery are perceived more thermally comfortable than streets without greenery. Moreover, momentary thermal perception tend to be related to the amount of street greenery. Here visual perception may influence thermal perception independently from micrometeorological evidence. Concerning long-term thermal perception respondents were hardly aware of influences by street greenery. Yet, people significantly valued the presence of street greenery in aesthetic terms. This study indicates that street greenery forms a convenient adaptive strategy to create thermally comfortable streets, in particular through street trees and vegetation with varying heights in the visual view of pedestrians.

Chapter 5 presents a comprehensive review of novel qualitative methodological approaches to examine subjective thermal perception. In this, qualitative methods such as interviews, cognitive mapping or unobtrusive observations, are linked to thermal and spatial information of people's perception. As such, the methods used in Chapters 2, 3 and 4 and their findings are placed in a broader context. The review discusses the methods based on dimensions that influence thermo-spatial perception: the nature and scale of spatial contexts, the kinetic state of the people and the time scale of their perception ('now' or 'the past'). The results show that the qualitative methods respond to the different dimensions by combinations of momentary and long-term thermal perception research in stationary mode and in motion in varying spatial environments. The review shows that the qualitative methods, complementary to quantitative methods, deliver explicit thermo-spatial information, that is relevant for climate-responsive design.

Chapter 6 presents the design guidelines for climate-responsive UGI that were derived from the results obtained in the studies presented in the Chapters 2, 3 and 4. The development of the guidelines occurred by a participatory 'Research through Designing' (RTD) approach. In two practical design settings, potential future end-users, being landscape architecture professionals and students, tested a set of preliminary guidelines in site specific design assignments. Observations of the design processes, plan analysis of the design proposals, and questionnaires with the participants provided insights into the usefulness of the preliminary guidelines. These insights directed the refinement of the preliminary guidelines into revised design guidelines for climate-responsive UGI. The generally applicable guidelines at city, park, and street scale levels were accompanied with operational principles that support their implementation in specific sites. In this study the participatory RTD approach proved valuable to connect microclimate science and design practice. In addition, the practical design settings showed that for implementing guidelines in site-specific design, a basic understanding of microclimate processes and skills to conduct microclimate analysis are essential.

Chapter 7 synthesizes the findings of the previous chapters and answers the research questions. Concerning the research sub-question 1, the findings of Chapters 2, 3 and 4 reveals that UGI improves subjective thermal perception across all scale levels. People evaluate urban environments with UGI as more thermally comfortable and prefer them to non-green environments. Additionally, a more varied vegetation in the visual field of pedestrians probably leads to a better thermal perception. These findings are in line with and can mostly be explained by the objective microclimate conditions. One can say '*green is perceived to be cool*' and '*green is cool*'. However, people's subjective thermal reality can deviate from the objective thermal reality. Consequently, comprehensively studying thermal comfort needs to respond to both realities: to the physical environment, and to how people subjectively perceive this environment.

Concerning the research sub-question 2, this thesis provides a list of spatially explicit characteristics of UGI. Upwind vegetation cover in urban environments, as well as size and leaf density of tree canopies enhance objective thermal conditions in urban environments. An enhanced ratio of street greenery in the visual field of pedestrians and conscious distribution of tree canopy cover can improve subjective thermal perception. Moreover, this thesis argues for creating a diversity in microclimates, in particular, a diversity in solar exposure. Creating a wide range of sunny, half-shaded and shaded places within urban environments, for instance through the conscious distribution of tree canopy covers, simultaneously accommodates different user preferences under varying diurnal (and seasonal) thermal conditions.

Concerning the research sub-question 3, this thesis offers a methodological model that describes the sequential steps taken to develop evidence-based and useful design guidelines for climate-responsive UGI. The three steps of knowledge generation taken in this research are (I.) observation and monitoring, (II.) generalisation, (III.) transforming and refining. Related to the two phases of this research, (I.) observation and monitoring and (II.) generalisation are part of the Research for Design studies (Chapters 2, 3 and 4), whereas the (III.) transforming and refining was done in the participatory RTD study (Chapter 6). The fourth step of the framework, (IV.) specification and implementation, is not part of the thesis. However, since the implementation phase actually was 'simulated' in the participatory RTD study, insights in the implementation phase were gathered ahead of it, and the knowledge provided was revised to enhance its usefulness in design practice.

Finally, concerning the main research question this thesis delivered nine design guidelines for climate-responsive UGI on city, park and street level. Together with the operational principles provided and a basic understanding of microclimate processes, these design guidelines are relevant for '*clever*' climate-responsive design of UGI, rather than the adage '*the more green, the better (adapted to urban heat issues)*'. Instead of the ubiquity of UGI, this thesis thus argues for urban green that is '*clever and cool*': climate-responsive UGI that is designed resource efficiently, is based on site-specific microclimate analysis, and considers spatial conditions as well as the behavioural demands of urban dwellers.

Future research on objective thermal conditions should be extended to more cities, and moreover investigate diurnal and seasonal impacts of UGI. Concerning subjective thermal perception, research should further unravel the impact of UGI thermal perception and behavioural response. With regards to the participatory RTD approach, further advancing this approach with larger numbers of (professional) participants and more exhaustive datasets can enhance the reliability and robustness of results. Once the provided design guidelines are implemented in real urban sites, post-implementation monitoring should investigate the actual effects on urban heat mitigation. Such monitoring provides continuous feedback that can strengthen the connection between scientific microclimate knowledge and the urban design practice.

A growing number of Dutch cities considers environmental sustainability as the core of their urban development strategies. Similar developments occur in cities around the world. Both citizens and business benefit from a range of policies and initiatives supporting the development of attractive, high-quality urban areas that are sustainable, carbon neutral and climate-responsive. Therefore, I expect local authorities to benefit from the knowledge and guidelines provided by this thesis. Both can be valuable for those involved in generating urban heat mitigation strategies, for instance as part of the new legislation on the environment ('Omgevingswet'), or for those involved in site-specific design, like landscape architectural and urban designers. The first set of guidelines for '*clever and cool*' climate-responsive UGI is ready for application; now it would be encouraging to see public and private actors to implement them to create more thermally comfortable and liveable urban environments.

Samenvatting

Het ontwerpen en realiseren van klimaatbestendige steden is een manier om stedelijke hitteproblemen te verminderen en steden voor te bereiden op de effecten van de toekomstige verandering van het klimaat. Het doel van ontwerpen met invloed op het stadsklimaat, zogenaamd klimaat- of hittebestendig ontwerpen, is prettige en thermisch comfortabele leefomgevingen te creëren. De noodzaak om landschapsarchitecten en andere ontwerpers van stedelijke buitenruimtes gespecialiseerde kennis te bieden voor het klimaatbestendig ontwerpen is de basis voor dit proefschrift. De focus ligt daarbij op het ontwerpen met stedelijk groen. Het begrip stedelijk groen is een overkoepelende term voor alle groene, d.w.z. beplante, ruimten en elementen zoals parken, tuinen en straatbomen. Op dit moment zijn vaak algemene, populaire opvattingen zoals '*groen is goed*' of '*hoe groener, hoe beter*' bepalend voor het ontwerpen van klimaatbestendige buitenruimtes. Alleen is deze puur kwantitatieve benadering onrealistisch; niet alleen vanuit de nodige ruimteclaims in dicht bebouwde steden, maar ook vanuit het oogpunt van onderhoud en irrigatie. Om effectief te kunnen ontwerpen met stedelijk groen is nieuwe kennis en een wetenschappelijke onderbouwing nodig, die richting geeft aan het ontwerp van groene, klimaatbestendige buitenruimtes. Degelijke empirisch onderbouwde kennis, toegepast in de ontwerppraktijk, kan bijdragen hittestress in steden te verminderen en thermisch comfortabele leefomgevingen te creëren.

Dit onderzoek richt zich op het effect van groen in de stad op het stedelijk microklimaat. Dit schaalniveau is relevant voor ontwerpers omdat objectieve thermische condities, bijvoorbeeld lucht- of stralingstemperatuur, en de subjectieve beleving daarvan door stadsbewoners, grotendeels bepaald wordt door de ruimtelijke inrichting van de stad. Hierbij horen onder meer bebouwing, verharding, water en groen. Tot op heden heeft microklimaatonderzoek voornamelijk de effecten van stedelijk groen op objectieve thermische condities onderzocht. Daarbij horen de matigende effecten van boomkronen op de luchttemperatuur (T_a) of de stralingstemperatuur ('mean radiant temperature', T_{mrt}). Dergelijke studies zijn slechts beperkt uitgevoerd in het gematigde klimaat van Nederland. Bovendien komt de beschikbare kennis niet overeen met de vraag naar ruimtelijk expliciete informatie, die ontwerpers van stedelijke buitenruimtes nodig hebben.

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Naast het beïnvloeden van objectieve thermische omstandigheden, heeft stedelijk groen ook effect op de temperatuurbeleving en het gedrag van mensen (de subjectieve thermische perceptie). Hieronder wordt verstaan hoe een persoon fysieke thermische condities ervaart en daarop anticipeert; bijvoorbeeld in een groene omgeving ten opzichte van een niet-groene omgeving. Binnen de term thermische perceptie wordt een onderscheid gemaakt tussen de korte en lange termijn. De korte termijn thermische perceptie richt zich op een ervaring op de actuele temperatuurbeleving op een specifiek moment ('nu') en lange termijn thermische perceptie op de temperatuurbeleving over een langere periode ('in het verleden'). In beide typen onderzoek wordt de subjectieve thermische perceptie gekoppeld aan ruimtelijke kenmerken van de omgeving en biedt nieuwe ruimtelijke expliciete kennis, die essentieel is voor klimaatbestendig ontwerpen. Op dit moment zijn studies naar de subjectieve thermische perceptie ondervertegenwoordigd in stedelijk microklimaatonderzoek. Een gevolg hiervan is dat de beschikbare wetenschappelijke kennis over stedelijk groen nauwelijks zijn weerklank vindt in de huidige ontwerppraktijk. Om de impact van wetenschappelijke microklimaatkennis in de stedelijke ontwerppraktijk te vergroten, moet deze meer relevant zijn voor het ontwerp en de ruimtelijke inrichting van buitenruimtes en dus ruimtelijk expliciet. Bovendien moet degelijke vakspecifieke kennis op een manier gecommuniceerd en gepresenteerd worden, die toegankelijk en direct toepasbaar is voor ontwerpers.

Een hulpmiddel, dat vakspecifieke, empirisch onderbouwde kennis toegankelijk en toepasbaar kan maken voor de ontwerppraktijk zijn ontwerprichtlijnen. Ontwerprichtlijnen worden in dit onderzoek beschouwt als empirisch onderbouwde, algemeen toepasbare kennis, die het ontwerpproces in alle mogelijke ruimtelijke en functionele omstandigheden ondersteunt en die als bruikbaar worden beschouwd door ontwerpprofessionals. In dit proefschrift wordt bruikbaarheid gedefinieerd als de combinatie van een drietal criteria: begrijpelijkheid voor ontwerpers, toepasbaarheid in ontwerp en haalbaarheid in de praktijk. Tot nu toe beschrijven slechts enkele studies hoe ontwerprichtlijnen op basis van fundamentele kennis kunnen worden ontwikkeld. Ook zijn er weinig studies uitgevoerd, die bestaande ontwerprichtlijnen testten op hun bruikbaarheid in de ontwerppraktijk. De haalbaarheid en nut van deze theoretische modellen moet dus nog worden bevestigd in nieuw uit te voeren onderzoek.

Het doel van dit proefschrift was om empirisch onderbouwde en bruikbare richtlijnen te genereren, die ontwerpers ondersteunen stedelijk groen effectief in te zetten bij de inrichting van thermisch comfortabele buitenruimtes. Dit onderzoek beantwoordde de hoofdonderzoeksvraag: *Wat zijn bruikbare, empirisch onderbouwde ontwerprichtlijnen voor klimaatbestendig stedelijk groen?* Deze onderzoeksvraag is onderverdeeld in de volgende deelvragen:

- *Wat is de impact van stedelijk groen op de subjectieve thermische perceptie van mensen in relatie tot objectieve microklimaatomstandigheden?*
- *Wat is ruimtelijk expliciete kennis betreffende de effecten van stedelijk groen op de thermische perceptie?*
- *Wat zijn empirisch onderbouwde en bruikbare ontwerprichtlijnen voor klimaatbestendig stedelijk groen en hoe kunnen deze worden ontwikkeld op basis van de empirische kennis die in dit proefschrift is gegenereerd?*

Om de onderzoeksvragen te beantwoorden werd een tweefasig aanpak gekozen met een reeks onafhankelijke deelstudies. De eerste fase omvat een 'Research for Design' studie bestaande uit veldwerk op stad-, park- en straatniveau (Hoofdstuk 2, 3 en 4) en een methodologisch literatuuroverzicht (Hoofdstuk 5). De tweede fase omvat een participatief 'Research through Designing' studie waarin ontwerprichtlijnen in actieve ontwerpsessies zijn getest en later verbeterd (Hoofdstuk 6).

Hoofdstuk 2 presenteert een onderzoek naar subjectieve thermische perceptie van groen stedelijke buitenruimten en objectieve thermische omstandigheden in parken, het stadscentrum en het buitengebied van een stad. Evenals het veldwerk op park- en straatniveau (Hoofdstuk 3 en 4) richtte zich het onderzoek op warme zomerperioden overdag in het gematigde klimaat van Nederland. Aan de hand van vragenlijsten met voetgangers werd de lange termijn thermische perceptie van bewoners in drie Nederlandse steden (Rotterdam, Arnhem en Utrecht) bestudeerd. Om de subjectieve thermische perceptie te verifiëren werden objectieve thermische condities in parken in Utrecht onderzocht. Hiertoe zijn mobiele metingen gedaan. Bakfietsen waren uitgerust met micro-meteorologische en GPS sensoren om in-situgegevens te verzamelen in 13 parken, in het stadscentrum en in het open grasland buiten de

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stad. De analysis richtten zich op afhankelijkheden tussen thermische omstandigheden en ruimtelijke variabelen van parken (oppervlakte van parken, grootte van het totaal aan boomkruinen, groenfractie aan de loefzijde van de parken).

De resultaten laten in alle drie steden zien dat mensen stedelijke groene ruimten als thermisch comfortabel ervaren. Mensen beoordelen groene stedelijke ruimten als meer thermisch comfortabel dan stedelijke ruimtes met water of voornamelijk verharde oppervlakken. De positieve impact van stedelijke groene ruimten op de subjectieve thermische perceptie komt overeen met de objectieve thermische resultaten. Tijdens de heetste periode van de dag was de stralingstemperatuur (T_{mrt}) in parken gemiddeld 1,7 K lager dan in het stadscentrum en 13,6 K lager dan in de omliggende graslanden. De thermische variatie tussen parken werd significant beïnvloed door de ruimtelijke kenmerken van de groenfractie in aangrenzende wijken aan de loefzijde van parken en door de totale oppervlakte aan boomkruinen in het park.

Hoofdstuk 3 presenteert een onderzoek waarin de thermische perceptie en het adaptief gedrag (locatievoorkeuren) van parkbezoekers zijn onderzocht. Het veldwerk vond plaats tijdens zomerdagen en tropische dagen, waarbij de laatstgenoemde dagen volgens weerscenario's in de toekomst vaker zullen optreden. Gelijktijdig werd in een park in Utrecht en een park in Wageningen de korte termijn thermische perceptie van parkbezoekers onderzocht middels enquêtes. Daarbij zijn specifieke locaties van zittende en liggende parkbezoekers in kaart gebracht middels discrete observaties. Informatie over het aantal parkbezoekers en hun voorkeuren voor blootstelling aan de zon zijn daarna in verband gebracht met de luchttemperatuur (T_a) van meteorologische referentiestations en met de groene inrichting van de parken.

Uit de resultaten blijkt dat de geïnterviewde parkbezoekers gedurende alle onderzochte dagen een hoog niveau van thermisch comfort ervaarden. Parkbezoekers hielden bij het kiezen van hun specifieke verblijfslocatie in het park voornamelijk rekening met de mate aan blootstelling aan de zon. De voorkeuren waren significant gerelateerd aan T_a: het merendeel van parkbezoekers koos op warme zomerse dagen (met T_a > 25 °C) een zonnige plek en in contrast daarmee op tropische dagen (met T_a > 30 °C) een schaduwrijke plek onder de bomen. Het kantelpunt lag bij ongeveer 26 °C T_a. Parken in het gematigd klimaat van Nederland kunnen dus een hoog niveau van thermisch comfort garanderen, zelfs op tropische dagen. Daarvoor moet bij de inrichting van het park rekening worden gehouden met de aanleg van verschillende microklimaten; plekken in de zon, de halfschaduw of de schaduw. Op basis van de onderzoeksresultaten lijkt een verhouding van 40% zon, 20% halfschaduw en 40% schaduw tegemoet te komen aan voorkeuren van parkbezoekers onder verschillende thermische omstandigheden (zomer en tropisch) en op verschillende tijdstippen van de dag. Deze resultaten en een ruimtelijke typologie van boomconfiguraties in parken zijn richtinggevend voor het ontwerpen van klimaatbestendige parken.

Hoofdstuk 4 presenteert onderzoeken naar de impact van straatgroen, op de subjectieve thermische perceptie en op objectieve thermische condities in negen straten in Utrechts. De staten hebben een vergelijkbare ruimtelijke opzet qua bebouwing en oriëntatie naar de zon, maar variërende hoeveelheid straatgroen (straatbomen, voortuinen). Veldwerk omvatte semigestructureerde interviews met voetgangers en mobiele micro-meteorologische metingen met de bakfietsen, die ook voor het onderzoek op stadsniveau zijn gebruikt (Hoofdstuk 2).

Resultaten tonen aan dat 10% meer boomkruinen in een straat de stralingstemperatuur (T_{mrt}) verlaagt met 1 °C. Deze verlaging van T_{mrt} is afhankelijk van de bladdichtheid en dus lichtdoorlaatbaarheid van de kronen van de aanwezige boomsoorten. Overeenstemmend met de objectieve resultaten geven de interviewresultaten aan dat straten met straatgroen als meer thermisch comfortabel worden waargenomen dan straten zonder groen. Bovendien lijkt de korte termijn thermische perceptie gerelateerd te zijn aan de hoeveelheid straatgroen. Ondervraagden waardeerden de aanwezigheid van straatgroen in esthetische termen. Het lijkt dat de visuele perceptie de thermische perceptie kan beïnvloeden, onafhankelijk van de objectieve micro-meteorologische condities. Groen in de straat draagt dus bij aan visueel aantrekkelijke en thermisch comfortabele straten; bijvoorbeeld door straatbomen in openbare en privé ruimten en door vegetatie met variërende hoogtes in het visuele zicht van voetgangers.

Hoofdstuk 5 presenteert een uitgebreid overzicht van onderzoeken, die nieuwe kwalitatieve methoden gebruiken om subjectieve thermische perceptie te bestuderen. Kwalitatieve methoden, zoals interviews, ‘cognitieve mapping’ of onopvallende observaties worden ingezet om informatie over de korte- en lange termijn thermische en ruimtelijke perceptie van mensen te genereren. In het overzicht worden de methoden aan de hand van drie aspecten beschreven, die de thermo-ruimtelijke waarneming beïnvloeden: (1) de ruimtelijke context en het schaalniveau, (2) de kinetische staat van mensen en (3) de tijdschaal van hun waarneming ('nu' of 'het verleden').

De resultaten laten zien dat de kwalitatieve onderzoeksmethoden zodanig zijn opgezet, dat zij de verschillende aspecten samenhangend benaderen: door combinaties van korte en lange termijn thermisch perceptieonderzoek, in de stationaire modus of in beweging en in verschillende ruimtelijke omgevingen. Door deze literatuurreview worden de in de hoofdstukken 2, 3 en 4 gebruikte methoden en de bevindingen in een bredere context geplaatst. Evenals de onderzoeken in de genoemde hoofdstukken, laat de review zien dat kwalitatieve methoden, complementair aan kwantitatieve methoden, expliciete thermo-ruimtelijke informatie opleveren. Deze informatie is relevant voor het ontwerp van klimaatbestendige buitenruimtes.

Hoofdstuk 6 presenteert de ontwerprichtlijnen voor klimaatbestendig stedelijk groen, die zijn ontwikkeld op basis van de resultaten in de hoofdstukken 2, 3 en 4. Voor de ontwikkeling van de richtlijnen is de participatieve aanpak van ontwerpend onderzoek gekozen (hierna RTD, 'Research through Designing'). In twee ontwerpsessies testten landschapsarchitectuurprofessionals en studenten een reeks voorlopige richtlijnen in concrete ontwerpopdrachten. De observaties van de ontwerpprocessen, plananalysen van de geproduceerde ontwerpen en vragenlijsten voor de deelnemers gaven inzichten in de bruikbaarheid van de voorlopige richtlijnen. Deze inzichten zijn gebruikt voor de verbetering/ verfijning van de voorlopige richtlijnen in de herziene ontwerprichtlijnen. Deze algemeen toepasbare richtlijnen voor klimaatbestendig stedelijk groen op drie schaalniveaus (stad, park en straat) zijn aangevuld met aandachtspunten, die de toepassing van de algemene richtlijnen op specifieke plekken ondersteunen. De participatieve RTD benadering bleek waardevol om fundamentele microklimaatkennis en kennis uit de ontwerppraktijk van landschapsarchitecten met elkaar te verbinden en ontwerprichtlijnen te ontwikkelen. Daarnaast bleek tijdens de ontwerpsessies met landschapsarchitecten, dat voor het implementeren van de algemene ontwerprichtlijnen in specifieke locaties een basiskennis van microklimaatprocessen en vaardigheden, om microklimaatanalyses uit te voeren, essentieel zijn.

Hoofdstuk 7 vat de bevindingen van de voorgaande hoofdstukken samen en beantwoordt de onderzoeksvragen. Met betrekking tot deelvraag 1 geven de bevindingen van de hoofdstukken 2, 3 en 4 aan, dat stedelijk groen de subjectieve thermische perceptie op alle schaalniveaus verbetert. Op warme zomerdagen geven mensen de voorkeur aan groene boven niet-groene omgevingen in de stad. Bovendien blijkt een in hoogte gevarieerde vegetatiestructuur tot een betere subjectieve thermische perceptie te leiden. Deze bevindingen liggen in de lijn met en kunnen grotendeels worden verklaard door de objectieve microklimaatomstandigheden. Geconcludeerd kan worden: '*groen wordt als cool ervaren*' en '*groen is cool*'. De subjectieve thermische realiteit van mensen kan echter afwijken van de objectieve thermische realiteit. Daarom moeten toekomstige studies over thermisch comfort van mensen recht doen aan beide werkelijkheden: aan de objectieve thermische condities in een fysieke ruimte en aan hoe mensen deze omgeving subjectief waarnemen.

Met betrekking tot deelvraag 2 biedt dit proefschrift een lijst met ruimtelijk expliciete kenmerken van stedelijk groen die het stadsklimaat en thermische perceptie beïnvloeden. De groenfractie in wijken aan de loefzijde van parken, evenals de grootte en de bladdichtheid van boomkruinen verbeteren objectieve thermische omstandigheden in stedelijke omgevingen. Een visuele diversiteit van straatgroen, bijvoorbeeld door hoogteverschillen, in het gezichtsveld van voetgangers en een bewuste aanleg van verschillende microklimaten (zon, halfschaduw, schaduw) kan de subjectieve thermische waarneming verbeteren en adaptief gedrag van mensen faciliteren. Het creëren van een breed scala aan zonnige, halfschaduwrijke en schaduwrijke plekken in stedelijke omgevingen biedt tegelijkertijd ruimte aan verschillende maten aan blootstelling van zon en gaat dus in op verschillende gebruikersvoorkeuren onder wisselende dagelijkse (en seizoensgebonden) thermische omstandigheden.

Met betrekking tot deelvraag 3 beschrijft dit proefschrift een methodologisch model in vier stappen om empirisch onderbouwde en bruikbare ontwerprichtlijnen voor klimaatbestendig stedelijk groen te ontwikkelen. De drie stappen voor het genereren van kennis, die in

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dit onderzoek zijn doorlopen, zijn (I.) observatie en monitoring, (II.) generalisatie, (III.) transformatie en verfijning. Gerelateerd aan de twee fasen van dit onderzoek, maken (I.) observatie en monitoring en (II.) generalisatie deel uit van de 'Research for Design' studies (Hoofdstukken 2, 3 en 4), terwijl de (III.) transformatie en verfijning deel uitmaakt van de participatieve 'Research Through Designing' studie (hoofdstuk 6). De vierde stap, (IV.) specificatie en implementatie, maakt geen deel uit van het proefschrift. Aangezien de implementatiefase echter daadwerkelijk werd 'gesimuleerd' in de participatieve RTD studie, zijn de inzichten verzameld en is de gegenereerde kennis beschreven om de bruikbaarheid van de ontwerprichtlijnen in de ontwerppraktijk te vergroten.

Met betrekking tot de centrale onderzoeksvraag levert dit proefschrift negen direct toepasbare ontwerprichtlijnen voor klimaatbestendig stedelijk groen op. De ontwikkelde richtlijnen bieden een handvat voor ontwerpers zoals landschapsarchitecten en stedenbouwers om stedelijke buitenruimtes beter klimaat- en hittebestendig in te richten: Het pleidooi is niet alleen maar '*meer groen*' maar vooral '*effectief groen*'. Effectief groen betekend dat voor elke specifieke locatie de juiste ontwerpkeuzes gemaakt wordt aan de hand van lokale ruimtelijke en functionele omstandigheden, een microklimaatanalyse (schaduw en wind) en het gedragspatronen van de bewoners. Voorbeelden hiervan zijn de beschikbaarheid van schaduw op de heetste tijd van de dag (12:00-16:00), zorgen voor voldoende groeiomstandigheden en irrigatie in de droge zomerperioden of het mogelijk maken van voldoende windcirculatie tussen de bomendaken boven straten met veel verkeer . Deze aandachtspunten en een basiskennis aan microklimaatprocessen kunnen in de praktijk helpen de algemene ontwerprichtlijnen op specifieke locaties toe te passen. Goede analyses van lokale omstandigheden en vooral het combineren met lokaal wateropslag dat voldoende irrigatie mogelijk maakt, zorgen voor effectief hittebestendig groen, dus groen dat '*clever en cool*' is.

Toekomstig onderzoek naar subjectieve thermische perceptie moet de relaties tussen stedelijk groen, thermische perceptie en het gedrag van mensen verder ontrafelen. Onderzoek naar objectieve thermische omstandigheden moet worden uitgebreid naar meer steden en bovendien de dag- en seizoeneffecten van stedelijk groen.

Betreffende de participatieve RTD benadering kan het vergroten van de aantal deelnemers in de ontwerpsessies en het gebruiken van meer omvangrijke empirische gegevens de betrouwbaarheid en robuustheid van de resultaten verbeteren. Zodra de ontwikkelde ontwerprichtlijnen zijn toegepast in fysieke stedelijke locaties, moeten vervolgstudies de feitelijke effecten monitoren. Dergelijke monitoring biedt continue feedback en een groeiende bron van empirische kennis over klimaatbestendig ontwerpen die op lange termijn de kwaliteit van de ontwerprichtlijnen ten goede kan komen.

Een groeiend aantal Nederlandse steden beschouwt klimaatadaptatie als een van de uitgangspunten voor verdere stedelijke (her-)ontwikkeling. Soortgelijke trends zijn ook te zien in veel steden over de hele wereld. Zowel burgers als bedrijven profiteren van beleidsmaatregelen en initiatieven gericht op stedelijk groen, die de ontwikkeling van hoogwaardige aantrekkelijke en klimaatbestendige stedelijke gebieden bevorderen. Ik hoop dat de in dit proefschrift gegeneerde kennis en ontwerprichtlijnen met name overheden ondersteunen. Deze kunnen waardevol zijn voor diegenen die betrokken zijn bij het genereren van klimaatadaptatiestrategieën, bijvoorbeeld als onderdeel van de nieuwe omgevingswet, of voor diegenen die betrokken zijn bij het ontwerp en de inrichting van specifieke buitenruimtes, zoals landschapsarchitecten en stedenbouwkundigen. De eerste set richtlijnen voor '*clever and cool*' klimaatbestendig stedelijk groen is klaar! Nu is de zet aan publieke en private actoren, die deze richtlijnen implementeren om meer prettige en thermisch comfortabele leefomgevingen te creëren.

Zusammenfassung

Die Planung und Realisierung von klimabewussten Städten ist eine Strategie, städtische Hitzeprobleme zu reduzieren und Städte auf die Auswirkungen des zukünftigen Klimawandels vorzubereiten. Ziel der Gestaltung von urbanen Freiräumen mit Einfluss auf das Stadtklima, die sogenannte klimabewusste oder -freundliche Gestaltung, ist es, angenehme und thermisch behagliche Freiräume zu schaffen. Die Notwendigkeit, Landschaftsarchitekten und anderen Entwerfern von urbanen Freiräumen, Fachwissen für klimabewusste Freiraumplanung zu bieten, ist die Motivation dieser Forschungsarbeit. Der Fokus liegt auf der Gestaltung mit Stadtgrün. Das Konzept des Stadtgrüns (auch städtisches Grün) ist ein Überbegriff für alle Pflanzen, wie Straßenbäume, und Grünflächen, wie Parks und Gärten, in der Stadt. Im Moment sind allgemeine, populäre Ansichten wie "*Grün ist gut*" oder "*Je grüner, je besser (die Klimafreundlichkeit von Freiräumen)*" richtungsweisend für den Entwurf klimafreundlicher Freiräume. Jedoch ist dieser rein quantitative Ansatz unrealistisch; nicht nur ausgehend von den notwendigen Platzansprüchen in dicht bebauten Städten, sondern auch ausgehend vom Standpunkt der Erhaltung und Pflege, wie beispielsweise der Bewässerung. Um mit städtischem Grün effektiv gestalten zu können, braucht es neue Erkenntnisse und ein wissenschaftliches Fundament, das den Entwurf grüner, klimabewusster Freiräume lenken kann. Empirisch fundiertes Fachwissen, das in der Entwurfspraxis angewendet wird, kann dazu beitragen, Hitzestress in Städten zu reduzieren und thermisch angenehme Freiräume zu schaffen.

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Diese Forschungsarbeit untersucht die Wirkung von Stadtgrün auf das städtische Mikroklima. Diese Skalenebene ist für Entwerfer relevant, da objektive thermische Bedingungen, beispielsweise Luft- oder Strahlungstemperatur, und das subjektive Erleben des Stadtklimas seitens der Stadtbewohner weitgehend geprägt werden durch die städtebauliche Struktur. Das Mikroklima wird demnach Großteils bestimmt durch das Zusammenwirken von bebauten und versiegelten Flächen, Wasserflächen und Stadtgrün. Bis heute hat die Forschung im Bereich des städtischen Mikroklimas hauptsächlich die Auswirkungen von städtischem Grün auf objektive thermische Bedingungen untersucht. Dazu gehören die positiven Effekte von Baumkronen auf die Lufttemperatur (T_a) oder die Strahlungstemperatur ("mean radiant temperature", T_{mrt}). Solche Studien wurden im gemäßigten Klima der Niederlande nur in begrenztem Umfang durchgeführt. Darüber hinaus entspricht das verfügbare Fachwissen nicht der Nachfrage nach räumlich expliziten Erkenntnissen, die Landschaftsarchitekten und andere Entwerfer von urban Freiräumen benötigen.

Städtisches Grün beeinflusst nicht nur die objektiven thermischen Bedingungen, sondern auch das Temperaturempfinden und folglich das Verhalten von Menschen. Dieses subjektive Wärmeempfinden beschreibt, wie eine Person objektive thermische Bedingungen erlebt und darauf reagiert; zum Beispiel in einer grünen Umgebung im Vergleich zu einer nicht-grünen Umgebung. Innerhalb des Begriffs thermische Wahrnehmung wird kurz- und langfristig unterschieden. Die kurzfristige (oder momentane) thermische Wahrnehmung konzentriert sich auf eine Erfahrung der aktuellen thermischen Bedingungen zu einem bestimmten Zeitpunkt ("jetzt"). Die langfristige thermische Wahrnehmung bezieht sich auf einen längeren Zeitraum ("in der Vergangenheit"). In beiden Konzepten ist das subjektive Wärmeempfinden mit räumlichen Merkmalen der Umgebung verknüpft und bietet daher räumlich explizite Erkenntnisse, die für eine klimafreundliche Freiraumgestaltung essentiell sind.

Derzeit sind Studien zur subjektiven thermischen Wahrnehmung in der städtischen Mikroklimaforschung unterrepräsentiert. Konsequenterweise sind die verfügbaren wissenschaftlichen Erkenntnisse über städtisches Grün kaum verankert in der aktuellen Entwurfspraxis von Landschaftsarchitekten und Freiraumplanern. Um den Einfluss von fundiertem Fachwissen zu städtischem Mikroklima in der Entwurfspraxis zu erhöhen, muss dieses Fachwissen relevant sein für die Freiraumgestaltung und damit räumlich explizit. Darüber hinaus müssen neue, wissenschaftlich unterbaute Erkenntnisse in einer für Landschaftsarchitekten zugänglichen und direkt anwendbaren Weise kommuniziert und präsentiert werden.

Ein Hilfsmittel, das fachspezifisches Wissen für die Entwurfspraxis zugänglich und nutzbar macht, sind Gestaltungs- oder Entwurfsrichtlinien. Gestaltungsrichtlinien gelten in dieser Forschungsarbeit als empirisch fundiertes, allgemein anwendbares Wissen, das den Entwurfsprozess in allen möglichen räumlichen und funktionalen Situationen unterstützt und das von Landschaftsarchitekten als nützlich erachtet wird. In dieser Arbeit wird Nützlichkeit definiert als die Kombination von drei Kriterien:

Verständlichkeit für Entwerfer, Anwendbarkeit im Entwurfsprozess und Realisierbarkeit in der Praxis. Bislang beschreiben nur wenige Studien, wie Entwurfsrichtlinien basierend auf empirischen Fachwissen entwickelt werden können. Darüber hinaus gibt es kaum Studien, die Gestaltungsrichtlinien auf ihre Nützlichkeit in der Entwurfspraxis getestet haben. Die Durchführbarkeit und Brauchbarkeit dieser theoretischen Modelle muss daher in neuen Forschungsarbeiten bestätigt werden.

Das Ziel dieser Forschungsarbeit war es, empirisch fundierte und nützliche Gestaltungsrichtlinien für städtisches Grün zu entwickeln, die Landschaftsarchitekten unterstützen, thermisch behagliche Freiflächen zu entwerfen. Diese Forschungsarbeit beantwortete die Frage: *Was sind nützliche, empirisch fundierte Gestaltungsrichtlinien für klimabewusstes Stadtgrün?* Diese Frage gliedert sich in folgende Teilfragen:

- *Welchen Einfluss hat Stadtgrün auf die subjektive thermische Wahrnehmung von Menschen in Bezug auf objektive Mikroklima-Bedingungen?*
- *Was sind räumlich explizite Eigenschaften von Stadtgrün, welche die subjektive thermische Wahrnehmung und die objektiven thermischen Bedingungen beeinflussen?*
- *Was sind nützliche Gestaltungsrichtlinien für klima-bewusstes Stadtgrün und wie können diese auf der Grundlage des empirischen Wissens, das in dieser Arbeit generiert wurde, entwickelt werden?*

Zur Beantwortung der Forschungsfragen wurde ein zweiphasiger Ansatz mit einer Reihe von unabhängigen Teilstudien gewählt. Die erste Phase besteht aus einer "Research for Design" -Studie, bestehend aus Feldforschung entsprechend den Entwurfsmaßstäben Stadt, Park und Straße (Kapitel 2, 3 und 4) und einer methodologischen Literaturübersicht (Kapitel 5). Die zweite Phase umfasst eine partizipative "Research through Designing"–Studie, in der Gestaltungsrichtlinien in Entwurf- Workshops mit praktizierenden Landschaftsarchitekten getestet und später verbessert wurden (Kapitel 6).

Kapitel 2 stellt eine Studie vor, in der subjektive thermischen Wahrnehmung grüner städtischer Freiräume und objektive thermische Bedingungen in Parks, dem Stadtzentrum und dem Außenbezirk einer

Stadt untersucht werden. Wie bei der Feldforschung auf den Maßstäben Park und Straße (Kapitel 3 und 4) konzentrierte sich die Untersuchung auf heiße Sommerperioden in dem gemäßigten Klima der Niederlande. Anhand von Befragungen von Fußgängern wurde die langfristige thermische Wahrnehmung von Bewohnern in drei niederländischen Städten (Rotterdam, Arnheim und Utrecht) untersucht. Zur Überprüfung der subjektiven thermischen Wahrnehmung wurden objektive thermische Bedingungen in Parks in Utrecht untersucht. Zu diesem Zweck wurden mobile Messungen mit Transportfahrrädern (Cargo-Bikes) durchgeführt. Diese Fahrräder waren mit mikro-meteorologischen und GPS-Sensoren ausgestattet, um Daten in 13 Parks, dem Stadtzentrum und auf offenem Grasland außerhalb der Stadt zu sammeln. Die Analyse konzentrierte sich auf Abhängigkeiten zwischen den thermischen Bedingungen und den räumlichen Eigenschaften von Parks, d.h. Oberfläche der Parks, Oberfläche der gesamten Baumkronen in den Parks, Grünanteil auf der Luvseite der Parks. Die Ergebnisse zeigen in allen drei Städten, dass Menschen urbane Grünflächen als thermisch behaglich empfinden. Menschen beurteilen grüne Freiräume als thermisch komfortabler als urbane Freiräume mit Wasser oder überwiegend versiegelten Flächen. Der positive Einfluss städtischer Grünflächen auf die subjektive thermische Wahrnehmung entspricht den objektiven thermischen Ergebnissen: Während der heißesten Zeit des Tages war die Strahlungstemperatur (T_{mrt}) in den untersuchten Parks im Durchschnitt 1,7 K niedriger als in der Innenstadt und 13,6 K niedriger als in den umliegenden Graslandschaften. Die thermischen Unterschiede zwischen den Parkanlagen wurden maßgeblich beeinflusst durch die Gesamtfläche der Baumkronen und den Anteil an Grünflächen in benachbarten Stadtteilen auf der Luvseite der Parks.

Kapitel 3 stellt eine Studie vor, die die subjektive thermische Wahrnehmung und das adaptive Verhalten (Standortpräferenz) von Parkbesuchern untersucht. Die Feldarbeit fand im Sommer an sogenannten warmen (T_a > 25 °C) und tropischen (T_a > 30 °C) Tagen statt. Tropische Tage werden laut Klimaprognosen in Zukunft häufiger vorkommen. In einem Park in Utrecht und einem Park in Wageningen wurden gleichzeitig Umfragen durchgeführt, die die kurzfristige/ momentane thermische Wahrnehmung von Parkbesuchern untersuchten. Darüber hinaus wurden in diskreten Beobachtungen die

Sitz- oder Liegeplätze von Parkbesuchern, im Folgenden bezeichnet als Standorte, sowie deren Präferenzen für die Sonnenexposition (Sonne, Halbschatten oder Schatten) kartiert. Informationen über die Anzahl der Parkbesucher und ihrer Standorte, wurden dann mit der Lufttemperatur (T_a) von meteorologischen Referenzstationen und der räumlichen Parkgestaltung in Beziehung gesetzt.

Die Ergebnisse zeigen, dass die befragten Parkbesucher an allen untersuchten Tagen ein hohes Maß an thermischem Komfort erfahren haben. Die Parkbesucher berücksichtigten bei der Wahl ihres Sitz- oder Liegeplatzes im Park vor allem die Sonnenexposition. Die Präferenzen der Besucher in beiden Parks zeigen einen signifikanten Bezug zur Lufttemperatur (T_a): die Mehrzahl der Parkbesucher präferierte an warmen Tagen (T_a > 25 °C) einen sonnigen Platz, und im Gegensatz dazu an tropischen Tagen (T_a > 30 °C) einen schattigen Platz. Der Umschlag- oder Wendepunkt lag bei ca. 26 °C T_a. Die Studie beweist, dass Parks im gemäßigten Klima der Niederlande auch an tropischen Tagen ein hohes Maß an thermischem Komfort garantieren können. Dafür muss jedoch bei der Parkgestaltung der Entwurf verschiedener Mikroklimata berücksichtigt werden: Bereiche in der Sonne, im Halbschatten oder im Schatten. Auf der Grundlage der vorliegenden Forschungsergebnisse scheint ein Anteil von 40% Sonne, 20% Halbschatten und 40% Schatten den Präferenzen der Parkbesucher unter verschiedenen thermischen Bedingungen (T_a > 25 °C und T_a > 30 °C) und zu verschiedenen Tageszeiten (11:00 bis 17:00) zu entsprechen. Diese Ergebnisse und eine Typologie von räumlichen Baumkonfigurationen in Parks können die Gestaltung von klimafreundlichen Parks unterstützen.

In **Kapitel 4** werden Studien zum Einfluss von Straßengrün auf die subjektive thermische Wahrnehmung und auf die objektiven thermischen Bedingungen in neun Straßen in Utrecht vorgestellt. Die Straßen haben eine ähnliche räumliche Gestaltung hinsichtlich der Ausrichtung zur Sonne, der Bebauung und der Materialisierung, aber unterschiedliche Ausmaße an Straßengrün (Straßenbäume, Vorgärten). Die Feldforschung umfasste semi-strukturierte Interviews mit Fußgängern und mobile mikro-meteorologische Messungen mit Transportfahrrädern, die auch in der Studie auf Stadtebene (Kapitel 2) zum Einsatz kamen.

Z

Die objektiven Ergebnisse zeigen, dass 10% mehr Baumkronen in einer Straße die Strahlungstemperatur (T_{mrt}) um 1 °C senken. Diese Reduktion von T_{mrt} hängt von der Blattdichte (und somit der Lichtdurchlässigkeit) und der Kronenoberfläche der vorhandenen Baumarten ab. In Übereinstimmung mit den objektiven Ergebnissen zeigen die Interviewergebnisse, dass Straßen mit Straßengrün als thermisch behaglicher empfunden werden als Straßen ohne Grün. Darüber hinaus scheint die kurzfristige Wärmewahrnehmung mit der Menge an Straßengrün zusammenzuhängen. Ebenfalls schätzten die Befragten das vorhandene Straßengrün aus ästhetischer Sicht. Es scheint, dass die visuelle Wahrnehmung unabhängig von den objektiven mikro-meteorologischen Bedingungen die thermische Wahrnehmung beeinflussen kann. Die Studie zeigt, dass Straßenbäume und Vorgärten dazu beitragen, dass Straßenräume als visuell ansprechend und thermisch komfortabel empfunden werden. Dies wird beispielsweise ermöglicht durch Straßenbäume in öffentlichen und privaten Bereichen und durch Vegetation mit unterschiedlichen Höhen im Sichtbereich von Fußgängern.

Kapitel 5 präsentiert einen umfassenden Literaturüberblick über neue qualitative Methoden zur Erforschung des Konzepts der subjektiven thermischen Wahrnehmung. Qualitative Methoden wie Interviews, "cognitive mapping" oder diskrete Beobachtungen werden genutzt, um Informationen über die kurz- und langfristige thermische Wahrnehmung in Bezug auf die räumliche Wahrnehmung von Menschen zu generieren. Der Literaturüberblick beschreibt die Methoden auf der Grundlage von drei Aspekten, die die thermo-räumliche Wahrnehmung beeinflussen: (1) der räumliche Kontext und die Maßstabsebene, (2) der kinetische Zustand der Menschen und (3) die Zeitskala ihrer Wahrnehmung ("jetzt" oder "die Vergangenheit"). Die Ergebnisse zeigen, dass die qualitativen Forschungsmethoden so konzipiert sind, dass sie die verschiedenen Aspekte kohärent umfassen; nämlich durch die Kombinationen von kurz- und längerfristiger thermischer Wahrnehmung, im stationären Modus oder in Bewegung und in verschiedenen räumlichen Umgebungen. Diese Literaturrecherche ermöglicht es die in den Kapiteln 2, 3 und 4 verwendeten Methoden und die Ergebnisse in einen breiteren Kontext zu stellen. Ähnlich wie in den oben genannten Kapiteln zeigt die Literaturübersicht, dass qualitative Methoden, die komplementär zu quantitativen Methoden eingesetzt werden, explizite thermo-räumliche Informationen liefern. Diese explizit räumlichen Erkenntnisse sind bedeutungsvoll für die Gestaltung von klimabewussten städtischen Freiräumen.

Kapitel 6 präsentiert die Entwicklung der Entwurfsrichtlinien für klimafreundliches städtisches Grün basierend auf den empirischen Ergebnissen der Feldforschung in Kapitel 2, 3 und 4. Bei der Entwicklung der Richtlinien wurde der methodologische Ansatz der partizipativen „Forschung mittels Entwurfsaktivitäten" (im Englischen participatory „Research Through Designing", im Folgenden RTD-Ansatz oder -Studie) gewählt. Der partizipative RTD-Ansatz beinhaltet die Entwicklung neuer Erkenntnisse, in diesem Falle Entwurfsrichtlinien, durch aktives Entwerfen mit potenziell zukünftigen Benutzern der Richtlinien. In zwei Entwurfs-Workshops testeten berufstätige Landschaftsarchitekten und Studenten derselben Disziplin eine Reihe vorläufiger Entwurfsrichtlinien in konkreten Entwurfsaufgaben für städtische Freiräume. Die Beobachtungen der Entwurfsprozesse, Plananalysen der erstellten Entwürfe und Umfragen mit den Teilnehmern am Ende der Workshops gaben Aufschluss über die Nützlichkeit der vorläufigen Richtlinien in der Entwurfspraxis. Selbige Erkenntnisse wurden verwendet, um die vorläufigen Richtlinien zu überarbeiten und zu verbessern. Die daraus resultierenden überarbeiteten Entwurfsrichtlinien für klimabewusstes städtisches Grün sind allgemein anwendbare Richtlinien in den Entwurfsmaßstäben Stadt, Park und Straße. Jene Richtlinien werden unterstützt durch eine Reihe von Entwurfstipps, die die Anwendung der allgemeinen Richtlinien in spezifischen städtischen Freiräumen spezifiziert. Der partizipative RTD-Ansatz erwies sich als nützlich, um empirisch unterbautes Mikroklima-Wissen und praktisches Entwurfs-Wissen der Landschaftsarchitekten zu verknüpfen und daraus Gestaltungsrichtlinien zu entwickeln. Darüber hinaus verdeutlichten die Entwurf-Workshops mit Landschaftsarchitekten, dass Voraussetzungen wie Grundkenntnisse der Mikroklima-prozesse und die Fähigkeit, diese entsprechende Prozesse (Wind, Besonnung) zu analysieren, nötig sind, um die allgemeinen Entwurfsrichtlinien angemessen und effektiv in bestimmten Orten anzuwenden.

Kapitel 7 fasst die Ergebnisse der vorangegangenen Kapitel zusammen und beantwortet die Forschungsfragen. In Bezug auf Teilfrage 1 zeigen die Ergebnisse der Kapitel 2, 3 und 4, dass städtisches Grün die subjektive thermisch Wahrnehmung auf allen Maßstabsebenen verbessert. An warmen Sommertagen bevorzugen Menschen grüne Freiräume in der Stadt als Aufenthaltsorte. Darüber hinaus führt eine in Höhe abgestufte Vegetationsstruktur im visuellen Feld von Fußgängern zu einer verbesserten subjektiven thermischen Wahrnehmung. Diese Befunde zur subjektiven thermischen Wahrnehmung stimmen mit den objektiven Mikroklima-Bedingungen überein und lassen sich daher weitgehend erklären. Zusammenfassend kann man sagen: "*Grün wird als cool erlebt*" und "*Grün ist cool*". Die subjektive thermische Realität der Menschen kann jedoch auch von der objektiven thermischen Realität abweichen. Daher müssen zukünftige Untersuchungen zum Konzept der thermischen Wahrnehmung von Menschen beiden Realitäten gerecht werden: den objektiven thermischen Bedingungen in einem physischen Stadtraum und der subjektiven thermischen Wahrnehmung dieses Stadtraumes durch die Menschen.

Im Hinblick auf Teilfrage 2 generierte diese Forschungsarbeit eine Liste von räumlich expliziten Merkmalen von Stadtgrün, die das Stadtklima und die thermische Wahrnehmung beeinflussen. Der Grünanteil in Stadtvierteln auf der Luvseite von Parks und die Größe und Blattdichte von Baumkronen in Parks und Straßenräumen verbessern objektive thermische Bedingungen in städtischen Umgebungen. Eine visuelle Vielfalt von Straßengrün, beispielsweise mit verschiedenen Höhenakzenten, im Sichtfeld von Fußgängern kann die subjektive thermische Wahrnehmung verbessern. Einen weiteren positiven Einfluss hat eine bewusste Gestaltung verschiedener Mikroklimata (Sonne, Halbschatten, Schatten) in urbanen Freiräumen. Diese ermöglichen Stadtbewohnern sich an die objektiven thermischen Bedingungen anzupassen und ihren individuellen Bedürfnissen entsprechende Freiräume aufzusuchen, die sie als behaglich oder thermisch komfortabel empfinden. Die Schaffung einer breiten Palette von sonnigen, halbschattigen und schattigen Plätzen in städtischen Umgebungen ermöglicht verschiedene Grade der Sonnenexposition. Das bedeutet, dass diese klimabewusste Gestaltung gleichzeitig oder mit variierenden täglichen (und jahreszeitlichen) Bedingungen unterschiedlichen Benutzerpräferenzen gerecht wird.

Im Hinblick auf Teilfrage 3 beschreibt diese Forschungsarbeit einen methodologischen Ansatz in vier Schritten, um empirisch fundierte und nützliche Gestaltungsrichtlinien für klimafreundliches Stadtgrün zu entwickeln. Die drei Schritte zur Generierung der Richtlinien, die in diese Forschungsarbeit durchgeführt wurden, sind (I.) Beobachtung und Monitoring, (II.) Generalisierung, (III.) Transformation und Verfeinerung. In Bezug auf die zwei Phasen dieser Forschung sind (I.) Beobachtung und Monitoring und (II.) Generalisierung Bestandteil der "Research for Design" - Studien (Kapitel 2, 3 und 4). Die (III.) Transformation und Verfeinerung dagegen ist Bestandteil der partizipativen Studie "Research Through Designing" (Kapitel 6). Der vierte Schritt (IV.) Spezifikation und Implementierung ist nicht Teil dieser Forschungsarbeit. Da die Implementierungsphase jedoch in der partizipativen RTD-Studie mittels Entwurfs-Workshops "simuliert" wurde, konnten die Erkenntnisse gesammelt und das generierte Wissen beschrieben werden, um die Nützlichkeit der Gestaltungsrichtlinien in der Entwurfspraxis zu erhöhen.

Im Hinblick auf die zentrale Forschungsfrage liefert diese Dissertation neun direkt anwendbare Gestaltungsrichtlinien für klimabewusstes Stadtgrün. Die hier präsentierten Richtlinien bieten Landschaftsarchitekten und Freiraumplanern Hilfsmittel, um städtische Hitzeprobleme zu vermindern und klimafreundliche städtische Freiräume zu entwerfen. Anstelle von *„Je grüner, umso besser"* plädiert dies Forschungsarbeit für den Slogan "*Je effektiver das Grün, desto besser (die Klimafreundlichkeit des Freiraumes)*". Effektives städtisches Grün bedeutet, dass für jeden spezifischen Standort die eine angemessene Gestaltung auf der Grundlage lokaler räumlicher, funktionaler und mikroklimatischer Bedingungen und der Verhaltensmuster der Benutzer und Bewohner getroffen wird. Hierzu zählt zum Beispiel, die Verfügbarkeit von Schatten während der heißesten Zeit des Tages (12:00 - 16:00), die Sicherung angemessener Wachstumsbedingungen und Bewässerung in den trockenen Sommerperioden für Straßenbäume oder das Ermöglichen ausreichender Luftzirkulation zwischen den Baumkronen über Straßen mit starkem Verkehr. Diese und andere Entwurfstipps und ein grundlegendes Wissen über Mikroklima-Prozesse können in der Praxis dazu beitragen, die allgemeinen Entwurfsrichtlinien für klimafreundliches städtisches Grün effektiv anzuwenden. Gute Analysen der lokalen mikroklimatischen Bedingungen (Besonnung und Wind) und vor allem die Kombination mit lokalen Kapazitäten für Wasserspeicherung, so dass ausreichende Bewässerung in trockenen Sommerperioden ermöglicht wird, sorgen für ein effektives hitzebeständig Stadtgrün.

Zukünftige Forschungen zur subjektiven thermischen Wahrnehmung müssen die Zusammenhänge zwischen städtischem Grün, thermischer Wahrnehmung und dem Verhalten der Menschen weiter untersuchen. Die Erforschung der Effekte von Stadtgrün auf objektive thermische Bedingungen muss auf weitere Städte ausgedehnt werden und auch andere Tages- und Jahreszeiten berücksichtigen. Im Hinblick auf die gewählte partizipative RTD-Methode kann die Erhöhung der Teilnehmerzahl in den Entwurfs-Workshops und die Verwendung umfangreicherer empirischer Daten zur Entwicklung der Richtlinien die Validität der Ergebnisse verbessern. Sobald Entwurfsrichtlinien angewandt und an konkreten städtischen Standorten realisiert wurden, können Folgestudien den tatsächlichen Effekt auf objektive thermische Bedingungen und subjektive Wahrnehmung aufzeichnen. Ein solches Monitoring liefert eine wachsende Quelle an empirischem Wissen zur Gestaltung von klimabewussten Freiräumen. Diese Art der Rückkoppelung kann die kontinuierliche Verbesserung und damit Qualität der Entwurfsrichtlinien auf lange Sicht gewährleisten.

Immer mehr Niederländische Städte betrachten die Anpassungen an den Klimawandel als eine wichtige Strategie für Stadtentwicklung und Stadterneuerung. Ähnliche Trends sind in vielen Städten weltweit zu beobachten. Sowohl Bürger als auch Unternehmer profitieren von städtebaulichen Verträgen, Planungsinstrumenten und Initiativen zum Erhalt und Ausbau von Stadtgrün, um so die Entwicklung von qualitativ hochwertigen, attraktiven und klimafreundlichen städtischen Gebieten zu fördern. Die Resultate dieser Forschungsarbeit, insbesondere die Entwurfsrichtlinien, können lokale und regionale Behörden dabei unterstützen; einerseits hiesige Klimaanpassungsstrategien zu entwickeln und anderseits um klimafreundliche urbane Freiräume zu gestalten. Die ersten Entwurfsrichtlinien für "*clever and cool*" klimabewusstes Stadtgrün sind verfügbar! Jetzt ist es an der Zeit, dass öffentliche und private Akteure diese Richtlinien anwenden, um angenehme und klimafreundliche urbane Freiräume zu schaffen.

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About the author

About the author

Wiebke Klemm is a professional landscape architect with a demonstrated history in policy, design and research oriented agencies. She graduated as landscape architect from TU Dresden, Germany in 2003. After her study she started her career as research assistant at the department of Landscape Architecture at the University of Wageningen. Her next position as a researcher was at the Netherlands Institute for Spatial Research, The Hague, where she contributed to studies monitoring urban and urban – rural developments to inform national policymakers. With the ambition to learn more about the design of outdoor urban spaces she switched to Bosch Slabbers garden- and landscape architects, The Hague, where she was involved as landscape architect in the design of urban spaces at various scale levels and contexts. The research through designing project 'Climate change adaptation in the city' (2010) in commission of the (former) Dutch Ministry of Housing, Spatial Planning and the Environment triggered her motivation to investigate into the role of urban green in the context of urban climate change adaptation. Subsequently she started her PhD research on climate-responsive urban green infrastructure at the department of Landscape Architecture at the University of Wageningen in 2011. The PhD research belonged to the Climate-Proof Cities project cluster of the Dutch 'Knowledge for Climate' programme. Throughout this research she combined her expertise and experience as professional landscape architect with new knowledge on urban micrometeorology to enhance climate-responsive urban designing, both in education and planning and design practice. The newly gained empirical knowledge was input in various BSc and MSc students projects that she supervised. She also shared the knowledge in guest lectures at universities and local authorities as well as in articles in newspapers and professional journals. She furthermore contributed to the urban design proposal 'On step beyond' that was submitted to the international architectural competition 'Re-Think Athens'. The project that was developed in a consortium of OKRA landscape architects, Mixst Urbanisme, WS Green Technology and Wageningen University, was awarded the 1st prize in 2014. For her efforts in knowledge dissemination she received the 'ECLAS Outstanding Doctoral Student Award 2014'. Parallel to her research activities, she worked as Quartermaster for a new research track 'Green Urban Planning and Design' within Wageningen University and as Coordinating Research Associate Green & Blue Living Labs at the Amsterdam Institute of Advanced Metropolitan Solutions (AMS). Currently she is applying her experience as a design professional and her scientific knowledge as senior policy advisor for outdoor spaces and sustainability at the municipality of The Hague and in her own consultancy firm UrbanGreenScape.

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The SENSE Research School declares that **Wiebke Klemm** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 57.9 EC, including the following activities:

Selection of SENSE PhD Courses

- Environmental research in context (2013)
- Research in context activity: 'Contribution to winning design proposal 'One step beyond' of the International Architectural Design Competition 'Re-Think Athens' (2012-2014)
- Workshop Valorisation of PhD-research in Climate-Science (2014)

Selection of Other PhD and Advanced MSc Courses

- Information Literacy, Information Literacy Team, Wageningen University (2011)
- Media training, Wageningen Graduate Schools (2013)
- Entrepreneurship in and outside science, Wageningen Graduate Schools (2014)

Selection of Management and Didactic Skills Training

- Supervising of three BSc. students and 11 MSc. theses in Landscape Architecture, the Laboratory of Geo-information Science and Remote Sensing , Nature Conservation and Plant Ecology Group, and the Environmental Technology group (2011-2016)
- Organisation of the BSc. design studio 'Urban climate in the Rivierenwijk in Utrecht' (2012-2013) and of the MSc. Atelier 'Green-Blue infrastructure for a resilient and healthy city' (2014)
- Guest lecturer for MSc courses at TU Delft and Utrecht University, and guest lecturer of both BSc. and MSc. courses at Wageningen University (2013-2018)

Selection of Oral Presentations

- *Impact of green infrastructure on residents' perceived thermal comfort.* BIOMET Human-Plant-Atmosphere conference in the 21th century, 2 December 2014, Dresden, Germany
- *Developing evidence-based design guidelines for climate-responsive green infrastructure - a methodological approach*. 9th International Conference on Urban Climate, 20 July 2015, Toulouse, France
- *Climate-responsive design of urban green.* Presentations at the Dutch municipalities of Utrecht (24 November 2014), The Hague (20 April 2016), and Amsterdam (9 May 2017)
- *Green infrastructure for climate-responsive urban environments – linking research and implementation in design practice*. Nexus Conference, 17 May 2017, Dresden, Germany
- *Keynote presentation: Green-Blue Living Labs approach in urban environments.* Dutch-German Circular Economy breakfast at IFAT, 17 May 2018, Munich, Germany

SENSE Coordinator PhD Education

Dr. Peter Vermeulen

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Colophon

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