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Comparison of microclimate measurements and perceptions as part of a global evaluation of environmental quality at neighbourhood scale

A. Lemonsu¹ · A. Amossé^{1,2} · D. Chouillou² · N. Gaudio³ · S. Haouès-Jouve² · J. Hidalgo² · J. Le Bras¹ · D. Legain¹ · S. Marchandise² · B. Tudoux²

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Abstract

The EUREQUA project raises the issue of the definition and evaluation of the environmental quality of neighbourhoods. The approach consists of integrating and cross-referencing observable data characterising the physical environment and people's perception of their quality of life. The study area is a neighbourhood in Toulouse (France) with high social and typomorphological diversity, subject to noise and air pollution nuisances. Three 3-day field campaigns were organised in January, April, and June 2014. Instrumented and commented walks took place three times per day. For each one, measurements of physical environmental parameters and surveys were performed simultaneously at six locations in the neighbourhood. The study focuses on microclimate and thermal comfort issues. It aims to compare in situ meteorological data of air temperature, humidity, wind speed, and mean radiant temperature, with quantitative results rating human perception of heat, humidity, wind, and thermal comfort. The variability in perception and measurements is mainly driven by seasonal effects, especially for heat and humidity, and, to a lesser extent, for wind. Wind perception and measurement also vary spatially, thus highlighting site effects. Linear models indicate a positive link between heat perception and mean radiant temperature, as well as between wind perception and mean and standard deviation of wind speed (with a higher sensitivity of people to wind under winter climate conditions). Finally, it is found that perception of thermal comfort is only slightly linked to the different microclimate dimensions, and is rather driven by other appreciation factors and emotional criteria related to the general environmental quality of the study area.

Keywords Outdoor thermal comfort · Urban climate · Micrometeorological measurements · Perception surveys · Cross-analysis

Introduction

Within the framework of urban planning or urban requalification projects, participative approaches, especially during the diagnostic phase, can raise inhabitants' and users' awareness of environmental issues and better meet their expectations in improving their living environment. As thermal comfort is an important dimension in evaluating

environmental quality of public spaces, it should motivate a climate-sensitive planning approach in urban design (Eliasson 2000). It can significantly influence the level of frequentation of these places and the behaviour and activity of people there (Thorsson et al. 2004; Eliasson et al. 2007; Lin 2009). This concept of thermal comfort integrates a set of climate sensations related to the perception of heat, wind, humidity, or sunlight (Andrade et al. 2011).

Several biometeorological indices were developed in recent years to describe the human sensation of thermal comfort through the integration of different environmental and biophysical parameters (Fanger 1972; Höppe 1999; Matzarakis et al. 1999; Fiala et al. 2012; Parsons 2014). However, the perception of people in a real outdoor environment is influenced by many factors, making it very complex to predict, meaning that these indices are not always suitable (Lin 2009; Lin et al. 2011; Makaremi et al. 2012). In response, several experimental studies have been carried out to combine surveys about human perception of climate dimensions with

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in situ measurements of micrometeorological variables, with the aim of studying how people are influenced by local-scale environmental conditions (Nikolopoulou et al. 2001; Stathopoulos et al. 2004), and how measurements can help to provide a realistic picture of people's perceptions and preferences (Cheng et al. 2012; Kántor et al. 2012; Maras et al. 2016). The results vary depending on the study areas and periods of time, cities, regional climate, and cultural characteristics (Nikolopoulou and Lykoudis 2006; Eliasson et al. 2007; Thorsson et al. 2007a; Ng and Cheng 2012; Lin et al. 2014). The methodological choices for both the experimental protocol and data analysis vary from one study to another (Kántor et al. 2012; Johansson et al. 2014), so the obtained results and conclusions can also differ.

The present study examines the link between the perception and measurement of meteorological conditions through the analysis of experimental data combining surveys and measurements. From data collected in a single neighbourhood in the city of Toulouse (France), but in several outdoor spaces and at different seasons, we specifically investigate to what extent people are sensitive to local variations in temperature, humidity, and wind conditions from one place to another, how this can influence their perception of thermal comfort and, finally, if other perceptive dimensions come into play. This is part of a more holistic approach that aims to define and qualify environmental quality at the neighbourhood scale, especially for the purpose of enriching the diagnostic phase in urban requalification programs, and ultimately providing a simplified protocol to stakeholders in charge of urban development. Consequently, the choice of neighbourhood, outdoor spaces, and implemented protocol was motivated by these more general objectives. The “Materials and methods” section presents first the study area and experimental protocol of commented and instrumented walks, then the statistical methods used for data analysis. The “Results” section presents the results in three steps: first, the investigation of spatial and temporal influences on microclimate perceptions and micrometeorological measurements; second, the analysis of heat, humidity, and wind perception in relation to micrometeorological measurements; third, the specific analysis of thermal comfort perception and its determinants. Before the conclusion, we discuss the experimental protocol, addressing its potential limitations as well as its innovative aspects.

Materials and methods

Study area and experimental protocol

The experimental campaign was carried out in a neighbourhood of the city of Toulouse (France). Located between the southern branch of Toulouse's ring road and a major traffic road (the Seysses road), the neighbourhood and its

population are subject to significant air and noise pollution. It is highly diversified both in terms of (i) socio-demographic and socio-economic characteristics of population and (ii) urban typologies (Fig. 1). Four different areas comprise the neighbourhood: according to the architectural classification proposed by Tomay et al. (2017) for French cities, the Tabar and Bordelongue areas are defined as “continuous row and mid-rise”, Seysses towers residence as “discontinuous row and mid-rise”, and Papus as “semi-detached low-rise”. These typologies correspond, respectively, to the generic local climate zones (LCZ, Stewart and Oke 2012) “compact mid-rise”, “open mid-rise”, and “open low-rise”.

Three intensive observational periods (IOPs) of three consecutive days each were organised in 2014, in winter (28–30 January), spring (8–10 April), and summer (17–19 June). During these IOPs, instrumented and commented walks took place three times per day at 10 am, 4 pm, and 7 pm (local time). The walk followed a predefined itinerary of about 2 km and stopped at six specific locations (hereafter called stop points and referred from T1 to T6, see Fig. 1) where micrometeorological measurements and surveys were conducted simultaneously (Fig. 2, right). The stop points were selected based on an initial stage of diagnosis (Berry-Chikhaoui et al. 2017) during which inhabitants identified places they liked or avoided. They were also characterised by different typomorphologies (Fig. 1). The first two stop points were in the Tabar neighbourhood: T1 was a public space with sandy soil and some trees, surrounded by buildings; T2 was on a roundabout in a more open area close to the ring road and very seldom frequented; T3 was at the foot of high towers (Bordelongue) along the Seysses road; T4 was in the heart of a residence characterised by high towers; T5 was along the Seysses road close to a busy intersection; and T6 was in a small street in the Papus residential neighbourhood.

The experimental protocol was designed based on the expertise and needs of each scientific discipline involved in order to address both disciplinary and interdisciplinary issues (Gauvreau et al. 2016). In addition to the results presented here, the questionnaire data on local environment appreciation were analysed in light of the socio-demographic characteristics of the respondents' corpus. The continuous recording of micrometeorological variables along the walks also made it possible to characterise the microclimate spatial variability for different time periods of the day and year (Carrissimo et al. 2015; Le Bras et al. 2015).

Questionnaire-based survey and corpus of participants

The survey consisted of a list of questions related to perceptions of the local environment (Table 1). For the microclimate, people were first asked to evaluate thermal comfort (P_comfort) at the present place based on a multiple choice answer scale ranging from “not comfortable” to “very

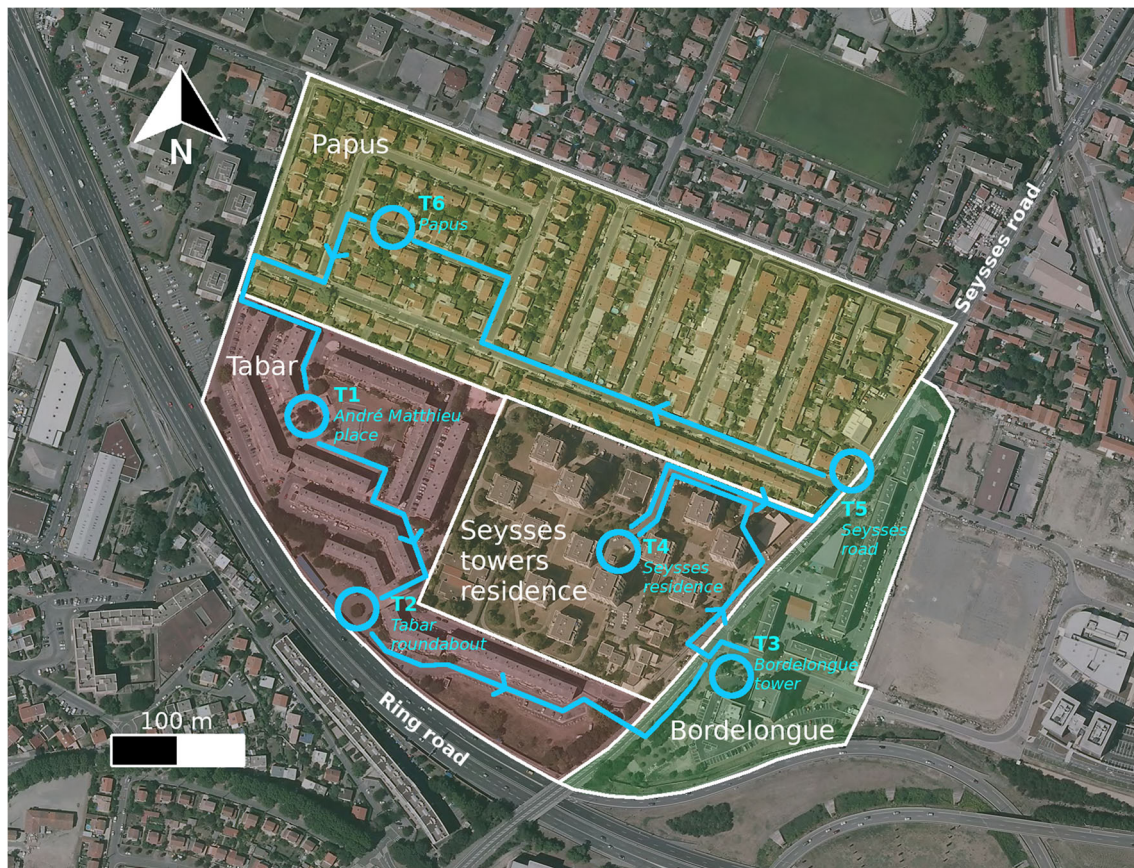


Fig. 1 Aerial photo of study area. The neighbourhoods that comprise the area are indicated by semi-transparent polygons. The predefined itinerary and stop points (T) are indicated by the thick blue line and blue circles

comfortable”. People were then questioned about the microclimate factors influencing their evaluation: heat (P_heat), humidity (P_hum), and wind (P_wind). For each additional factor, four levels of evaluation were proposed, as for thermal

comfort. For instance, heat perception could be evaluated as “cold”, “cool”, “warm”, or “hot”. These qualitative evaluations were converted into quantitative data by applying a rating from + 1 to + 4.

Table 1 Ensemble of dimensions about perceptions of environmental quality asked in the survey at each stop point

		Multiple choice answers (and rating)			
Code	Variable	(+ 1)	(+ 2)	(+ 3)	(+ 4)
Microclimate dimension perceptions					
P_comfort	Thermal comfort	<input type="checkbox"/> Uncomfortable	<input type="checkbox"/> Not very comfortable	<input type="checkbox"/> Comfortable	<input type="checkbox"/> Very comfortable
P_heat	Heat	<input type="checkbox"/> Cold	<input type="checkbox"/> Cool	<input type="checkbox"/> Warm	<input type="checkbox"/> Hot
P_wind	Wind	<input type="checkbox"/> Calm	<input type="checkbox"/> Quite calm	<input type="checkbox"/> Quite windy	<input type="checkbox"/> Windy
P_hum	Humidity	<input type="checkbox"/> Dry	<input type="checkbox"/> Quite dry	<input type="checkbox"/> Quite wet	<input type="checkbox"/> Wet
Other perceptive dimensions					
P_airq	Air quality	<input type="checkbox"/> Very poor	<input type="checkbox"/> Poor	<input type="checkbox"/> Good	<input type="checkbox"/> Very good
P_sound	Sound level	<input type="checkbox"/> Very quiet	<input type="checkbox"/> Quiet	<input type="checkbox"/> Loud	<input type="checkbox"/> Very loud
P_maint	Maintenance level	<input type="checkbox"/> Not maintained	<input type="checkbox"/> Poorly maintained	<input type="checkbox"/> Maintained	<input type="checkbox"/> Very well maintained
P_beau	Beauty level	<input type="checkbox"/> Ugly	<input type="checkbox"/> Quite ugly	<input type="checkbox"/> Quite beautiful	<input type="checkbox"/> Very beautiful
P_secur	Security level	<input type="checkbox"/> Unsafe	<input type="checkbox"/> Quite unsafe	<input type="checkbox"/> Quite safe	<input type="checkbox"/> Very safe
P_overall	Overall appreciation	<input type="checkbox"/> Not at all	<input type="checkbox"/> Quite no	<input type="checkbox"/> Quite yes	<input type="checkbox"/> Absolutely

Other perceptive dimensions were evaluated during the surveys with the same rating range (Table 1). They include two other dimensions of the physical environment: sound level (P_sound) and air quality level (P_airq), as well as other aspects of environmental quality: an overall appreciation of the place (P_overall), and the evaluation of level of maintenance (P_maint), beauty (P_beau), and sense of security (P_secur). A total of 185 voluntary participants were involved in the surveys with 68, 59, and 58 participants for January, April, and June IOPs, respectively.

Micrometeorological measurements

The sensors for micrometeorological measurements were installed on a shoulder-mounted portable structure (Fig. 2, left) with an associated GPS recorder. Air temperature, relative humidity, and wind speed were dynamically measured, as well as the grey globe temperature used to compute the mean radiant temperature (T_{mrt}) according to the following formulation (Thorsson et al. 2007b):

$$T_{mrt} = \sqrt[4]{\left[(T_g + 273.15)^4 + \frac{1.10 \cdot 10^8 \cdot U_a^{0.6}}{\varepsilon \cdot D^{0.4}} (T_g - T_a) \right]} - 273.15$$

where T_g is the grey globe temperature (°C), T_a is the air temperature (°C), U_a is the wind speed (m s⁻¹), ε is the globe emissivity (–), and D is the globe diameter (m). For the grey globes, the emissivity is 0.97 and the diameter is 40 mm.

During the walks, meteorological measurements were recorded near the respondents at each stop point for periods of 10–15 min (Fig. 2, right). The temporal averages of air temperature (M_tair, °C) and relative humidity (M_hum, %) were computed over the time period spent at each stop point, as well

as temporal average and standard deviation of wind speed (M_wind and M_windsd, m s⁻¹). Mean radiant temperature (M_tmrt, °C) was calculated according to M_tair, M_wind, and grey globe temperature measurements.

Statistical methods for data analysis

Data were analysed using R.3.2.3. software (R Core Team 2015). Two principal component analyses (PCA) were performed using the ade4 R package (Dray et al. 2007) in order to explore the effect of seasonality and sites (stop points) on micrometeorological measurements and microclimate perceptions. Then, a co-inertia analysis (CIA) was carried out between the two PCA to investigate which microclimate measurements and perceptions are correlated, considering that the CIA provides co-inertia axes with the maximum possible covariance with variables in each of the two data sets (measurements and perceptions). The strength of co-inertia is assessed using the RV coefficient, which is the coefficient of correlation between the two datasets, ranging from 0 to 1 (high correlation). Then, simple linear regressions were used to analyse the links between each perception (P_heat, P_wind, P_hum, P_comfort) and each measurement indicator (M_tair, M_tmrt, M_wind, M_hum) independently by IOP in order to remove the seasonal effect and compare trends from one period to another.

Results

Site and seasonal effects on microclimate perceptions and measurements

For micrometeorological measurements, 55 and 36% of the data variability are respectively explained by the first two axes

Fig. 2 Description of the portable structure for micrometeorological measurements (left) and photograph of the experimental protocol used during instrumented and commented walks (right)



of the PCA (Fig. 3a). Axis 1 highlights an opposition between thermal variables (M_{tmrt} , M_{tair}) and M_{hum} . Thus, this first axis shows a seasonal effect with a gradient from June (high temperatures and low M_{hum}) to January (low temperatures and high M_{hum}). Axis 2 is driven only by wind variables (M_{wind} , M_{windsd}) and displays a site effect: the stop points are distributed along the diagonal defined by wind measurements and are divided into two groups corresponding to locations more (T2-T3-T4) or less (T1-T5-T6) exposed to wind.

For microclimate perceptions, 57 and 21% of the data variability are respectively explained by the first two axes of the PCA (Fig. 3b). Along axis 1, P_{heat} and $P_{comfort}$ are positively associated but opposed to P_{wind} and P_{hum} . Therefore, as for micrometeorological measurements, the first axis catches the seasonal effect on perceptions, with January IOP perceived as windier and more humid than June, with April being intermediate. June is also perceived as being warmer and more comfortable. Stop point dispersion is much higher following axis 2 along a diagonal opposing P_{wind} and $P_{comfort}$. Stop points T2, T3, and T5 are systematically evaluated as windier sites and so are relatively uncomfortable, whereas T1 and T6 are perceived as calmer, with T4 as an intermediate point with variations depending on IOP.

Therefore, whether for micrometeorological measurements or microclimate perceptions, data are first influenced by general meteorological conditions (seasonal effect), as already shown in previous studies (Lin et al. 2011; Maras et al. 2016; Chow et al. 2016), and then, at a secondary level, by the site effect, i.e. by the heterogeneity of the urban landscape (e.g. land cover properties, morphological parameters, materials) characterising the six stop points. Seasonal distinctions are made in the same way in both PCA, i.e. June and January IOPs are opposed, with April IOP being intermediate. Stop points are also distinguished in the same way in both PCA within a given IOP, according to wind, except for T4 and T5, for which it is assumed that factors other than microclimate are involved.

These findings are reinforced by the co-inertia analysis (CIA) performed between the two PCA related to perceptions and measurements (Fig. 3c). CIA highlights a strong correspondence between the two datasets ($RV = 0.46$), and measurements and perceptions overlap for the three microclimate dimensions (humidity, temperature, wind). The two axes are opposing and regroup the same sets of microclimate dimensions as highlighted above, with a predominant seasonal effect and a site effect explained mainly by wind measurements and perception.

The net predominance of seasonal effects for both micrometeorological measurements and microclimate perceptions could hide and weaken more subtle relationships between measurement and perception as a result of the differences between experienced places at the neighbourhood scale.

Consequently, data are further analysed by considering IOPs separately.

Cross-analysis of microclimate perceptions and micrometeorological measurements

Variation in heat perception (P_{heat}) between IOPs

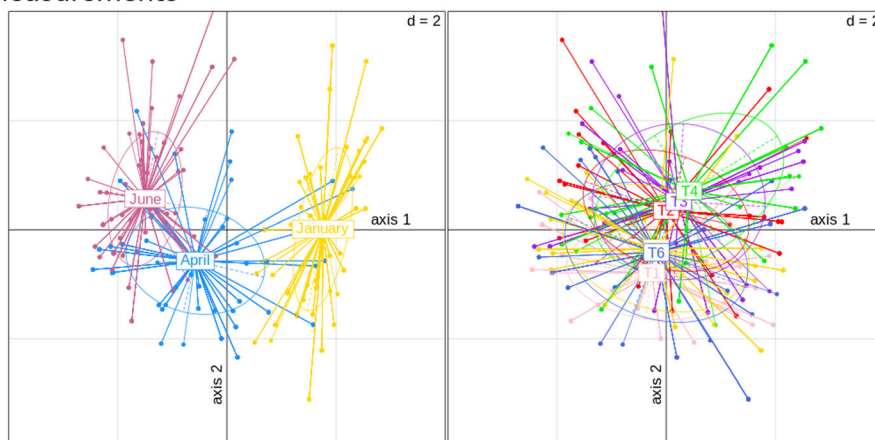
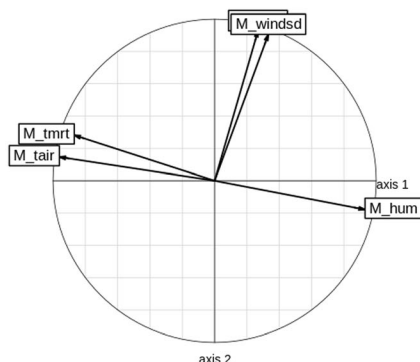
P_{heat} is positively linked to M_{tair} and negatively linked to M_{hum} in April and June only (Table 2), whereas it is positively linked to M_{tmrt} in all three periods but with different trends. The link is largely higher in April ($R^2 = 0.34$, p value $< 10^{-4}$). The slope of the regression is high, which translates as an important variability in P_{heat} associated with a large range of M_{tmrt} (Fig. 4a). For January and June, the regression slopes are lower and comparable, which corresponds to less variation in $Tmrt$ during each IOP. Nonetheless, an offset is observed between P_{heat} in January and June. For M_{tmrt} between 20 and 30 °C, P_{heat} varies from a rather cold sensation in January to a rather warm sensation in June. This difference can be related to the influence of other environmental parameters (e.g. M_{tair} and M_{hum} that are significantly lower and higher, respectively, in winter).

Variation in wind perception (P_{wind}) between IOPs

Linear regressions indicate a strong link between P_{wind} and M_{wind} whatever the IOP considered (R^2 of 0.68 for January, 0.65 for April, and 0.70 for June, Table 2). The regression slope is almost twice as large in April as in January and June (Fig. 4b), again because meteorological conditions evolve more during this period, along with wind sensation. The two regression models are comparable in January and June, with parallel regression lines but still an offset associated with a difference in P_{wind} . According to the linear regression equations, the transition M_{wind} between negative and positive evaluations of the wind ($P_{wind} = 2.5$) increases from 0.79 m s⁻¹ in January to 1.08 m s⁻¹ in April and 1.44 m s⁻¹ in June. Participants estimate conditions to be “windy” starting at a lower measured wind speed in winter than in summer. Therefore, individuals are more sensitive to the wind under winter climate conditions. P_{wind} is influenced by other climate parameters with a seasonal signature (colder and wetter conditions in winter) and translates into a stronger feeling of discomfort than under summer climate conditions. These results are in agreement with previous studies. Ventilation can be perceived as pleasant in warm weather, as shown by Spagnolo and de Dear (2003): preference votes for “more air movement” increase with operative temperature. Inversely, colder temperatures lead to negative sensitivity to wind, as noted in Stathopoulos et al. (2004), Westerberg et al. (2006), and Cheng et al. (2012).

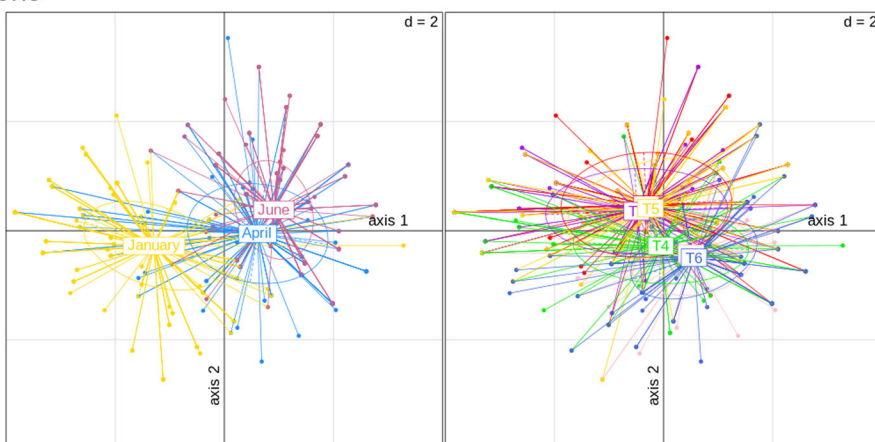
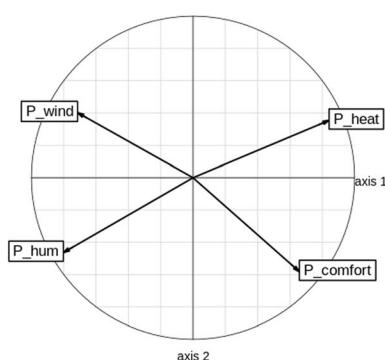
(a) PCA of micrometeorological measurements

%Inertia = 54.53 (axis 1) + 36.28 (axis 2)



(b) PCA of microclimate perceptions

%Inertia = 57.43 (axis 1) + 21.00 (axis 2)



(c) CIA of micrometeorological measurements and microclimate perceptions

RV = 0.46

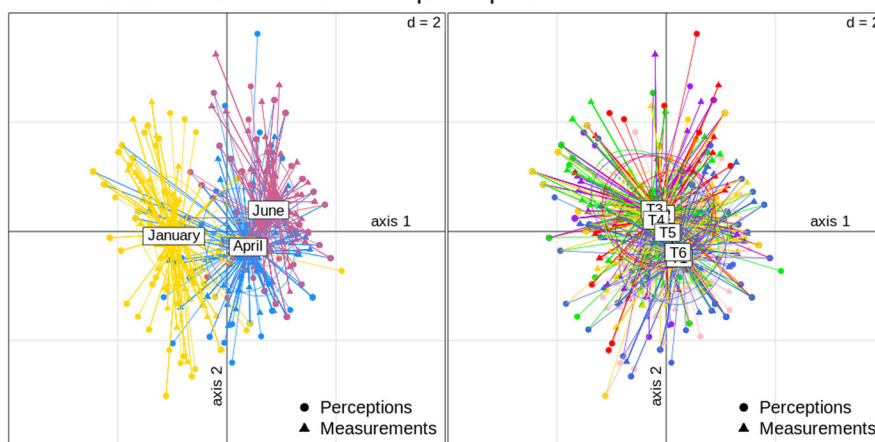
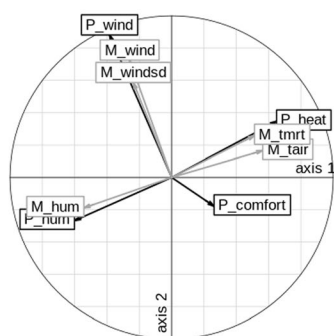


Fig. 3 Principal component analysis (PCA) of micrometeorological measurements (a) and microclimate perceptions (b), and co-inertia analysis (CIA) between both (c). For each analysis, results are presented

as form of correlation circles (left), and by distinguishing IOPs (middle) and stop points (right). For CIA, perceptions (circles) and measurements (triangles) are overlapped

Variation in humidity perception (P_hum) between IOPs

P_hum and M_hum are significantly and positively linked in January and April but not in June (Table 2). During this summer period, people are not sensitive to variations in M_hum (which remains less than 60%), whereas in April and January,

it seems that people better perceive these variations, which are also associated with higher values of M_hum (up to 80% in winter). Similarly to M_heat and M_wind compared to M_tair and M_wind, respectively, the trends differ between January and April (Fig. 4c). The linear regressions between P_hum and M_hum for the two periods have comparable slopes but

Table 2 Linear regression equations of perception dimensions (Y) as functions of the different microclimate measurements (X) for January, April, and June IOPs

		Variable	Equation	R^2	F	P
P_heat	January	M_tmrt	$Y = 0.013X + 1.417$	0.03	10.20	0.0016
		M_tair	$Y = 0.069X + 1.546$	0.25	79.88	< 0.0001
	April	M_tmrt	$Y = 0.031X + 1.920$	0.31	110.91	< 0.0001
		M_hum	$Y = -0.019X + 3.759$	0.28	97.30	< 0.0001
		M_tair	$Y = 0.043X + 2.029$	0.06	15.37	0.0001
		M_tmrt	$Y = 0.013X + 2.622$	0.07	16.20	< 0.0001
		M_hum	$Y = -0.009X + 3.449$	0.03	7.53	0.0065
P_wind	January	M_hum	$Y = -0.019X + 4.012$	0.03	9.51	0.0022
		M_wind	$Y = 0.802X + 1.865$	0.21	77.62	< 0.0001
		M_windsd	$Y = 1.467X + 1.918$	0.11	37.37	< 0.0001
	April	M_tair	$Y = -0.032X + 2.588$	0.04	10.35	0.0015
		M_hum	$Y = 0.011X + 1.489$	0.07	17.84	< 0.0001
		M_wind	$Y = 1.265X + 1.128$	0.26	85.29	< 0.0001
		M_windsd	$Y = 2.819X + 0.935$	0.20	60.11	< 0.0001
	June	M_tair	$Y = -0.047X + 3.343$	0.04	8.61	0.0037
		M_wind	$Y = 0.738X + 1.428$	0.19	53.67	< 0.0001
		M_windsd	$Y = 1.635X + 1.357$	0.15	41.90	< 0.0001
		M_tair	$Y = -0.131X + 4.056$	0.05	14.92	0.0001
P_hum	January	M_hum	$Y = 0.023X + 1.380$	0.07	21.97	< 0.0001
		M_tair	$Y = -0.069X + 3.417$	0.20	59.74	< 0.0001
	April	M_tmrt	$Y = -0.029X + 2.989$	0.22	69.19	< 0.0001
		M_hum	$Y = 0.023X + 1.033$	0.32	115.30	< 0.0001
		M_wind	$Y = 0.446X + 1.813$	0.03	8.27	0.0044
P_comfort	January	M_wind	$Y = -0.330X + 2.523$	0.04	12.43	0.0005
	April	M_wind	$Y = -0.677X + 3.235$	0.07	17.35	< 0.0001
		M_windsd	$Y = -1.484X + 3.330$	0.05	12.59	0.0005

R^2 , coefficient of determination; F , F value; P , p value

Only regressions with significant links are indicated

shift along the y-axis. For the same range of M_hum (between 50 and 70%), the conditions are perceived as wetter in January than in April.

Determinants of thermal comfort perception

Effect of micrometeorological measurements

The perception of thermal comfort is expected to offer a multifactorial and integrative assessment of microclimate conditions. But compared to micrometeorological measurements, P_comfort is significantly correlated (negatively) only to M_wind in January and April (Table 2). In June, no link is found between P_comfort and M_wind. Nonetheless, we showed that people perceive conditions as less windy in summer than in winter for the same M_wind range. This could be explained by the fact that wind causes a decrease in perceived temperature, thus increasing thermal comfort for warm summertime conditions.

Effect of multiple perceptive dimensions

When all perception dimensions (listed in Table 1) are taken into account, 44 and 19% of the data variability are respectively explained by the first two axes of the PCA (Fig. 5). Axis 1 highlights a main opposition between two groups: the first pools together P_sound and P_airq (environmental perceptions) and the second clusters a set of variables linked to visual and sensitive appreciation of the sites (i.e. P_secur, P_main, P_beau, P_overall). P_comfort is correlated to this second group of variables. Along this first axis, two groups of stop points are split: T1-T4-T6, which are positively assessed (with T6 being the most appreciated place), versus T2-T3-T5, which are perceived as ugly, unsafe, noisy, and air-polluted, and therefore uncomfortable. Only microclimate perceptions (P_hum, P_wind, P_heat) are distant from the first axis, and influenced by seasons on axis 2. However, P_comfort and P_heat are still in the same direction on axis 2, and opposed to P_wind and P_hum.

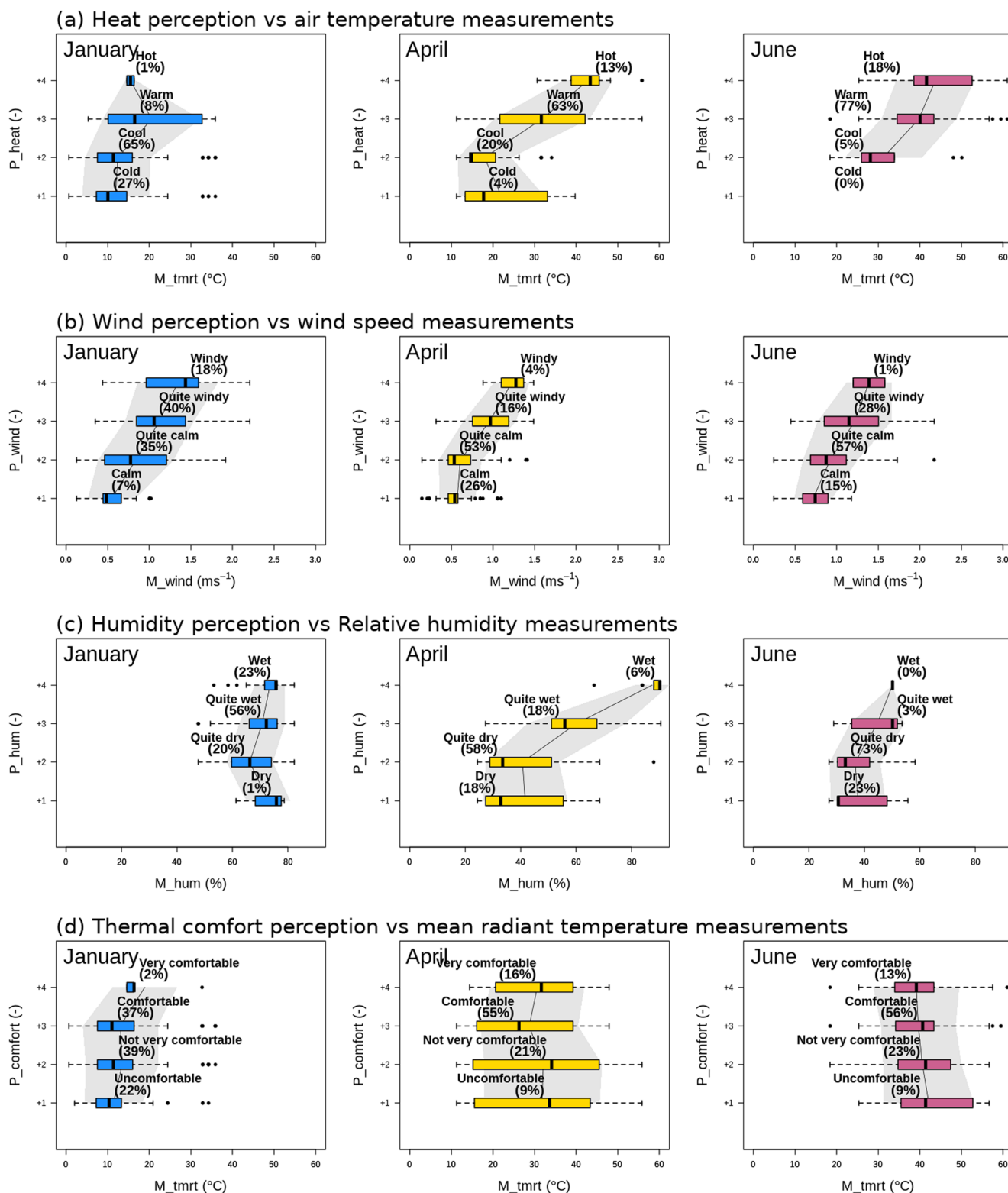


Fig. 4 Comparison between P_{heat} and M_{tmrt} (a), P_{wind} and M_{wind} (b), P_{hum} and M_{hum} (c), and P_{comfort} and M_{tmrt} (d) for January (blue), April (yellow), and June (purple) IOPs. Boxplots represent measurement distribution depending on answer options. Thin

dark line and grey area are mean measurement indicators by answer option and its standard deviation. The answer percentage of each option is indicated in brackets

These results suggest that aspects other than microclimate dimensions predominate in both the evaluation of places and in their comparison with each other, as axis 1 explains 44% of the data variability. Nevertheless, seasonality impacts the participants' evaluation of the stop points, as their perception of comfort is improved when the weather is milder. It is also interesting to note that the perception of thermal comfort evolves in the same way as the perception of non-climate-related factors; this raises the question of how this notion was interpreted by people in the surveys. This also undoubtedly relates to the fact that the perception of thermal comfort is global and encompassing, without any real discontinuity with the perception of other amenities and sources of well-being in a given location, such as its aesthetics or its level of calm (Berry-Chikhaoui et al. 2017).

Linear regression models were computed between P_comfort and other perceptions for the three IOPs separately (Table 3). For environmental dimensions, P_comfort is significantly correlated to P_heat, P_wind, and P_hum, primarily in January, and inversely to P_airq and P_sound in April and June. Here, summertime meteorological conditions are not hot enough to significantly influence the sensation of comfort, whereas people are more sensitive to them in winter, to the detriment of the other environmental factors. The other appreciation factors (P_main, P_beau, P_secur) are positively linked to P_comfort in the same way whatever the season, demonstrating the influence of the emotional dimension (Knez and Thorsson 2006, 2008; Eliasson et al. 2007). Finally, P_overall encompasses all emotional and environmental perceptions.

This result reflects the multidimensional nature of environmental quality, which encompasses a wide range of very different aspects and perceptions. The concept of thermal comfort, as addressed (or understood) by survey respondents, seems to be more aligned to this global evaluation of the quality of the place than to microclimate dimensions. On the other hand, the study area is subject to strong environmental

nuisances (noise and atmospheric pollution) related to the proximity of the ring road, which could supersede microclimate and thermal comfort issues. This is also supported by the fact that meteorological conditions were not extreme during the IOPs (no heat wave condition, for instance).

Discussion

The experimental protocol established for the EUREQUA project was quite ambitious due to its multiple objectives dedicated to a global evaluation of environmental quality. It aimed to (i) cover several time periods, (ii) document several locations, (iii) measure various physical parameters of local environment, and question various dimensions of the perception of the living environment. This framework enforced experimental constraints, e.g. the questionnaire had to be short enough to ensure that the instrumented and commented walk was not too long. This probably led to certain methodological limits regarding analyses specifically and exclusively dedicated to the climatology dimension.

Some information related to the respondents (such as clothing insulation) was not collected, so it was not relevant to compute thermophysiological indices based on environmental occupation parameters (Thorsson et al. 2004). The survey questionnaire asks respondents to express their sensation regarding each dimension (e.g. the “warm” sensation) but not the associated preference which addresses if the conditions are satisfying, not warm enough or too warm, as it can be the case in numerous other studies (e.g. Spagnolo and de Dear 2003; Kantor et al. 2012). Such preference votes could help to better analyse the differences in perception of climate dimensions between seasons, as well as the link between independent climate dimensions (heat, wind, humidity) and the global evaluation of thermal comfort. Finally, during the surveys, people circulated and settled freely within the area of the stop point. Consequently, individuals were able to adapt their behaviour

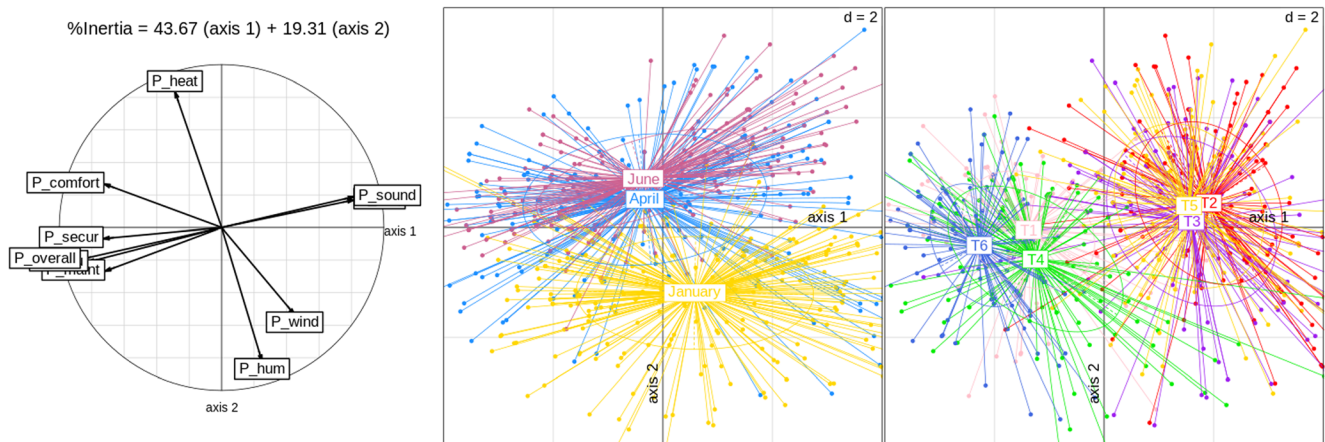


Fig. 5 Principal component analysis (PCA) of all perceptions addressed in the survey. Results are presented in the form of correlation circles (left), and by distinguishing IOPs (middle) and stop points (right)

Table 3 Coefficient of determination computed for each IOP between the data of thermal comfort perception and other perception data

		Code	Variable	R^2 Jan	R^2 April	R^2 June
Perceptions of environmental conditions	Climate	P_heat	Heat	0.32 *	NS	NS
		P_wind	Wind	0.30 *	0.14 *	NS
		P_hum	Humidity	0.17 *	NS	NS
	Air quality	P_airq	Air quality	NS	0.26 *	0.27 *
	Sound	P_sound	Sound level	NS	0.31 *	0.23 *
Other perceptions		P_maint	Maintenance	0.16 *	0.13 *	0.17 *
		P_beau	Beauty	0.26 *	0.19 *	0.20 *
		P_secur	Sense of security	0.20 *	0.20 *	0.17 *
		P_overall	Overall appreciation	0.30 *	0.35 *	0.32 *

*Indicated for p value < 0.001

to immediate micrometeorological conditions, which was not the case for other nuisances, especially noise.

The experimental protocol combines temporal and spatial coverage of the study area. This makes it possible to analyse both site effects and seasonal effects, as well as the competition that can exist between the two in the perception and assessment of microclimate dimensions, as well as in the characterisation of micrometeorological variables. Following a predefined itinerary within the neighbourhood that includes stop points where identical questionnaires are filled out makes it possible to compare the perceptions of a single group of people (Cheng et al. 2012) in different places, which reinforces the robustness of evaluations. Nonetheless, the choice of stop points may influence the results.

The cross-analysis of microclimate perceptions and micrometeorological measurements shows some robust statistical links between heat perception and temperature and between wind perception and wind speed. People are able to evaluate these dimensions individually. For the more integrative dimension of thermal comfort, however, their appreciation is here strongly related to a more overall evaluation of environmental quality. Comparison of the survey results shows a clear spatial distinction between the different places. The six selected stop points are classified in two contrasted groups that are positively and negatively evaluated on the basis of an ensemble of criteria. The most negatively evaluated places associate a clear perception of environmental nuisances (such as noise and pollution) with a feeling of a degraded or unpleasant condition of the place (ugly, feeling of unsafety, not maintained, etc.). This distinction between places is persistent with season and time of day, and is reflected in the evaluation of thermal comfort.

This spatial variability is clear in terms of the different perceptive dimensions queried (including thermal comfort, wind, and heat perception). This is not the case for measured micrometeorological variables. Even if some variations are noted at the scale of the neighbourhood (between the different stop points), these variations are not large enough to

differentiate between different microclimates based on location. Only the wind speed measurement makes it possible to differentiate stop points statistically. T1 on André Matthieu place is sheltered from the wind, and so is always less windy than T2, T3, and T4. T5 and T6 are also less windy, but to a lesser extent. Depending on the season and especially the orientation of dominant flow, which influences wind local circulations or channelling effects inside urban canopy, the windiest point is T3 or T4. The spatial variations in wind speed established by in situ measurements are perceived by respondents and seem to play a substantial role in the evaluation of locations.

Conclusion

The experimental data collected in a neighbourhood of the city of Toulouse at three time periods of the year show that microclimate perceptions and micrometeorological measurements are strongly influenced by the seasonal evolution of weather conditions. To a lesser degree, a site effect is nonetheless noted both on wind measurement and perception, leading to distinctions in the evaluation of the various stop points.

Cross-analysis of microclimate perceptions and micrometeorological measurements through simple linear regressions shows some robust statistical links, especially between P_heat and M_tmrt, P_hum and M_hum, and P_wind and M_wind. The statistical significance of these relationships and trends of linear regressions lines vary with IOPs.

The sensitivity of people to heat is more perceptible in June, when sunshine conditions are at their maximum and favour significant variation in thermal exchanges. They depend on both the hour of the day and the surface characteristics of the urban landscape at stop points that govern shadow effects, radiation trapping and surface emission, and consequently Tmrt. Conditions are perceived as colder in winter than in summer for the same range of Tmrt. The radiation effect on P_heat is masked by lower M_tair and higher M_hum. For P_hum, the

comparisons to measurements clearly indicate that people are sensitive only to the very wet conditions reached in winter. On the contrary, wind is a key dimension in microclimate perception whatever the season. Inside the urban canopy at the level of pedestrians, wind speed variations in time and space qualified by in situ measurements are of some tenths of m s^{-1} only. People are nevertheless sensitive to these small variations, which can also influence the global P_{comfort} when the weather is cold. For comparable M_{wind} , the perception of the ventilation effect of a place is evaluated more positively in summer and more negatively in winter.

Finally, P_{comfort} , which is expected to represent an integrative evaluation of microclimate conditions, is found here to not be correlated to micrometeorological measurements, and only slightly to perceptions of individual microclimate dimensions (except wind in winter). For the study area, a place of important and diverse environmental nuisances, the microclimate issue seems minor, and the notion of thermal comfort blends in with a more global evaluation of environmental quality.

This experimental work based on scientific and interdisciplinary expertise makes it possible to consolidate some results of previous studies, especially the strong sensitivity of people to wind. However, the multiple dimensions addressed by surveys underline the importance of emotional factors in the perception of the environment, such that thermal comfort is quite challenging to evaluate objectively. This provides evidence in support of participative diagnostics for urban requalification projects in order to satisfy the expectations of residents and users.

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References

- Andrade H, Alcoforado M, Oliveira S (2011) Perception of temperature and wind by users of public outdoor spaces: relationships with weather parameters and personal characteristics. *Int J Biometeorol* 55(5):665–680
- Berry-Chikhaoui I, Dorier E, Haouès-Jouve S, Flamand A, Chouillou D, Hoornaert S, Marry S, Marchandise S, Richard I, Rouquier D, Rouyer A (2017) Environmental quality seen through the prism of inhabitant assessment. The prism effect of territorial disparities. *Méditerranée*, 123 | 2014:89–105
- Carrissimo B, Qu Y, Bresson B, Daviau N, Gaudio N, Milliez M (2015) Spatial variability, horizontal anisotropy and diurnal evolution of measured infrared fluxes in a city neighborhood of Toulouse. 9th International Conference on Urban Climate, Toulouse, France
- Cheng V, Ng E, Chan C, Givoni B (2012) Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong. *Int J Biometeorol* 56(1):43–56
- Chow W T L, Assyakirin Binte Ali Akbar S N, Heng S L, Roth M (2016) Assessment of measured and perceived microclimates within a tropical urban forest. *Urban Forestry and Urban Greening* 16: 62–75
- Dray S, Dufour AB, Chessel D (2007) The ade4 package-II: two-table and K-table methods. *R News* 7(2):47–52
- Eliasson I (2000) The use of climate knowledge in urban planning. *Landscape Urban Plan* 48:31–44
- Eliasson I, Knez I, Westerberg U, Thorsson S, Lindberg F (2007) Climate and behaviour in a Nordic city. *Landscape Urban Plan* 82(1):72–84
- Fanger PO (1972) Thermal comfort. McGraw Hill, New York
- Fiala D, Havenith G, Bröde P, Kampmann B, Jendritzky G (2012) UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *Int J Biometeorol* 2012 May;56(3):429–441
- Gauvreau B, Guillaume G, Can A, Gaudio N, Lebras J, Lemonsu A, Masson V, Carissimo B, Richard I, Haouès-Jouve S (2016) Environmental quality at district scale: a transdisciplinary approach within the EUREQUA project, First International Conference on Urban Physics, Quito, Ecuador
- Höppe P (1999) The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *Int J Biometeorol* 43(2):71–75
- Johansson E, Thorsson S, Emmanuel R, Krüger E (2014) Instruments and methods in outdoor thermal comfort studies – the need for standardization. *Urban Climate* 10(2):346–366
- Kántor N, Egerházi L, Unger J (2012) Subjective estimation of thermal environment in recreational urban spaces—part 1: investigations in Szeged, Hungary. *Int J Biometeorol* 56(6):1075–1088
- Knez I, Thorsson S (2006) Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square. *Int J Biometeorol* 50(5):258–268
- Knez I, Thorsson S (2008) Thermal, emotional and perceptual evaluations of a park: cross-cultural and environmental attitude comparisons. *Build Environ* 43:1483–1490
- Le Bras J, Gaudio N, Lemonsu A, Legain D, Quinteiro L, Masson (2015) Cross-analysis between variability of the urban climate and the landscape heterogeneity at the scale of a neighborhood. 9th International Conference on Urban Climate, Toulouse, France
- Lin T-P (2009) Thermal perception, adaptation and attendance in a public square in hot and humid regions. *Build Environ* 44(10):2017–2026
- Lin T-P, de Dear R, Hwang R-L (2011) Effect of thermal adaptation on seasonal outdoor thermal comfort. *Int J Climatol* 31: 302–312
- Lin T-P, Andrade H, Oliveira S, Hwang R-L, Matzarakis A (2014) Outdoor thermal perception in different climatic regions. Initial results from Taichung (Taiwan) and Lisbon (Portugal). *Finisterra* 49(98):113–131
- Makaremi N, Salleh E, Jaafar MZ, GhaffarianHoseini A (2012) Thermal comfort conditions of shaded outdoor spaces in hot and humid climate of Malaysia. *Build Environ* 48(1):7–14
- Maras I, Schmidt T, Paas B, Ziefle M, Schneider C (2016) The impact of human-biometeorological factors on perceived thermal comfort in urban public places. *Meteorol Z* 25(4):407–420
- Matzarakis A, Mayer H, Iziomon MG (1999) Applications of a universal thermal index: physiological equivalent temperature. *Int J Biometeorol* 43(2):76–84

- Ng E, Cheng V (2012) Urban human thermal comfort in hot and humid Hong Kong. *Energy and Buildings* 55:51–65
- Nikolopoulou M, Lykoudis S (2006) Thermal comfort in outdoor urban spaces: analysis across different European countries. *Build Environ* 41(11):1455–1470
- Nikolopoulou M, Baker N, Steemers K (2001) Thermal comfort in outdoor urban spaces: understanding the human parameter. *Sol Energy* 70(3):227–235
- Parsons K (2014) *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort, and performance*, Third Edition, CRC Press, 635pp
- R Core Team (2015) *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>
- Spagnolo J, de Dear R (2003) A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Build Environ* 38(5):721–738
- Stathopoulos T, Wu H, Zacharias J (2004) Outdoor human comfort in an urban climate. *Build Environ* 39(3):297–305
- Stewart ID, Oke TR (2012) Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society* 93:1879–1900
- Thorsson S, Lindqvist L, Lindqvist S (2004) Thermal bioclimatic conditions and patterns of behaviour in an urban park in Göteborg, Sweden. *Int J Biometeorol* 48(3):149–156
- Thorsson S, Honjo T, Lindberg F, Eliasson I, Lim E (2007a) Thermal comfort and outdoor activity in Japanese urban public places. *Environ Behav* 39(5):660–684
- Thorsson S, Lindberg F, Eliasson I, Holmer B (2007b) Different methods for estimating the mean radiant temperature in an outdoor urban setting. *Int J Climatol* 27(14):1983–1993
- Tornay N, Schoetter R, Bonhomme M, Faraut S, Masson V (2017) GENIUS: a methodology to define a detailed description of buildings for urban climate and building energy consumption simulations. *Urban Climate* 20:73–95
- Westerberg U, Linden E, Nilsson H (2006) Perceived windiness in urban spaces. 6th International Conference on Urban Climate, Göteborg, Sweden