Towards green design guidelines for thermally comfortable streets

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ABSTRACT: Creating thermally comfortable streetscapes is a rather new challenge for urban designers in The Netherlands and other countries with moderate climates. This is due to the lack of evidence based design guidelines. By combining research methods from micrometeorology and landscape architecture, we work on the development of such guidelines. For that purpose, we investigated physical and psychological impacts of street greenery on thermal comfort in three street types with varying vegetation density. Our preliminary results, based on a data analysis of one day of our measurement series, did not show significant cooling effects through greenery. Similar air temperatures were measured. In streets with large tree crowns on both sides, the mean radiant temperature (T_{mrt}) was 2.5 K lower than in streets without greenery. However, higher T_{mrt} values were found in streets with smaller trees and small front gardens. Interview results indicated that people perceived thermal conditions in streets with greenery to be more comfortable than in streets without greenery, even though they were hardly aware of this positive influence of street greenery on their thermal comfort. Furthermore, people significantly valued the presence of greenery in aesthetic terms. Our results suggest that street greenery contributes to both, improving physical and -more significantly- improving psychological thermal comfort and raising aesthetic appreciation of streetscapes.
Keywords: Thermal comfort; vegetation; street design; micrometeorological measurements; structured interviews

INTRODUCTION

Climate projections indicate that heat waves in the Netherlands are likely to become more frequent in the next decades. The consequences are especially felt in urban areas because of the existing Urban Heat Island (UHI) effect. UHI values up to 7 K in hot summer weather conditions were measured in Dutch cities [1]. These developments may lead to significantly higher temperatures in urban environments which, not only affect human health, but also thermal comfort of inhabitants in various urban spaces. Heat in urban streets has impact on pedestrians, but also indirectly on indoor thermal comfort.

Green infrastructure has the ability to effectively reduce urban heat and improve thermal comfort on various scale levels [2-4]. Greenery in urban streets, such as trees, ameliorates thermal conditions for pedestrians [3, 5-8]. Even though researchers indicate the positive effects of greenery on thermal comfort in streets, urban designers in The Netherlands and other countries with moderate climates lack applicable knowledge on how to design thermally comfortable streetscapes through street greenery.

Microclimatic conditions in street canyons are strongly determined by the street design that affects solar and long-wave radiation. Spatial parameters of the built configuration highly affect thermal conditions: the aspect ratio (height-to-width ratio or H/W ratio) [9-13], the orientation of the street canyon towards the sun [9, 12] and surface albedo [14]. In order to improve microclimatic conditions, variables like aspect ratio and street orientation, can hardly be influenced in existing urban morphologies without having to tear down and reconstruct many buildings.

Street greenery forms an alternative solution to mitigate radiation which can be implemented more easily within existing street canyons. Shading and evapotranspiration are the dominant processes of street greenery that affect the urban microclimate [2-4]. Solar heat gain and long-wave radiation from surfaces in the canyon are reduced through shading. That results in lower air and surface temperatures during daytime. Tree shading even has the ability to compensate influences of aspect ratio and street orientation on thermal conditions in a street [15]. Furthermore, plants convert solar into latent heat by evapotranspiration and thus temper the air temperature.

Even though the positive effects of street greenery on thermal conditions are generally known, the physical and psychological impacts of street greenery on thermal comfort were not assessed systematically yet. Only few studies investigated the magnitude of the cooling effect of street greenery through micrometeorological measurements. One example is the study of Shashua-Bar et.al [16] within -besides others- a street canyon with 60% tree crown coverage and heavy traffic in Tel-Aviv, Israel. They measured a maximum air temperature cooling effect of trees of 1.3 K at 15:00 h (local time). However, we do not know if the cooling would be the same in more temperate climate zones.

Studies on people's attendance and perception of urban spaces clearly document, that climate-responsive microclimate design can improve human thermal comfort [17]. However, the impact of street greenery on psychological thermal experience was never investigated [18].

In general, physical and psychological impacts of street greenery on thermal comfort were not assessed in such a way that they eventually yield useable design guidelines. To gain insight into the physical and psychological impact of street greenery on thermal conditions we conducted a study of streets with similar spatial layout, but differing amount of street greenery.

METHOD

For our investigations we chose nine streets with row houses in the Rivierenwijk neighbourhood, located in the city of Utrecht in The Netherlands (Fig. 1). We selected this type of residential streets, because they represent the most common street type in The Netherlands [19].

Table 1: Spatial characteristics of the nine investigated streets

Street type	Nr.	Street name	Aspect or h/w ratio	Azimuth	Estimated greenery cover		
					Tree	Low veg.	In total
			(-)	(°)	(%)	(%)	(%)
Without Greenery	1A	Alblasstraat	0.50	203	0.0	0.0	0.0
	1B	Soestdijkstraat	0.60	195	1.5	0.0	1.5
	1C	Noordeindestraat	0.60	196	0.0	0.0	0.0
		average	0.57	198	0.5	0.0	0.5
With trees	2A	Berkelstraat	0.50	174	8.7	0.0	8.7
	2B	Vaartscherijnstraat	0.40	195	47.2	0.0	47.2
		average	0.45	185	28.0	0.0	28.0
With trees combined with font gardens	3A	Verlengde Hoogravensweg	0.43	196	7.9	24.3	32.1
	3B	Snipstraat	0.44	209	11.1	9.9	21.0
	3C	Sternstraat	0.44	208	12.9	12.3	25.2
	3D	Duikerstraat	0.44	208	14.9	11.7	26.7
		average	0.44	205	11.7	14.5	26.2

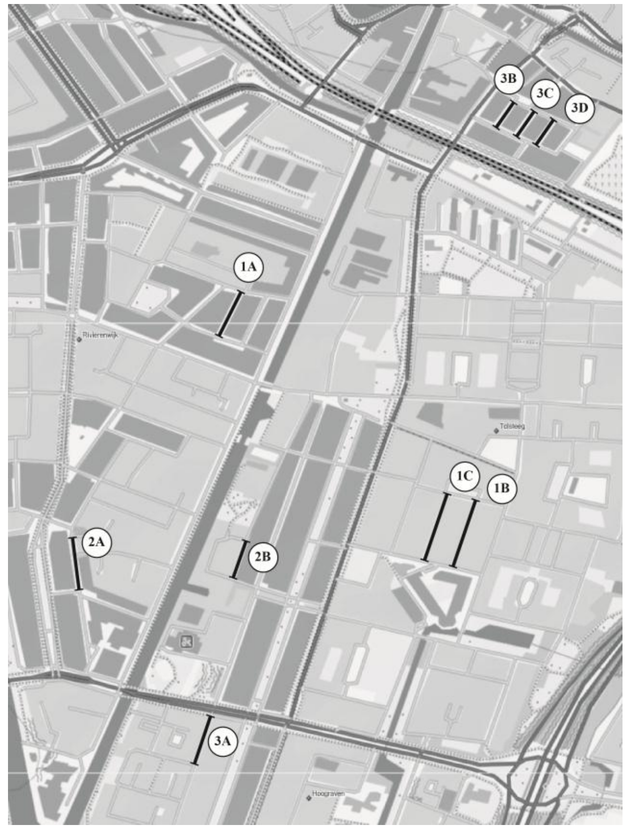
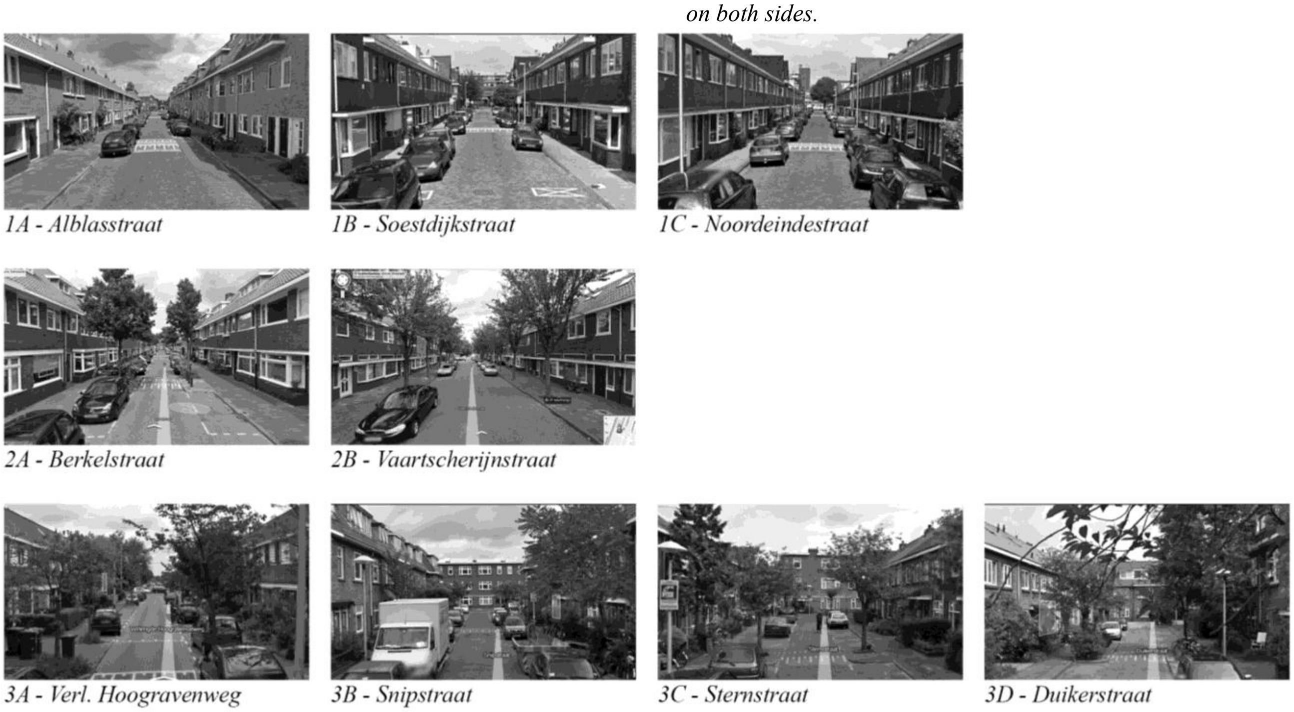


Figure 1: Location of the nine streets located in the Rivierenwijk neighbourhood

Figure 2: The examined street types: 1. no greenery, 2. street trees on both sides, 3. street trees combined with front garden on both sides.



All nine streets were characterised by a similar geometric configuration (Table 1, Fig. 2), including an average aspect ratio of 0.48 (SD 0.073), a northeast-southwest street orientation (average azimuth of 198°, SD 10), ground surface materials of brownish bricks, greyish tiles and facades of reddish bricks. The streets were divided into three types, depending on their present amount of street greenery: 1. no greenery, 2. street trees on both sides and 3. streets trees combined with front gardens on both sides. Trees in street type 2 had an average height of 10 m, crown diameter of 5 m (crown coverage of entire street canyon 8.7%) and 7 m (crown coverage of entire street canyon 47.2%). Trees in street type 3 had an average height of 6 m, a crown diameter of 3-5 m (crown coverage of entire street canyon 11.7%). We did not consider very small beds of low vegetation next to facades in street type 1 and 2 as their size of a few tiles is too small for considerable impact.

Micrometeorological measurements

We conducted continuous mobile measurements in July and August 2012 using two cargo-bicycles [20] along a trajectory covering all nine streets. We cycled in the middle of the streets.

Figure 3: Cargo-bicycle equipped with micrometeorological measurement sensors

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 (Fig. 3). Wind speed measurements were corrected for bicycling speed. Data were recorded every second and combined with location data from a GPS device. We collected data on eight days mainly between 9:00 and 15:00 UTC. On two days, the local weather conditions were variable and partly cloudy with average daily temperatures of 15.2°C and 17.2°C. The other six days had fair the weather conditions with clear skies and an average daily temperature ranging from 21.0°C to 27.6 °C.

Additionally, solar radiation was measured on the first five measurements days at a fixed point along the traverse using a Decagon QSO-S Photosynthetically Active Radiation (PAR) sensor.

Interviews

Along with the meteorological measurements we conducted structured interviews with pedestrians in the nine selected streets on eleven days from June to September 2012. In total, 106 randomly selected pedestrians were interviewed. Respondents represent both sexes and all ages (without children) and were well acquainted with the specific street in which they were interviewed. Respondents thus represent the inhabitants of the chosen streets or the immediate vicinity as there are mainly people leaving or reaching home within residential streets. 87 persons did not want to take part in the interview for various reasons.

Respondents were asked about their momentary perception of the microclimate (e.g. temperature, sun, wind, humidity) at that specific place. Also people's long-term perception of the microclimate was investigated by asking them about zones they find thermally comfortable or uncomfortable within that specific street. The latter was documented on a so-called mental microclimate map [21]. Furthermore, respondents were asked to assess variables of the street layout (e.g. aspect ratio, profile distribution and materials) and variables of greenery (e.g. distribution within the streets and amount of trees or bushes).

Data analyses

We analysed the micrometeorological data in five steps. First, we refined the whole dataset to the data that was recorded within the nine streets. Then we filtered out all measurement data with wheel speed below 1m/s to exclude moments that the cargo-bicycle stood still. Consequently, only data-sets which were unique for one measurement point were included in the further analyses. This way we minimized measurement uncertainties.

Second, we arranged all street data according to the location and the time of entering the street canyon with the cargo-bicycle to time frames, e.g. 09:00-10:00 UTC, 10:00-11:00 UTC etc. This way, we got an overview of the daily number of completed measurements within all streets; where 'completed' means one measurement in each of the nine streets within one timeframe. Our completed measurement data mainly represents a time window of higher solar altitude (see Fig. 4).

Third, we used air temperature (T_{air}), humidity (h), wind speed (u) and solar radiation measurements to calculate mean radiant temperature (T_{mrt}) and PET (physiological equivalent temperature) using the human thermal energy model RayMan [22, 23]. T_{mrt} is an important parameter for micrometeorological conditions on sunny weather conditions [23, 24] and represents human radiation load.

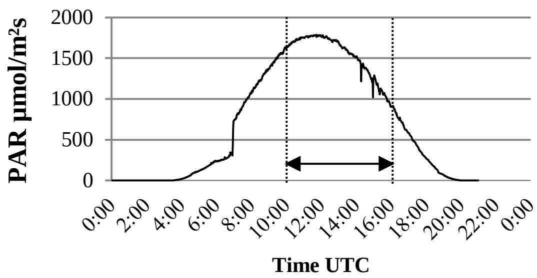


Figure 4: Solar radiation measurements, 26 July 2012 Utrecht (The arrows represent the most common hours of micrometeorological measurement during the measurement campaign.)

Fourth, we calculated the average values of T_{air}, h, u, T_{mrt} and PET to describe the microclimatic conditions for every time window in each street and, subsequently in each street type. Finally, we compared the conditions between the three street types.

Data analysis of the structured interviews was performed using Excel. We arranged all responses according to the type of street where the interview was conducted. Then we calculated relative frequencies for every single answer on the questionnaire for each street type. This way, we were able to compare responses between the three street types.

Finally, we compared the micrometeorological measurement results with the evaluations and subjective perception of the interviewees.

RESULTS/ DISCUSSION

The preliminary results presented here are based on the measurements of 18 August 2012, a (tropical) hot and sunny day. Compared to normal conditions in that period with a maximum air temperature of 23°C and a relative duration of sunshine of 43%; values of 32°C and 78% were recorded on that day [25]. In the field we measured maximum PET values up to 45°C (15:00 UTC) which according to Matzarakis [26] represents extreme heat stress.

Our measurement results do not show significant differences between the street types, based on averaged measurements of air temperature (T_{air}), mean radiant temperature (T_{mrt}) and physiological equivalent temperature (PET) (Fig. 5). The results did not show large cooling effects through greenery. Air temperatures were rather similar which is not in line with measured cooling effects of street trees in Tel-Aviv, Israel [16].

Our result could be explained by several aspects: First of all, the differences in the amount of present greenery in the investigated streets was possibly too small (Table 1); only one street 2B Vaartscherijnstraat, was characterized by a considerable tree crown cover (47,2%). Second, the measurement campaign was set-up in an existing neighbourhood with - despite of a careful selection of streets – small differences in the built configuration. We did not correct for aspect ratio and street orientation neither for albedo. We re-analysed the data excluding the street 2A, Berkelstraat, because of large variance in street orientation and tree crown cover compared to street 2B, Vaartscherijnstraat (Table 1); but we did not find significant differences in the re-analyses. Third, as the streets without greenery (type 1) in average are more narrow, earlier shading by buildings in the afternoon decreases radiation within the canyons (see error bars Figure 5). Fourth, obviously the continuous mobile measurements cause a time delay. Uncertainties are involved as we were not able to measure at the same time in every street.

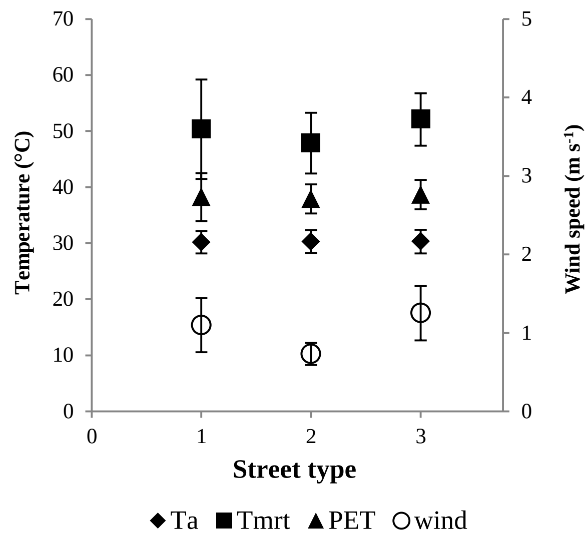


Figure 5: Micrometeorological conditions measured between 9:00 and 16:00 (UTC). Horizontal axis represents street types 1. without greenery, 2. with trees, 3. with trees combined with front gardens (error bars represent one standard deviation), 18 august 2012

However, small differences in Tair, T_{mrt} and PET were found between the three street types. Streets with trees, especially street 2B Vaartscherijnstraat, were more thermally comfortable than the other types due to considerable trees canopies that lowered radiation fluxes. Average T_{mrt} values from streets with the largest tree crown cover (type 2) were 2.5 K lower than streets without greenery (type 1). However, streets with trees and front gardens were 1.8 K warmer (type 3).

The contradiction may be related to the small size of street trees in type 3 which resulted in similar radiation input in both types of streets. The streets without greenery (type 1) had an average aspect ratio of 0.57 in contrast to an average aspect ratio of 0.44 for streets with trees combined with front gardens (type 3). The tree canopy coverage of 15% in street type 3 made the street smaller. In fact this is in line with the previous study of Shashua-Bar [15], which considered tree shading a compensative factor for lower aspect ratios.

Further analysis of the measurement data is necessary to gain more in-depth knowledge of thermal circumstances in the investigated street canyons and the underlying parameters.

In contrast to the measurement analyses, the interview results indicated a significant relationship between the momentary perception of the microclimate and the existing amount of greenery in a street. Respondents generally perceived momentary thermal conditions in streets with greenery as more comfortable than in streets without greenery. We draw this conclusion from both, the evaluation of momentary, single parameters, e.g. temperature, sun, humidity and wind, and the evaluation of the momentary microclimate in general (Fig. 6).

Interestingly, even though people evaluated momentary microclimates more comfortable in streets with greenery, they were hardly aware of the positive influence of street greenery on their thermal perception. This insight is based on the analyses of the mental maps, where only 15% of the people attributed their thermally comfortable zones to the presence of green. At the same time, 37% of the respondents replied that their zones of comfort and discomfort within the street canyon would depend on the time of the day. This indicates that people are aware of their choices to walk on the sunny or the shady side of the street and confirms earlier studies [27].

Figure 6: Evaluation of the momentary microclimate conditions (based on n=106 on 11 days in summer 2012)

People significantly valued the presence of greenery in aesthetic terms, independent from microclimatic aspects (Fig. 7). When asked for the evaluation of the green design of the street, 77% of the respondents in streets with street trees combined with front gardens qualified the design as pleasant; whilst 24% of the respondents in street without greenery qualified the design as pleasant.

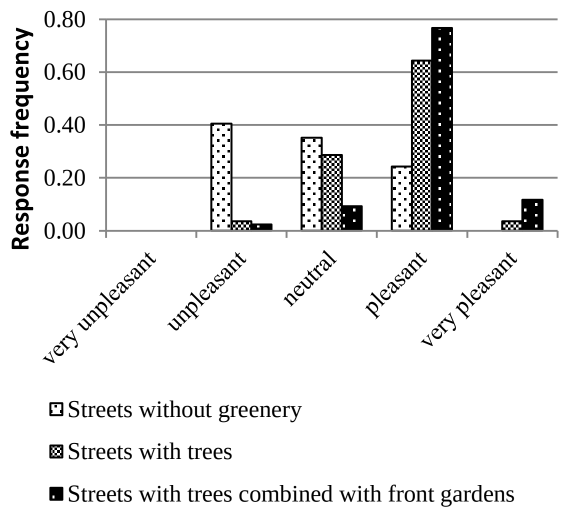


Figure 7: Evaluation of the green street design (based on n=106 on 11 days in summer 2012)

When combining micrometeorological measurement and interview results, our preliminary findings are remarkable. The streets with trees combined with front gardens on both sides are found to be the most thermally comfortable street type by interview respondents. This is in contrast with our preliminary physical measurement results. Based on this findings, we assume that other aspects, such as aesthetical appreciation, influence human thermal comfort at street level.

CONCLUSIONS

Our preliminary results suggest that street greenery improves physical and -more significantly- psychological thermal comfort on warm summer days. Results of our empirical study in the moderate climate of the Netherlands, suggest that shading though tree crown cover compensate aspect ratio influences and that large tree covers (47%) lower mean radiant temperature. This is in line with similar research in warmer climate regions.

Interview results indicate that people in general experience thermal conditions as more comfortable in streets with greenery than in streets without greenery. Additionally, we found that street greenery raises aesthetic appreciation of streetscape – independent from microclimatic aspects. Further research should investigate in the influence of aesthetic appreciation of urban spaces on people's thermal comfort more in depth.

By giving insight into physical and psychological impacts of street greenery on human thermal comfort, our findings contribute to develop design guidelines for thermally comfortable streets. Furthermore, they can be used for strengthening urban planning policies to implement street greenery in existing and new neighbourhoods.

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