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Cross-analysis for the assessment of urban environmental quality: An interdisciplinary and participative approach

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Abstract

The goal of this research is to assess environmental quality at the neighbourhood level through a multi-dimensional and multi-sensory approach that combines social and physical methodologies. For this purpose, an interdisciplinary protocol has been designed to simultaneously collect physical parameter measurements (related to microclimate and acoustics) and survey data on perceptions (involving residents and non-residents). The cross-referenced analysis of data collected at six contrasting places in a district in Toulouse (France) enabled us (i) to better understand and prioritise the factors that influence residents' assessment of the quality of their living environment and (ii) to understand to what extent the differentiation of the places by the inhabitants converges with the differentiation of these places based on acoustic and micrometeorological measurements. The statistical analysis based on individuals showed the importance of noise and air quality that rank just after the aesthetic dimension for all respondents. Nevertheless, the quality of maintenance and the feeling of security that the place inspires seem to be as crucial as these environmental criteria for the inhabitants. The analysis focused on the sites highlighted the consistency between the typology of places based on perceptions and that based on acoustic measurements, which confirms the high inhabitants' sensitivity to this environmental component.

Keywords

Built environment, decision support, environmental design, statistical analysis, urban planning

Introduction

Since urban environmental quality can be considered by looking at it through different lenses and at different levels (depending on the scientific disciplines), there is no specific universal definition to describe it. Within the disciplines of social sciences and humanities (SSH), the notion of environmental quality is approached from two main angles. In the first approach driven by environmental psychology, environmental quality (together with well-being and quality of life) is experienced in an individual way. This points to the subjective aspect of this notion, the inter-individual variability of the evaluation hierarchy and the mechanisms of accumulation and perceptual compensation between nuisances and environmental amenities (Gidlöf-Gunnarson and Öhrström, 2007; Marans, 2003; Van Poll, 1997). Most other social sciences focus on the socially constructed character of the environmental quality as a value given to the living environment. It refers to socio-spatial practices and to the attachment to places that relate to a collective dimension of the experience of environmental quality. Attention is paid to environmental value systems as a whole, taking into account socio-economic relationships and the political issues underlying them (Emelianoff, 2007). Other studies question the effects of environmental quality promoted as a key element of urban planning action frameworks, with, on the one hand, the expected benefits in terms of competitiveness and territorial attractiveness (Florida, 2002) and, on the other hand, the tangible risks of exclusion and urban segregation (Berry-Chikhaoui et al., 2007; Napoléone, 2006).

Nevertheless, since the 1990s, several works in social sciences have led to the emergence of a widely shared definition of environmental quality as the result of objective and subjective values that characterize the living spaces of the inhabitants at different spatial and temporal scales (Bonaiuto et al., 1999, 2003; Pacione, 2003; Van Poll, 1997). Thus, the last decades have seen the development of tools to manage stakeholder participation processes, both in terms of urban planning strategies (nature/building, economy, biodiversity, land using, etc.) and in terms of physical assessment of the influent parameters/indicators for urban well-being (thermal comfort, environmental acoustics, air and water quality, ground characteristics, etc.). This finding supports the idea that environmental quality study lends itself to interdisciplinary approaches that cross the two major fields of knowledge that are SSH and the physical sciences of the environment (PSE).

Different disciplines of PSE are exploring this approach by confronting quantitative physical data – that may give a picture of the environmental conditions, their quality, and the possible presence of nuisances – with sensitive assessments. At the forefront of these issues, the environmental acoustics increasingly addresses the sound characterisation through qualitative and holistic approaches, based on soundscape (Kang et al., 2016) or sound ambiance (Thibaut, 2011) paradigms, which aim to account for the context, background perception and understanding. Moreover, recent characterisation methods for the urban sound environment are multi-source oriented (i.e. road traffic and other human activities, or even animals), and often rely on participative approaches (Aletta and Kang, 2015; Aumond et al., 2018). The decision-making in environmental acoustics itself turns towards more participative approaches, by actively involving city dwellers, as well as noise experts and city stakeholders (Alves et al., 2015) and taking advantage of the new insights from the smart city, as described in Can et al. (2020). In urban meteorology and bioclimatology, the integrative notion of thermal comfort is based on the combination of local weather conditions of temperature, humidity, wind and radiation experienced by the human body (Andrade et al., 2011). It is evaluated according to different indices (Fanger, 1972; Fiala et al., 2012; Höppe, 1999; Matzarakis et al., 1999; Parsons, 2014) and associated to heat-stress levels (Bröde et al., 2012). Some studies specifically address the gap that may exist between these relatively theoretical assessments and the perception of people in their own living environment. The comparison of physical measurements with individuals' feeling shows that the perception of thermal comfort is influenced by psychological and cultural factors (Eliasson et al., 2007; Lin et al., 2014; Ng and Cheng, 2012; Nikopoulou and Lykoudis, 2006; Thorsson et al., 2007a). The analysis of cognitive maps also shows the link between the visual and spatial perception of outdoor spaces and microclimatic perception (Lenzholzer and Koh, 2010). Finally, many studies have also explored the link between the perception of air quality and local air pollution. It is difficult to establish a robust relationship between the two (Brody et al., 2004; Jacobson, 2005; Paas et al., 2016) as perception is influenced by multiple factors, especially visual, olfactory and sound nuisances, individual characteristics and health status (Brody et al., 2004; Nikolopoulou et al., 2011; Oltra and Sala, 2014).

Although interdisciplinary research on the confrontation of physical measurements and perceptions is now quite extensive, few of them combine this interdisciplinary approach with embracing several environmental dimensions. At the neighbourhood level, Kabisch et al. (2018) qualify the local residential quality through an interdisciplinary perspective. They rely on survey data, urban land use and typomorphology information, and microclimatic simulations to show the links between the social context, physical and material conditions, and the surrounding environmental conditions. Some still rarer studies are now investigating multi-factor and multi-sensory approaches. Experiments by Yang et al. (2019), in indoor environments with controlled environmental conditions, underline the interrelation between the global perception of comfort and the acoustic, thermal, and visual dimensions. In an outdoor environment, Pantavou et al. (2017) analysed the perception of air quality with regard to personal factors, measurements of pollutant concentrations and also thermal perception. The results show that heat stress acts as an additional factor in the assessment of poor air quality. Engel et al. (2018) cross-referenced data on air and sound quality perception, combined with pollution and acoustic measurements, finding positive correlations especially in the evaluation of urban parks. La Malva et al. (2011, 2015) compared the living spaces of two neighbourhoods based on a cross-analysis of the soundscape, lightscape, thermalscape and airscape. They conclude on the predominance of sound perception in the overall assessment of places, in comparison with other environmental dimensions (whose influences are less systematic), and find a link between urban characteristics and the sound environment.

The results of the few existing works mentioned above support the relevance of multi-dimensional and multi-sensory approaches in the assessment of environmental quality, but some issues are still little or not addressed. In particular, multi-dimensional crossing is mainly based on perceptions (e.g. perception of sound and air quality), less systematically on measurements. The studies that compare measurements and perceptions usually focus on a limited number of environmental components. Moreover, cross-analysis of data with regard to potential spatial (multi-site) and temporal influences is little discussed. In this paper, we seek to deal with the multi-dimensional and multi-sensory approach, and this for several urban spaces in a neighbourhood and at different periods of time, with a view to meeting two scientific objectives: (i) to better understand and prioritise the factors that influence residents' assessment of the quality of their living environment, (ii) to understand to what extent the differentiation of the places by the inhabitants converges with the differentiation of these places based on acoustic and micrometeorological measurements.

The multi-factor definition of environmental quality is especially relevant for guiding urban planning and design choices. The challenge is to consider the multidimensional aspect of this environmental quality to meet inhabitants' expectations as well as possible while considering the environmental nuisances that might be there and that threaten public health objectively (Can et al., 2011; Haouès-Jouve et al., 2016; Klemm et al., 2015, 2017; Kweon et al., 2005; Musy et al., 2012). In line with this work, our research aims to build interdisciplinary scientific expertise in environmental quality at the neighbourhood level that incorporates the knowledge and expertise of inhabitants to guide future urban redevelopment projects.

The paper first presents, in Section 'Methodology' the general framework of the study consisting of the interdisciplinary methodological approach and the experimental protocol. Then the analysis and cross-analysis of measurements and survey data are detailed and discussed in Section 'Analysis of measurements and survey data'. Finally, Section 'Conclusion' summarises the results obtained and discusses their benefits in terms of decision-making support for public policies.

Methodology

General presentation

This work has been carried out through an interdisciplinary research programme that brought together researchers in urban geography, sociology, atmospheric physics, acoustics, and architecture, in collaboration with officials in three French cities (Toulouse, Paris and Marseille). The key goal was to assess the environmental quality at the neighbourhood scale by combining physical approaches with subjective ones that account for the knowledge and experience of inhabitants. The former are based on measurements and numerical modelling, while the latter mobilise social surveys comprising interviews, questionnaires and focus groups. For conciseness, this paper focuses on two main dimensions – acoustics and microclimate – through experimental data (cross-analysis of in situ measurements and inhabitant surveys) collected in one district (Toulouse, France).

The central principle of the proposed method for assessing urban environmental quality is detailed in Figure 1. First, a qualitative survey based on interviews and commented walks (Figure 1(1)) examined how inhabitants perceive and use their living spaces and how they define and evaluate their environmental quality. This preliminary diagnosis also made it possible to identify several emblematic places perceived positively or negatively by the inhabitants. In a second phase, experimental campaigns combining measurements and perception surveys were carried out in the neighbourhood (Figure 1(2)). These campaigns made it possible to build up a database of measurements and surveys, which led to various statistical analyses (Figure 1(3)). Finally, these different steps informed the design of a methodological guide developed as a decision-making aid for urban requalification (Figure 1(4)).

Choice of the study area

The study area selected for this paper is a district in the French city of Toulouse (Bordelongue-Papus-Tabar, 43°34′18″ N, 1°24′47″ E). This area has environmental issues relating to both noise and atmospheric pollution, due to its proximity to high traffic roads. It combines a fine-grained social mix and diverse typo-morphological features that enhance the understanding of the environmental quality in relation to the socio-territorial complexity.

The study area is located 4.5 km south of the city centre (Figure 2, right). It covers an area of about 600 m × 600 m, between the South branch of Toulouse's ring road and a major traffic road (Route de Seysses). Due to this geographic context, it is subject to significant noise and air pollution, which is aggravated by its location under the flight path of Toulouse-Blagnac airport (Figure 2, left). The settlement is composed of a patchwork of typo-morphological entities corresponding to successive periods of urbanisation: workers' bungalows from the 1950s (Papus); social housing from the late 1950s and early 1960s (Tabar and Bordelongue), and closed mid-range condominiums (the Tours de Seysses) built in 1972 (Figure 2, right). Despite a certain degree of social mixing, it is primarily a working-class neighbourhood where the average household income is about half the median income of the greater Toulouse urban area.

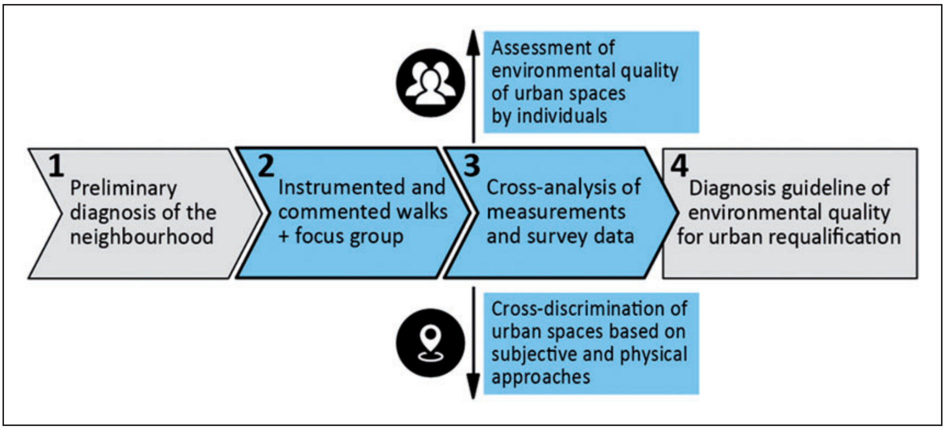

Figure 1. The general framework of the study. (Steps specifically detailed in the paper appear in blue).

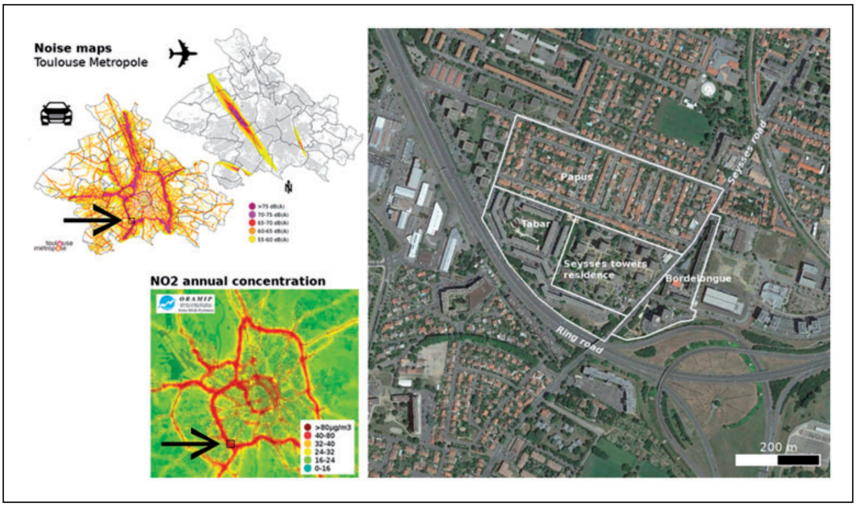

Figure 2. Aerial photograph of the study area, supplemented by the noise maps for road and air traffic (top left) provided by the Toulouse city council, and the map of the annual NO_2 concentration provided by the regional institute for air quality monitoring (bottom left).

A preliminary diagnosis was carried out among some 20 inhabitants, combining free and commented walks (along the route of their choice) and interviews (Figure 1(1)). The objective was to understand the environmental issues (amenities, nuisances, environmental conflicts, etc.) that emerge from the more global representations and perceptions of the living environment (Berry-Chikhaoui et al., 2014b). This survey also enabled us to identify several emblematic public spaces in the district (Figure 3) that are appreciated or, on the contrary, considered unpleasant by the residents. The methodological protocol of the next stage of the research was built around these specific sites.

Experimental protocol combining in situ measurements and inhabitant surveys

Instrumented and commented walks. The second stage was the organisation of interdisciplinary in situ experimental campaigns (see Figure 1). Three-day intensive observational periods (IOP) were carried out in winter (28–30 January), spring (8–10 April) and summer (17–19 June) 2014, following the same experimental protocol. To inform the environmental quality interdisciplinary analyses, an innovative protocol called "instrumented and commented walks" was set up. The walks took place three times per day at 10 a.m., 4 p.m. and 7 p.m. local time, and involved combining mobile measurements of physical parameters and social surveys with groups of respondents. The participants followed a predefined itinerary of about 2 km and stopped at six specific locations (hereafter called stopping points, see Figure 4), selected from the preliminary diagnosis. At each stopping point, the respondents filled out a questionnaire-based survey to assess the environmental quality of the place through various dimensions. At the same time and in the same location, acoustic and micrometeorological data were recorded so that the perceptions and measurements could be compared. This protocol is innovative in the sense that: (i) it covers multiple periods of the day, hence embracing perception variations throughout the day and (ii) it examines several environmental dimensions through both subjective and physical assessments.

Figure 3. Aerial photograph of the study area with the predefined route and location of stopping points indicated in blue, and photographs of the immediate environment of the six stopping points.

In-situ measurements of environmental parameters. During the walks, micrometeorological and acoustic data were recorded continuously, and coupled with corresponding global positioning system coordinates. Micrometeorological sensors were installed on a portable system carried on the shoulders of an operator (Figure 4(b)) to measure street-level air temperature, air humidity, wind speed and mean radiant temperature. In addition, infrared surface temperatures were measured at each stopping point (ground, sky and eight other images on a vertical plan according to eight viewing directions), through a dedicated camera (Figure 4 (c)). Regarding acoustic measurements, a sound level meter carried on the back of an operator (Figure 4(d)) was configured to measure the 1 s-evolution of A-weighted sound pressure levels $L_{eq,A,1s}$, and the 1 s-evolution of the 31 third octave bands $L_{eq,f,1s}$, from 20 Hz to 20 kHz. Based on the measurements, a set of micrometeorological and acoustic indicators (Table 1) was computed at each stopping point, which are known to reflect both the physical and perceptual characteristics of these two environmental dimensions (Gauvreau et al., 2016).

Survey protocol and questionnaire. The respondents were asked to assess various aspects of the quality of the neighbourhood, both qualitatively and quantitatively by filling out the same questionnaire at each stopping point (Figure 4(f)). It was structured into five thematic sections with several questions, some of which were open-ended.

First, the respondents were asked to give their personal assessment of the stopping point by providing and ranking three to five words describing the place from their point of view. Two questions were asked to assess their microclimatic perception: (1) their evaluation of

Figure 4. Experimental protocol combining (a, f) questionnaire-based surveys with (b) measurements of micrometeorological parameters, (c) infrared thermography, and (d) sound recordings, and (e) a focus group.

the climatic comfort, heat, humidity and wind at the stopping point, based on four possible levels (Table 2); (2) the temperature at the stopping point according to their own perception. Concerning sound comfort, the first two questions were aimed at evaluating the sound level from *very quiet* to *very loud*, and the sound from *unpleasant* to *pleasant* (Table 2). They were followed by textual data to define the aspects of the local environment these perceptions were based on. They were also asked about their perceived level of air quality, from *very low* to *very good* (Table 2), which was supplemented by a multiple-choice question on the main evaluation criteria used by the respondents (odour, traffic, landscapes, respiratory conditions). The stopping points were also described according to other themes: the overall assessment level (from *not at all* to *absolutely*), beauty, maintenance and sense of security in the place (Table 2). The survey questionnaire was supplemented with personal information about the respondent, i.e. age, gender, professional and marital status, residential status, how long they had lived in the neighbourhood and in the city.

After each walk, a focus group (Figure 4(e)) was held with the respondents to discuss the most and least valued places and the reasons behind this assessment. People were also asked

Table 1. Definition and description of the indicators based on acoustic and micrometeorological measurements.

Disciplines	Indicators	Description	Unit
Acoustics	M_LA90	Sound pressure level exceeded for 90% of the measurement period (background noise)	dB(A)
	M_LA50	Sound pressure level exceeded for 50% of the measurement period (mean sound level)	dB(A)
	M_LA10	Sound pressure level exceeded for 10% of the measurement period	dB(A)
	M_LA_sd	Sound pressure level standard deviation over the measurement period	dB(A)
	M_LA10_90	Amplitude of sound pressure levels variation over the measurement period (M_LA10-M_LA90)	dB(A)
	M_MI_LF	Cumulative time when the L1s exceeds the sound pressure level exceeded for 50% of the measurement period for low frequencies (20–125 Hz) +15 dB	%
Meteorology	M_tair	Air temperature averaged over the measurement period	°C
	M_hum	Air relative humidity averaged over the measurement period	%
	M_wind	Wind speed averaged over the measurement period	$m\ s^{-1}$
	M_windsd	Wind speed standard deviation over the measurement period	$m\ s^{-1}$
	M_tmrt	Mean radiant temperature averaged over the measurement period	°C

Table 2. Survey questionnaire related to the quantitative evaluation of the different dimensions of environmental quality.

			Multiple choice answers (and rating)			
	Indicator	Variable	(1)	(2)	(3)	(4)
Climate	P_heat	Heat	Cold	Cool	Warm	Hot
	P_wind	Wind	Calm	Quite calm	Quite windy	Windy
	P_hum	Humidity	Dry	Quite dry	Quite wet	Wet
	P_comfort	Thermal comfort	Uncomfortable	Not very comfortable	Comfortable	Very comfortable
Air quality	P_airq	Air quality	Very poor	Poor	Good	Very good
Sound	P_sound	Sound level	Very quiet	Quiet	Loud	Very loud
Other	P_maint	Maintenance level	Not maintained	Poorly maintained	Maintained	Very well maintained
	P_beau	Beauty level	Ugly	Quite ugly	Quite beautiful	Very beautiful
	P_secur	Security level	Unsafe	Quite unsafe	Quite safe	Very safe
	P_overall	Overall assessment	Not at all	Not really	Somewhat	Absolutely

about their determinants of environmental quality and how this could be improved in their neighbourhood.

The 27 instrumented and commented walks carried out in Toulouse (three IOPs lasting 3 days done at three different times each day) generated 185 questionnaires, i.e. nearly

7 participants per walk on average. We chose to make up groups of fewer than 10 participants, so that the subjective experience and the evaluation were not perturbed by the participants themselves. A data subset (Table 2) related to the perceptual evaluation of different environmental dimensions at each stopping point was selected for comparison with the physical measurements that were collected synchronously.

Analysis of measurements and survey data

Assessment of the environmental quality of urban spaces by individuals

Main criteria involved in the overall assessment of urban spaces. To assess the criteria involved in the assessment of the overall quality of the stopping points (P_overall), the random forest supervised classification method was applied to rank the SSH variables (Table 2). The relative importance of variables was determined using both the Mean Decrease Accuracy (MDA) and the Mean Decrease Gini (MDG). The MDA evaluates the importance of a variable in the classification accuracy it leads to, whereas the MDG evaluates the ability of a variable to differentiate one heterogeneous item in several homogeneous groups. These two scores were normalised and aggregated in a single classification estimator which ranked the SSH variables with a score from 0 to 10. In addition, the out-of-bag error estimation evaluates the accuracy of the random forest. The responses to the surveys completed by residents (480 profiles for Toulouse, Figure 5(a)) and non-residents (620 profiles for Toulouse, Figure 5(b)) were analysed separately, with the three IPOs (winter, spring, summer) pooled together.

This analysis shows that the prevailing dimension in the assessment of the overall quality of the stopping points was their aesthetics, both for residents and non-residents. This is probably due to the experimental protocol, which first called on the respondents' visual sense. For both groups, strictly environmental indicators related to the assessment of the climatic comfort, acoustic comfort and air quality came second, although the order of these dimensions differed between the two groups. They preceded the perception indicators

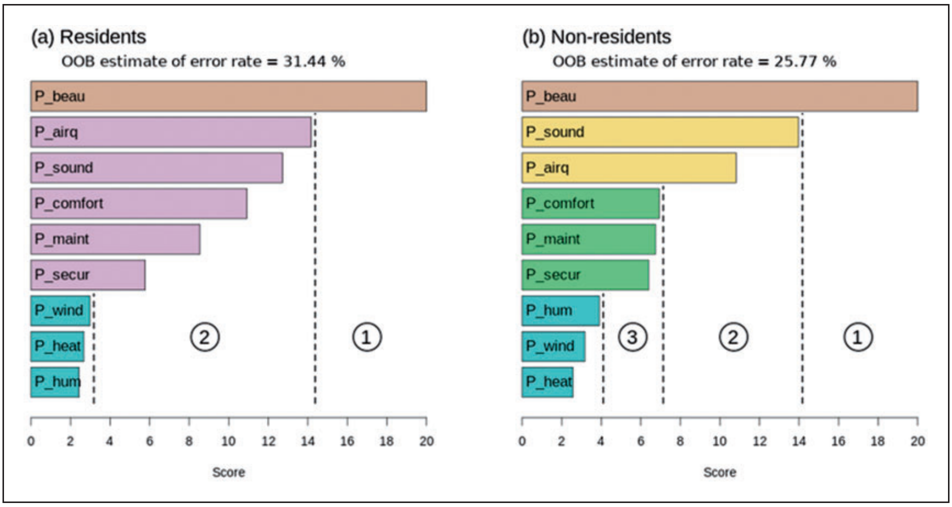

Figure 5. Scores of SSH variable importance considering (a) residents and (b) non-residents separately. OOB: out-of-bag.

related to maintenance and the feeling of security. This prioritisation was due to the neighbourhood's high exposure to noise and air pollution. The three climate-related indicators (perception of heat, wind and humidity) were ranked last, with scores significantly lower than those of previous indicators. Their low influence contrasted with the relative importance of the climate comfort in the overall assessment of the places. Therefore, the assessment of climate comfort did not seem to result from the integration of the assessment of the various climate components taken individually.

Different threshold effects were noted between the two classifications. Two significant thresholds separate the dimensions into three groups of different importance for the non-residents' classification. The beauty of the place (1 in Figure 5(b)) stands out before the combination of acoustic comfort and air quality (2) that are clearly ahead of climate comfort, maintenance and the feeling of security (3). For the residents, the beauty of the place stands out (1 in Figure 5(a)) as clearly as for the non-residents, but the threshold effect disappeared between the following two groups. This gap revealed an intrinsic difference in the pattern of overall appreciation of stopping points between residents and non-residents. The predictability of a statistical model associated with non-residents could be relatively satisfactory by retaining only the first three dimensions. For residents, more dimensions (i.e. six) are involved in the evaluation, demonstrating the greater complexity of the assessment pattern for familiar places. The daily occupation of places enriches while nuancing and complexifying the assessment.

Individual expertise in the assessment of sound and microclimate environments. The previous analysis showed the prevalence of acoustics and air quality perceptions in the overall assessment of stopping points compared to the perception of climatic aspects. These perceptions were compared with the physical measurements using simple linear regressions to investigate potential links or differences between subjective and objective assessments. The cross-analysis of data was done for acoustics and the climate, but not for air quality since in situ measurements of pollutants were not available.

The linear regressions relating the noise perception (P_sound, perception of noise level rated from 1 to 4 according to the possible responses) to all the measurement-based acoustic indicators have been calculated. The most robust relationships were obtained for the three indicators related to the sound pressure level (i.e. M_LA90, M_LA50, M_LA10), confirming results from the literature (Aumond et al., 2017). As an example, the linear regression between M_LA90 (background noise, in dBA) and P_sound is presented in Figure 6, top. A significant positive relationship between the two variables occurred regardless of the campaign ($R^2 \geq 0.54$, p-value $< 1.10^{-4}$). For each campaign (i.e. each season), the survey responses were homogeneously distributed between *loud*, *quiet* and *very quiet* (between 25% and 33%), corresponding to an equally homogeneous spread of M_LA90 over a wide range of 40–65 dBA.

The correlations between perceptions and measurements of the various climatic dimensions (temperature, humidity, wind) have already been analysed in detail by Lemonsu et al. (2018). The linear regression calculated between air temperature measurements (M_tair) and heat perception (P_heat) is presented here. There was no significant link between the two variables (Figure 6, bottom) for the January campaign and a slightly significant positive link for the June campaign ($R^2 = 0.06$, p-value $= 0.0003$), which are both characterised by stable weather conditions and a low spread in temperature measurements (5°C for January and 9°C for June). The link was stronger for the April campaign ($R^2 = 0.23$, p-value $< 1.10^{-4}$) for which the weather conditions varied more, resulting in a greater measurement dispersion (15°C).

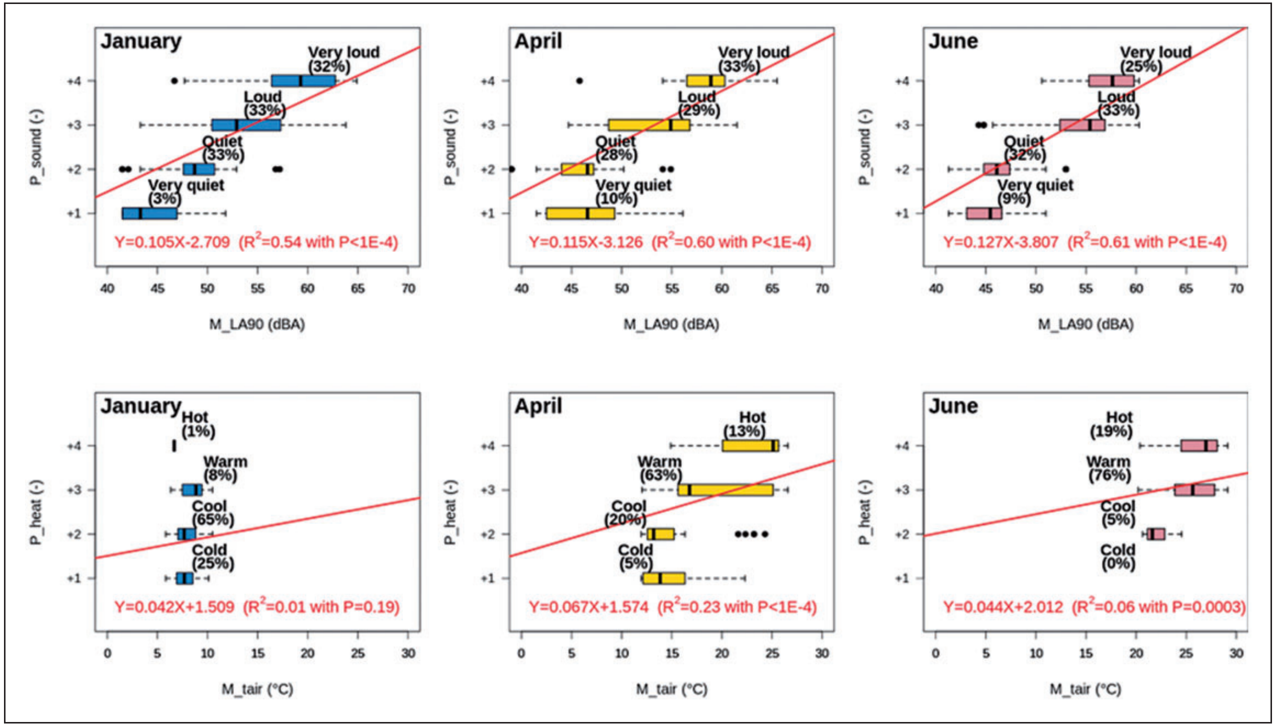

Figure 6. Linear regressions between sound perception and measured LA90 (top) and between heat perception and measured mean radiant temperature (bottom), for the three IOPs in January, April and June. The red line is the linear regression line, supplemented by the equation and correlation coefficient written in red. Boxplots represent the measurement distribution depending on the answer options. The answer percentage of each option is indicated in brackets.

The comparison of both data cross-analyses argue in favour of the respondents having greater expertise and sensitivity in assessing the noise level than the temperature. This finding had already been highlighted by La Malva et al. (2015) who showed the prevalence of the perception of the sound environment in relation to that of the thermal environment in the global evaluation of two neighbourhoods of Milan (Italy). These results converged with what the qualitative surveys of the first diagnosis phase showed (Berry-Chikhaoui et al., 2014): the collected speeches indicated the respondents had genuine expertise in diagnosing discomfort caused by noise, whatever its origin, whereas less attention was paid to climatic conditions. The reference to the climate mainly appeared to describe situations of multiple-exposure to environmental nuisances (e.g. wind effect on atmospheric pollutant dispersion).

Cross discrimination of urban spaces through subjective and physical approaches

The aim here is to understand to what extent does urban spaces discrimination based on surveys data converge with the one resulting from acoustic or micrometeorological measurements. The point was first to investigate how these three independently analysed data sets made it possible to differentiate between stopping points and to build typologies of places. Then, the analysis focused on how the perception-based typology converged with each of the measurement-based typologies. Principal component analyses (PCA) were performed separately for SSH variables, acoustic indicators and micrometeorological indicators, in order to produce the typologies. Afterwards, the correlation between perception- and measurement-based typologies was investigated through co-inertia analysis (CIA) between SSH variables and acoustic indicators, and between SSH variables and micrometeorological indicators.

Development of urban spaces typologies based on surveys and measurements. The PCA for SSH variables indicated that 44% of the data variability was explained by axis 1 and 19% by axis 2 (Figure 7(a)). As noted along axis 1, the respondents provided a clear-cut positive or negative evaluation of stopping points, based on criteria combining environmental perceptions (P_sound, P_airq, P_comfort) with an assessment of security, maintenance, beauty (P_secur, P_main, P_beau), and the overall assessment parameter (P_overall). Two groups of stopping points were distinguished along axis 1: T1–T4–T6 were greatly appreciated and perceived as quiet, clean, comfortable and secure (especially T6, located in the bungalow zone of the study area), contrary to T2–T3–T5. The second axis opposed the perception of climate indicators, and more particularly of P_heat and both P_wind and P_hum. However, these climate perceptions did not seem to influence the global perception of the stopping points.

For acoustic measurements, 52% and 32% of the data variability were respectively explained by the first two axes of the PCA (Figure 7(b)). Axis 1 highlighted an opposition between the sound level indicators, i.e. M_LA90 and M_LA50, which quantify the background noise and the median sound level, respectively, and M_MI_LF, which captures the acoustic events emergence in low frequency within the background noise (Table 1). Axis 2 was mainly related to the sound level variability (M_LA10_90 and M_LA_sd). These results are in line with the literature (Torija et al., 2013). Two groups were distinguished along axis 1: quiet stopping points (T1–T4–T6), with both a low sound level and few acoustic events, and noisy stopping points (T2–T3–T5). These latter are spread along axis 2 according to sound variability: T2 was characterised by low-frequency background noise due to the

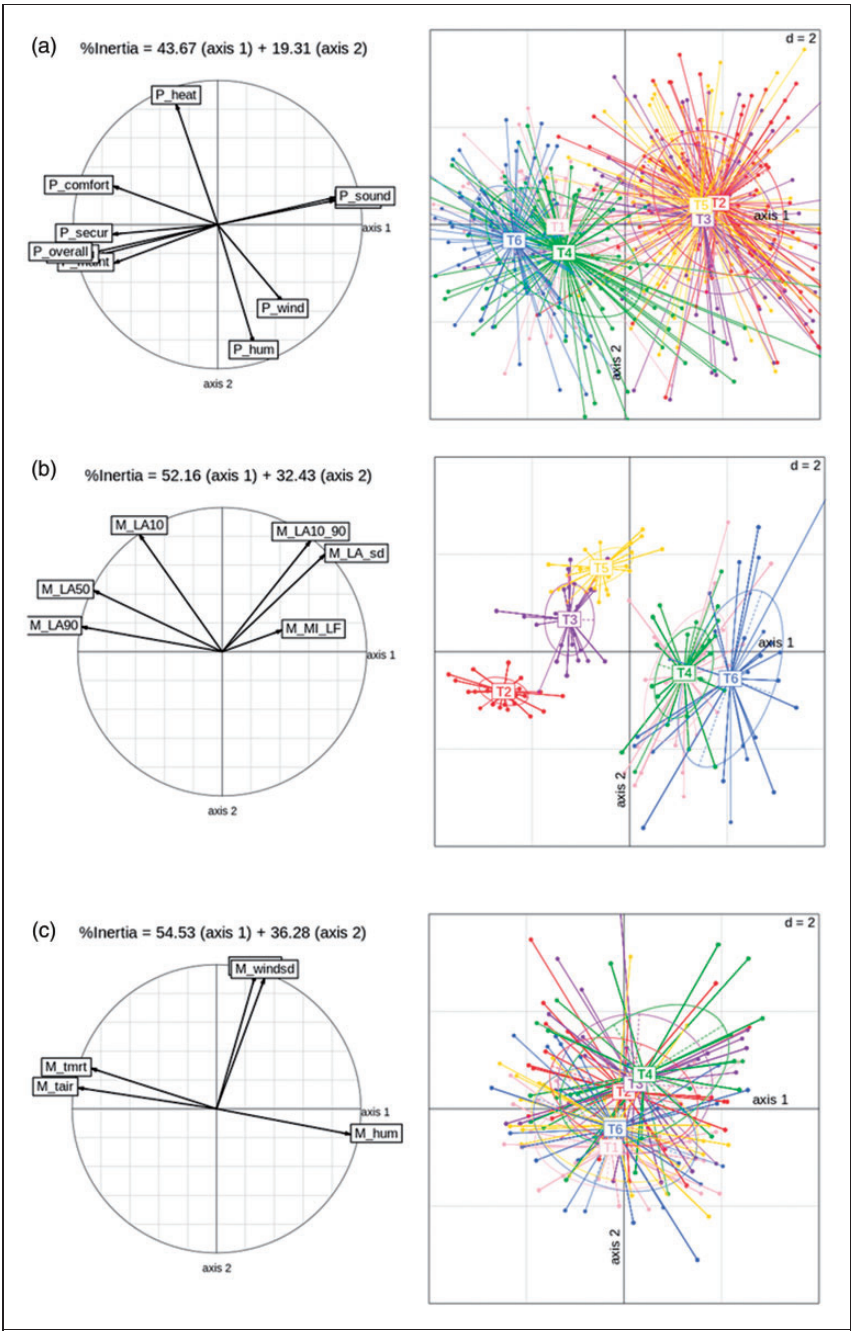

Figure 7. Principal component analysis (PCA) of SSH (a), acoustics (b) and micrometeorological variables (c). Results are presented in the form of correlation circles (left), and by distinguishing stopping points (right).

proximity of the ring road, whereas T5 was associated with the intermittent noise of traffic on the road where it is located. The sound environment was intermediate for T3.

The PCA of micrometeorological indicators highlighted the prevailing influence of temperature (M_tmrt, M_tair) and humidity (M_hum) variability, as observed along axis 1 (54% of variability, Figure 7(c)). As discussed by Lemonsu et al. (2018), this variability is mainly due to seasonal effects, and not to site characteristics. Nonetheless, axis 2 explained 36% of the data variability, mainly driven by variations in mean wind speed (M_wind) and the standard deviation of wind speed (M_windsd). The stopping points were distributed along the diagonal defined by wind measurements in two main groups T2–T3–T4 and T1–T5–T6 that stand out as locations respectively more and less exposed to wind.

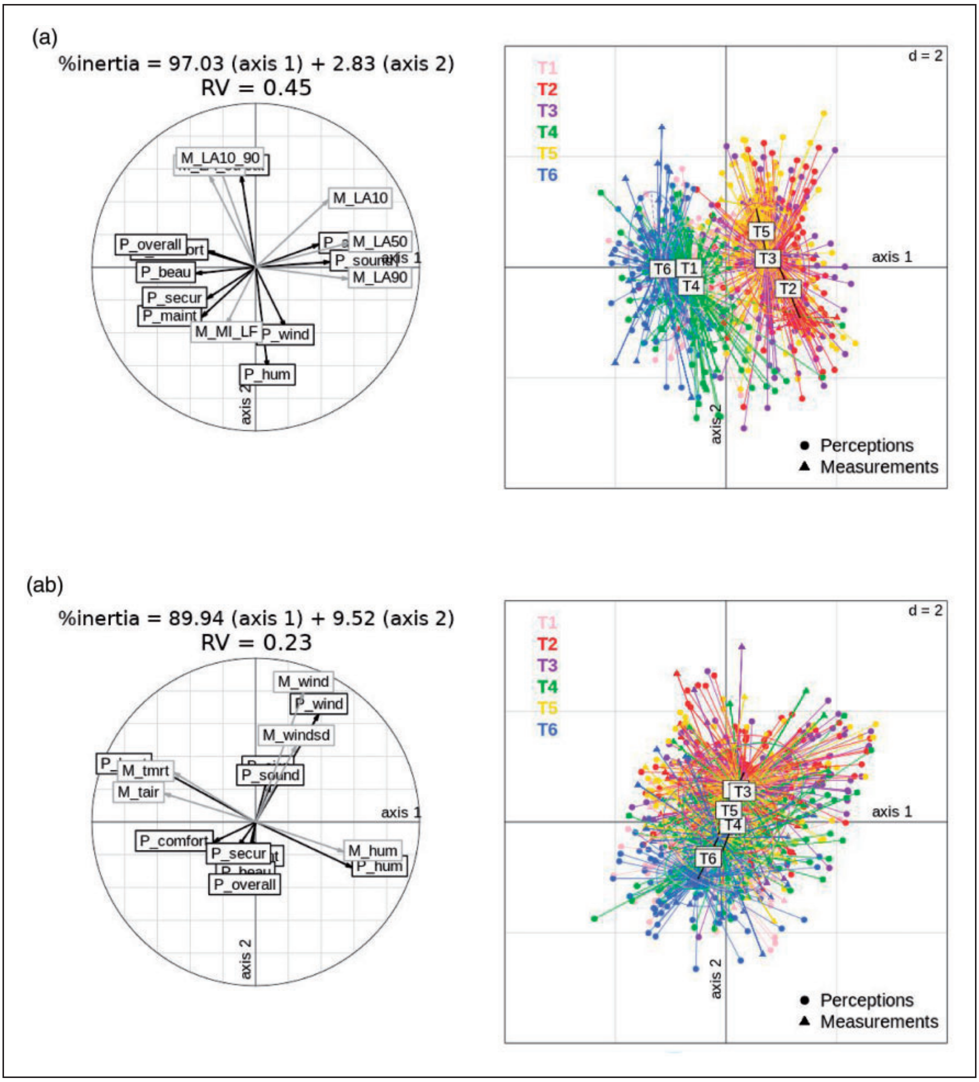

Figure 8. Co-inertia analysis (CIA) between SSH perception variables and (a) acoustic indicators, and (b) micrometeorological indicators. Results are presented in the form of correlation circles (left), and by distinguishing stopping points (right). Perceptions (circles) and measurements (triangles) are overlapped.

Cross-referencing of place typologies. The typologies arising from the PCA were compared using CIA. The CIA between SSH perceptions and acoustic indicators was associated with a high RV coefficient (Robert and Escoufier, 1976) of 0.45, illustrating a strong correlation between both data sets (Figure 8(a)). Axis 1 explained more than 97% of the data variability. The two data sets were coherent: the same group of locations (T1–T4–T6) was positively evaluated by respondents according to a set of criteria (including sound perception P_sound) and characterised by a quiet sound environment (M_LA90, M_LA50, M_MI_LF). They both grouped T2-T3-T5 into a second group which was negatively evaluated and characterised by a noisy sound environment. As shown in the PCA analyses, the coherence was reinforced by the fact that the same two stopping points T2 and T6 stand out within each group. However, the PCA of the acoustic indicators indicated that the description of the sound environments was enriched by the additional indicators M_LA10_90 and M_LA_sd for measuring sound variability (Can and Gauvreau, 2015). This supports the interest of taking measurements using such acoustic indicators, which are better correlated with sound perception by inhabitants.

The respondents demonstrated real expertise in diagnosing noise pollution (particularly related to road, rail and air traffic), not only based on noise intensity but also on its modulation over time and its more or less continuous nature, as already illustrated in Berry-Chikhaoui et al. (2014). Their diagnosis was based on the following criteria: distance from the noise source, morphology and configuration of buildings, and weather conditions (prevailing wind).

The correlation was significantly lower between SSH variables and micrometeorological indicators (RV coefficient = 0.23, Figure 8(b)). Except for wind indicators, the micrometeorological indicators did not make it possible to clearly distinguish the stopping points. Analysing the data together without separating the IOPs highlighted the predominance of seasonal variability (axis 1 explains 90% of the variability). Nonetheless, the cross-analysis of climate measurements and perceptions underlined the respondents' sensitivity to wind in their evaluation of stopping points (Lemonsu et al., 2018). This trend is observed along axis 2 (9% of the data variability) with a coherence between P_wind and M_wind, M_windsd, which was however buffered by other perceptions considered as more important by the respondents. For instance, T4 was objectively windy based on measurements, but greatly appreciated according to other criteria (comfort, cleanness, security, etc.).

Conclusion

This research helps to better understand the criteria that come into play in the assessment of environmental quality at the neighbourhood scale. The method involved: (i) a dedicated innovative protocol that involved both qualitative assessments and physical measurements of several environmental dimensions covering different periods of the day and different seasons, (ii) state-of-the-art statistical methods for the multi-level processing and analysis of a corpus of heterogeneous experimental data both from measurements and surveys.

Our work confirms the multidimensional nature of the overall evaluation of the living environment, associating strictly environmental dimensions (microclimate, acoustic ambience and air quality) with other dimensions such as the aesthetics of the places, the quality of their maintenance and the feeling of safety that they inspire. Our work allows us to go further in the understanding of the hierarchy of these different dimensions and in the clarification of the relations which exist between the appreciation of the environmental quality of places and their acoustic ambiences as given by the measurements.

Thanks to the analysis focused on individuals, it was possible to prioritise the different criteria involved in the assessment of the overall environmental quality of the places and highlighted the importance of noise and air quality that rank just after the aesthetic dimension for all respondents. Nevertheless, the quality of maintenance and the feeling of security that the place inspires seem to be as crucial as these environmental criteria for the inhabitants. This specific attitude of the inhabitants reflects the intimate relationship they develop with their living spaces and the high expectations they place on them in terms of safety and maintenance.

The analysis focused on the sites was carried out through a PCA on each corpus of data (perceptions, acoustic measurements, micrometeorological measurements), and then through CIA. The results highlighted the consistency between the typology of places based on perceptions and that based on acoustic measurements, which confirms the high inhabitants' sensitivity to this environmental component. Compared to previous studies, our multi-site approach consolidates this result by testing it on five contrasted urban sites.

Another meaningful result of this work was to build a new method that can be used to articulate the characterisation of the materiality of the urban environment (microclimate, soundscape, air quality, etc.) with the subjective and social characterisation of the living environment. This method results in the design of an innovative interdisciplinary experimental protocol for the simultaneous collection of physical parameter measurements and survey data on perceptions and representations.

One of the endpoints of this work was to adapt this protocol to build an innovative public action mechanism – named 'methodological guide for urban environmental requalification' – to produce diagnoses and urban design scenarios in an interdisciplinary and participative way. The guide retained the approach of combining physical measurements and survey data in order to enrich the usual territorial diagnoses by drawing up a shared inventory of the environmental quality of the area to requalify. In order to make the method applicable without any researcher involvement, a major simplification effort was made on the questionnaires and measurement protocols. Designed for outdoor urban spaces, the guide can be adapted to the available human and financial resources, the scales of urban intervention and the number of environmental components to be taken into account.

This research work showed the interest and feasibility of integrating a participative and instrumental component into territorial diagnoses, in order to better take onboard environmental quality in urban planning. The involvement of inhabitants is valuable to benefit from their expertise as users and from their ability to formulate expectations that can inform requalification scenarios. The instrumental approach helps to raise local actors' awareness of environmental quality and to add an objective dimension to perceived disturbances such as thermal stress or some types of atmospheric pollutions.

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