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Article

A Quantitative and Qualitative Experimental Framework for the Evaluation of Urban Soundscapes: Application to the City of Sidi Bou Saïd

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Abstract: This research introduces an experimental framework based on 3D acoustic and psychoacoustic sensors supplemented with ambisonics and sound morphological analysis, whose objective is to study urban soundscapes. A questionnaire that highlights the differences between what has been measured and what has been perceiveSd by humans complements the quantitative approach with a qualitative evaluation. The comparison of the measurements with the questionnaire provides a global vision of the perception of these soundscapes, as well as differences and similarities. The approach is experimented within the historical center of the Tunisian city of Sidi Bou Saïd, demonstrating that from a range of complementary protocols, a soundscape environment can be qualified. This framework provides an additional dimension to urban planning studies.

Keywords: environmental acoustics; urban heritage; soundscape; psychoacoustics

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1. Introduction

Sounds are often associated with the context of a particular place, time and activity and contribute to the characterization of an environment [1,2]. The term soundscape can be compared to the term landscape as used to characterize places; a soundscape is defined by all the sounds as they are perceived by humans in an environment [1]. It should be noted that the definition of the concept of "soundscape" has been subject to discussions in the literature, sometimes with divergences between a focus on the physical and acoustic dimensions versus the incorporation of human perceptual and cognitive aspects. We retain the consensus definition given by the ISO 12913-1 [3] standard, which considers the soundscape in its physical, perceptual and contextual dimensions. The notion of soundscape has been applied to a wide range of fields from urban planning to environmental acoustics and sound art, to mention a few [4]. An Italian musician defined soundscape as "All waveforms transmitted faithfully to our audio cortex by the ear and its mechanisms" [5]. Soundscapes generally reflect our experience of the sounds of an environment and have been widely applied to quantitative noise evaluations and pollution in urban environments [6,7]. Noise pollution in urban areas leads to the disturbance of the natural acoustic morphology of the environment, thus threatening the quality of life of various species, not only humans but also natural ones.

The interest in using psychoacoustic parameters in soundscape studies has been identified by Hall et al. [8]. Such approaches can identify acoustic properties in urban areas where noise pollution is a threat to human quality of life. On one hand, soundscapes are an integral part of human existence, and as such, they are a key factor in people's well-being [9,10]. On the other hand, noise is a major cause of psychological disorders such as stress and chronic diseases. Sounds affect the workings of the human mind; they inform our conscious and subconscious decisions. Over the past few years, urban designers have increasingly incorporated soundscapes as a relevant dimension into their planning studies and strategies [11–13]. Despite the importance of soundscapes in shaping human well-being, recent research still does not fully consider the psychoacoustic dimension, as it is generally based on quantitative approaches that evaluate harmful noise impacts on auditory perception and human health [14].

The search for a better understanding of a soundscape requires a multidisciplinary approach combining several experimental protocols as well as qualitative evaluations [15]. Recent developments in soundscape research have seen a growing emphasis on the integration of quantitative and qualitative approaches, as well as the application of novel technologies for soundscape characterization and design. Kang [16] provides a comprehensive review of the current state-of-the-art in soundscape research, highlighting the need for multidimensional frameworks that combine acoustic measurements with human perceptual assessments and the potential of such approaches for informing urban planning and design.

This paper introduces a multidimensional framework based on the integration of the acoustic and electroacoustic dimensions that extends a soundscape experimental environment developed in previous work [17]. This works takes it further by developing a series of complementary signal processing, analysis and visualizations that provide additional data acoustic and psychoacoustic interpretation capabilities of the peculiarities of the soundscapes that emerge from a given urban environment. To complete this quantitative dimension, a qualitative questionnaire reflects the perceptions of different user categories. The comparison of these quantitative and qualitative approaches favors the identification of similarities and differences between the measured and the perceived, on the whole bringing relevant elements of analysis and evaluation of urban soundscape atmospheres and further insights for the design of sustainable and healthy urban communities and cities [18]. Our approach can be qualified as exploratory and experimental research since it combines quantitative and qualitative dimensions [19]. The rest of this paper is structured as follows. Section 2 introduces the modelling background and related work, while Section 3 describes the modelling principles of our approach and the experimental setup. Section 4 develops the experiments applied to the urban context of the Tunisian city of Sidi Bou Saïd, and Section 5 discusses the findings. Finally, Section 6 concludes the paper and outlines a few perspectives.

2. Modelling Background and Related Work

2.1. Conflicting Soundscape Definitions

The concept of soundscape has been defined in different ways, leading to diverging perspectives on its meaning and scope. Some early definitions focused more narrowly on the physical and acoustic properties of the sonic environment, such as Southworth [20] describing soundscape as the "sonic environment of cities". Others have taken a broader view encompassing human perception, such as Schafer's foundational work [21] defining soundscape as the sounds perceived and understood by humans. Recent approaches have continued to differ on where the emphasis should lie regarding the soundscape. A few studies place more weight on the measurable acoustic aspects and noise impacts [6,7]. In contrast, other researchers highlight the importance of perceptual and cognitive factors in soundscape assessment [22–24]. According to Wiemann et al. [25], the ISO 12913-1 [3] definition marks an attempt to find consensus by differentiating the soundscape (perceptual construct) from the acoustic environment (physical phenomenon). This article adopts the ISO 12913-1 [3] definition as a broad framework, while specifically focusing on acoustic, psychoacoustic and perceptual dimensions as detailed in the following section.

2.2. Urban Soundscape Introduction

The concept of urban soundscape has been primarily introduced by Southworth [20]. This notion of an urban sound environment perceived by humans was explicitly mentioned and later popularized by Schafer in his book "The Tuning of the World (The

Soundscape)" [21]. A soundscape is a constituent element of the quality of an urban environment [26–29].

2.3. Consensus ISO Definition

The international standard ISO 12913-1 [3] introduces a consensus on the definition of a soundscape based on the diversity of current research contributions. According to Wiemann et al. [25], this international standard differentiates the soundscape (i.e., perceptual construction) from its acoustic environment (i.e., physical phenomenon). First, a soundscape can be qualified from the sound sources emanating from a landscape; they are classified into three main categories: geophony (i.e., sounds generated by geophysics), biophony (i.e., biologically produced sounds) and perceived anthrophony (i.e., sounds produced by machines) [22–24,30–32]. Secondly, A soundscape can be qualified not only from its intrinsic acoustic characteristics but also by its psychoacoustic and cognitive components [14,28,33,34]. Soundscape acoustics should evaluate, with appropriate sensors, different sound levels, low background noise, no echo or flutter and finally quality sound delivery [14,33,34].

On the cognitive side, the human perception of an environment soundscape can either emphasize a sense of well-being or discomfort [35–38]. Several authors have highlighted the role and potential of human perceptions in soundscape analysis [39–41]. The notion of well-being associated with humans offers a new perspective for the study of soundscapes, and that must be qualified by positive and negative perceptions [42]. Terhardt and Stoll [43] introduced a qualitative descriptor for determining the "pleasant" nature of noise. A calm soundscape gives a human a positive feeling of rest and tranquility [11]. Pheasant et al. [44] evaluate the quality of an environment as a "space that can facilitate a state of tranquillity" and therefore well-being. According to the ISO 12913-3 [45], qualitative perceptions of a soundscape, although partly subjective, should complement quantitative measurements. Axelsson et al. [22] suggested that the quality of perceived sound sources is a better indicator than sound levels alone.

Natural sounds contribute positively (e.g., birdsong), while technological sounds (e.g., road traffic) most often contribute negatively [46–49]. Several approaches introduced qualitative approaches to associate a soundscape with specific terms related to human perception and emotion: calm, pleasant, exciting, hectic, monotonous, boring and chaotic [3,22,50,51]. According to Fiebig et al. [2], emotions were first modelled as bipolar confrontation [52], a concept still relevant in the characterization of a soundscape such as "Pleasure"/"Unpleasure", "Tension"/"Relaxation" or "Stimulating"/"Soothing" [22,53].

These quantitative and qualitative parameters that reflect anthropogenic and non-anthropogenic soundscapes are of great importance to fully replicate complex environments, as they usually appear in urban contexts. Overall, these concepts and protocols offer novel opportunities for the modelling of urban soundscapes. However, it appears that there is still a need to integrate the complete extent and properties of the different physical dimensions associated with the notion of urban soundscape. These should be integrated using complementary sensors, interfaces, data manipulation and visualization capabilities that together provide a computational and interpretable framework. This is well-expected progress for the practical integration of the notion of concepts within feasible protocols. This leads us to introduce an experimental protocol and in situ application applied to the Tunisian city of Sidi Bou Saïd, made of a series of complementary real-time recording systems that (1) physically integrate soundscape data according to the acoustic and psychoacoustic dimensions, (2) complement them with 3-dimensional videos that materialize the physical environment and (3) a series of complementary visualizations that analyze the specific properties that emerge according to several spatial, temporal and semantic dimensions.

These quantitative soundscape measures and evaluations are supplemented by a qualitative questionnaire that expresses different human perceptions according to different levels of pleasure and displeasure and for different categories of users acting in the environment. The comparison of these quantitative and qualitative perceptions offers a valuable opportunity to exhibit differences and similarities between the measured and the perceived, about different user categories, places and as applied to different contextual environments, thus providing a series of insights on the respective impact of the diversity of soundscapes that have been identified.

Finally, our approach builds on standard methods such as ISO 12913 [3,45,50] and the model of Axelsson et al. [22], while introducing some adaptations. In particular, the work of Mitchell et al.l. [54] shows great methodological similarities with our experimental framework based on acoustic and psychoacoustic measurements as well as perceptual questionnaires. However, our approach is distinguished by the use of multidimensional visualization and analysis techniques for the measured soundscapes. Moreover, the questionnaire used here slightly differs from the standard attributes given in ISO 12913-2 [50]. These changes were introduced to better reflect the bipolar perceptions of pleasure/displeasure, rather than isolated attributes. They are justified by the need to adapt the standardized methods to the specific context of our case study and population, in order to best capture the diversity of perceived soundscapes. Thus, our approach relies on established methods while proposing extensions to address our issues.

3. Modelling Approach

This section introduces the principles of the quantitative and experimental modelling approach to the characterization of urban soundscapes, the data integration, processing and restitution systems, as well as the qualitative questionnaire that reflect the inhabitants' and users' perception of the soundscape of a given urban environment. The respective components of the modelling framework combine a quantitative approach, an experimental setup, data representation and processing capabilities and a qualitative questionnaire.

3.1. Quantitative Approach

The quantitative approach is based on the following (Figure 1):

- A series of complementary techniques for the integration of sounds at different levels of abstraction, from ambisonics to acoustic, psychoacoustic to immersive, to reflect the widest possible spectrum of soundscape physical realities;
- A wide variety of processing and analysis to associate sound measurements to urban places, through their immersion in virtual representations that replicate the physical environment of the places observed;
- Two sound morphological aggregated indices that favor the interpretation of the soundscape patterns that emerge: loudness and sharpness that respectively reflect the sound pressure level and the sensation reflected by high-frequency sounds;
- A qualitative field survey which has the objective to compare these different levels of sound quantitative measurements with the perceptions of different categories of humans acting in these environments.

The objective is to generate a virtual soundscape environment that "transfigures" the places observed into complementary physical replications according to different acoustic and psychoacoustic dimensions and then associate them with humans' positive and negative perceptions (from pleasant to unpleasant perceptions). The approach is applied to 16 locations previously chosen for their quality and diversity in the Tunisian city of Sidi Bou Saïd, a historical place that encompasses a rich variety of urban environments.

3.1.1. Soundscape 3-Dimensional Analysis and Visualization

The data processing, restitution and analysis of urban soundscapes are based on a combination of interactive psychoacoustic and acoustic data integration processes applied to the specific places selected in the urban environment. The restitution methods selected for the modelling of soundscape environments respectively identify the acoustic and psychoacoustic characteristics. The first approach, derived from signal processing, is based on a spectrogram that gives a time/frequency visual representation of a sound signal amplitude valued by intensities (Figure 2a: yellow for a high amplitude to red and black for no signal). Such a sound signal gives the morphology frequency wherein interpretation is conducted according to specific known properties of the environment. For implementation purposes, O3A Flare (Figure 2c), one of the main plug-in libraries of "Blue Ripple Sound" has been applied. It gives an ambisonic 3D representation of superior order, whose interest is to reflect the extent of the sound variability in a three-dimensional space [55]. The second sensor used, NX Virtual Mix Room (Ambisonics Quad), from the WAVES family of plug-ins, is a real-time analysis system that represents the direction of sounds in Ambisonics channels (Figure 2b). The directional components of the interpreted sounds are projected onto a sphere, which retains the spatial dimension and the cardinal directions, azimuths and elevations. Figure 2d gives an interactive link by QR code to a video for an illustration of a visual interpretation.

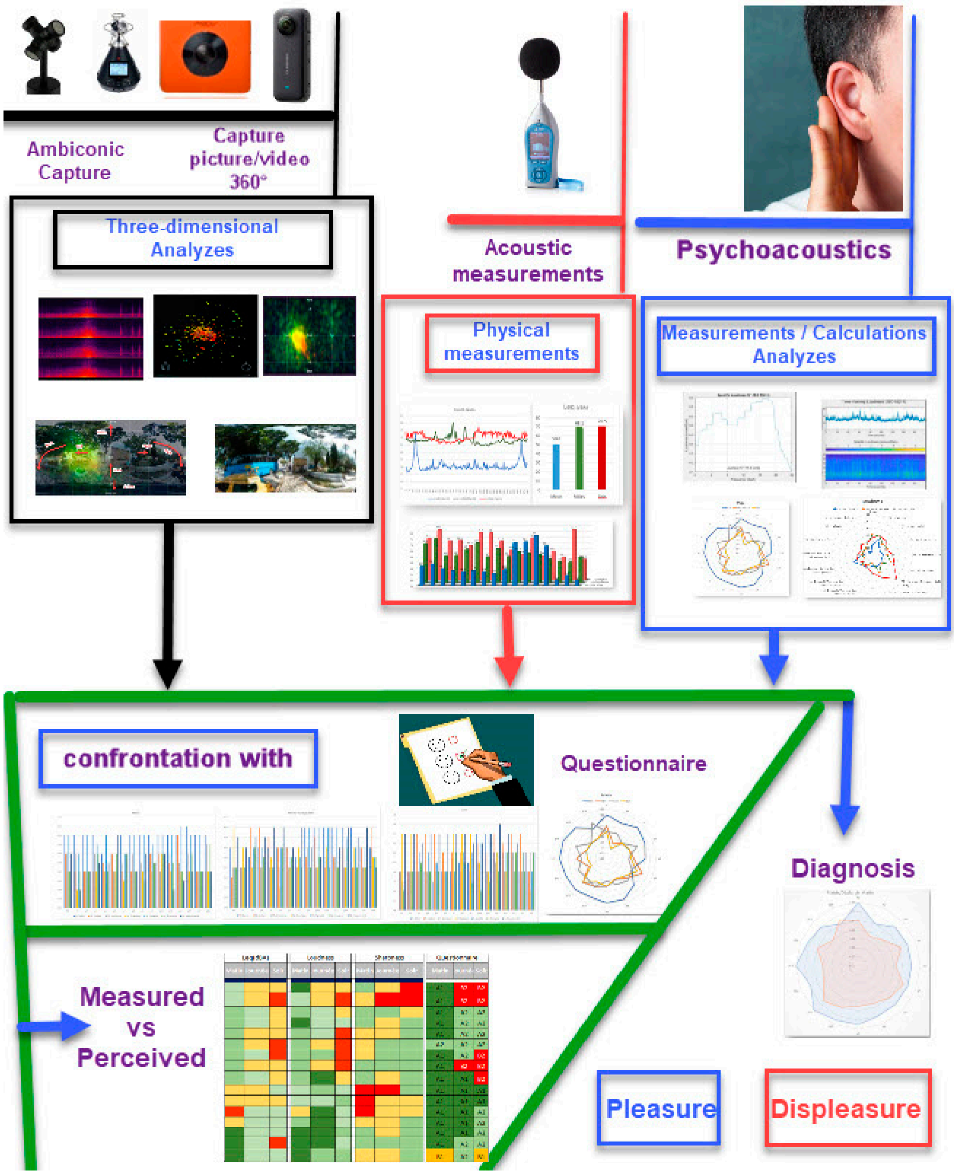
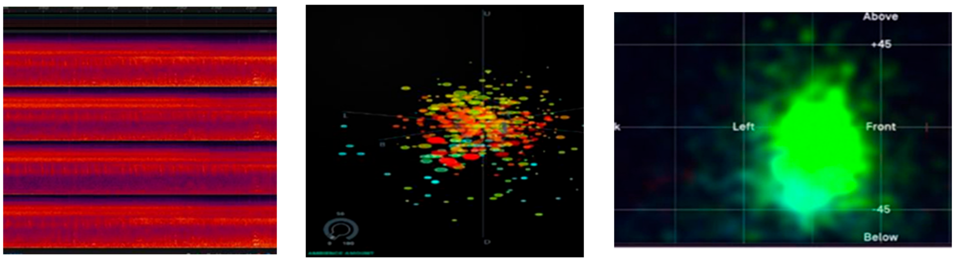


Figure 1. Methodological principles.

3.1.2. Psychoacoustic Modelling

The substantial amount of recent works on the modelling and interpretation of sound environments has enabled the implementation of ISO standards combining soundscapes and psychoacoustics [50,56–58]. This provides a reference for data collection, while ISO

1293-1 [3] gives sound support for conceptualizing the relation between psychoacoustics, acoustics and human perceptions. Among the different soundscape metrics identified, two important ones are loudness and sharpness. The loudness evaluates the energy impact on humans from an acoustic point of view; it denotes the sound level perceived on a linear scale and is fixed by the ISO 532-1 standard [59]. Sharpness measures the sensation caused by high frequencies contained in noise and implies whether its high-frequency components are likely to affect humans or not [60]. These two metrics are particularly appropriate for a psychoacoustic analysis of urban sound environments. Other specific indices such as sound fluctuations over time or roughness for rapid variations are not retained for our approach but could be explored in further work. Several diagrams (Figure 3) highlight the specific outputs generated by sharpness and loudness properties. The three sub-figures in Figure 3 illustrate different aspects of the psychoacoustic analysis. Figure 3a shows the specific loudness (N) as defined by ISO 532-1 [59], which represents the loudness distribution across different frequency bands. Figure 3b displays the time-varying loudness, also defined by ISO 532-1, indicating how the overall loudness changes over time. Figure 3c presents the time-varying sharpness, as defined by DIN 45692 [61], which describes the high-frequency content of the sound and its evolution over time. Together, these diagrams provide a comprehensive view of the psychoacoustic characteristics of the analyzed soundscapes and a detailed interpretation of their perceptual properties.

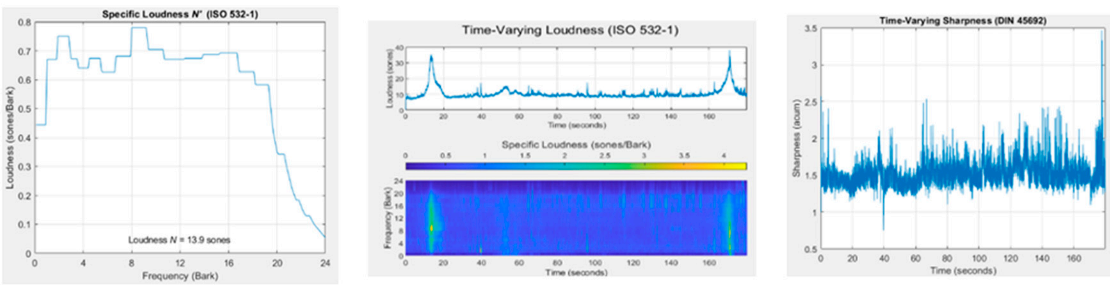


(**a**) (**b**) (**c**)

https://bit.ly/v-3-d

(**d**)

Figure 2. Soundscape visual representations. (**a**) Spectrogram. (**b**) NX Virtual Mix Room. (**c**) O3A Flare. (**d**) Visualisation tools.



a b c

Figure 3. Loudness and sharpness examples.

Additional relevant references on psychoacoustic analysis of soundscapes have been incorporated. Hall [62] evaluated various psychoacoustic metrics for urban soundscape assessment. Yang [63] examined sharpness, fluctuation strength and roughness for soundscape evaluation. Aletta et al. [64] analyzed psychoacoustic annoyance in urban parks. Millán-Castillo et al. [65] applied psychoacoustics to analyze acoustic environments. Lawrence [66] reviewed various psychoacoustic indicators used in soundscape studies. Ooi et al. [67] developed a model using psychoacoustic metrics to predict soundscape quality. Ooi et al. [68] applied psychoacoustic analysis to characterize urban soundscapes.

3.2. Questionnaire

Let us introduce the principles behind the questionnaire that gives a qualitative model of the humans' perception of a given soundscape. The survey is conducted by confronting "Pleasure"/"Displeasure" sentiments to support an interpretation much more in reference to positive or negative perceptions, from four bipolar factors (A1, A2, B1, B2) using the seven classes of terms related to perception and human emotion, grouped to define more homogeneous and easier to interpret categories.

The four bipolar factors are based on an aggregation of terms from the soundscape circumplex initially proposed by Axelsson et al. [22] and later adopted as a standard structure in ISO 12913-2 [50]. The seven scales used were the following: Calm, Chaotic, Monotonous, Eventful, Pleasant, Unpleasant and Vibrant. Notably, the Unpleasant attribute was intentionally utilized in deriving both the B1 and B2 factors. The four bipolar factor ratings (A1, A2, B1, B2) were calculated from the seven attribute scale ratings through an averaging model. The A1 rating is obtained by averaging the Calm and Pleasant scale ratings. The A2 rating is derived from the Eventful and Vibrant ratings. The B1 rating used the Monotonous and Unpleasant ratings, while B2 is derived from Chaotic and Unpleasant. This model condensed the multidimensional perceptual responses into four summary factors for analysis. The four bipolar factors (A1, A2, B1, B2) are calculated from these seven attribute scales, with the Unpleasant attribute repeated in computing the B1 and B2 factors. This redundancy emphasized the Pleasant/Unpleasant distinctions when consolidating into four summary dimensions, an approach adopted from Liu et al. [69]. To simplify the number of perceptual dimensions for respondents, we adapted this structure into four broader bipolar factors rather than retaining the eight unipolar factors of the circumplex. Our factors A1 and A2 relate to the pleasantness dimension, while B1 and B2 represent unpleasantness. This adaption of the standard circumplex was necessary to tailor the questionnaire to our specific context while retaining links to established soundscape models. This adaption condensed the multidimensional model into four summary factors to focus the key perceptual dimensions for our specific urban context and research goals. The factors retain links to the pleasantness–eventfulness attributes while simplifying the questionnaire. Tailoring an established soundscape framework was necessary to optimize the survey for this study. This novel adaption represents a methodological contribution for focused soundscape assessment.

- A: Pleasure
    - A1: Calm + Pleasant: Relaxing and calm
    - A2: Exciting + Eventful: Pleasant and rich in events
- B: Displeasure
    - B1: Monotonous + Boring: Unpleasant and without events
    - B2: Chaotic + Eventful: Unpleasant and rich in events

Several preliminary constraints are applied to ensure the effectiveness and accuracy of the questionnaire. First, according to [50,70–72], survey participants must be identified and the conditions of their selection specified (e.g., residents or external visitors to the place, experts or not, age, gender, hearing ability). The subjective nature of soundscape perception based on an individual's cultural background and personal experiences is another important factor to consider. While the initial case study did not explicitly account for these anthropological influences, incorporating this context more fully could enrich the analysis. For example, examining variations in responses across cultural groups represents a valuable direction for further refining the questionnaire. The choice of the questions and terms used and their exact translations in the case of diverse cultural communities are considered [50]. Such evaluations must cover a wide range of auditory sensations and all the contextual variables to fully understand the place from a social point of view (i.e., different categories of populations from regular to irregular usages). It is in this context and under these constraints that such a qualitative questionnaire can be compared to physical measurements. This indeed applies to a certain degree as it has been shown that personal and contextual characteristics are likely to impact soundscape evaluations [27]. This confrontation of acoustic and psychoacoustic measurements with this social dimension supports an experimental validation of our modelling approach and possibly the elements of analysis and reproduction of the approach in other urban contexts.

In the context of our research, the respondents were divided into three main categories representing different users' interactions with the environment and perceptions. For instance, usual users of this urban environment have a perception of the sound environments strongly influenced by their knowledge of the place and habits and therefore are likely to be sensitive to unusual and/or accidental sounds, whereas people visiting the site would be more strongly inclined to perceive sounds of new cultural interest to them [28,54,68,73]. These users with a knowledge of the environment have been placed in a category with the B label. A second group is made up of tourists who have a different sensitivity from the other groups because they are in discovery mode while bringing their own culture and perception; this group has the label C. A third group, with label A, has been created, essentially composed of experts or professionals working in these places and potentially less sensitive to sound environments and who can give a more thoughtful interpretation of the sound morphology of the places. All respondents have been made aware of the objective of the questionnaire and have consented to have their responses processed in accordance with privacy and confidentiality rules.

4. Experimental Results

After establishing the methodological framework, this section presents the implementation of the proposed approach through a case study conducted in the Tunisian city of Sidi Bou Said. The experimental design follows a systematic protocol to collect complementary soundscape data across multiple locations in the urban environment. Both quantitative measurements and qualitative surveys are carried out to characterize the soundscapes from various perspectives. The results are structured to first illustrate findings from select representative points of interest across the three daily periods—morning, midday, and evening. Following these specific examples, the section summarizes the acoustic, psychoacoustic and perceptual measurements for all locations through graphical analysis. Finally, the measured quantitative soundscape properties are compared and contrasted with the human subjective evaluations to reveal key similarities and differences between the objective and perceived soundscapes. The case study provides a practical demonstration of the multidimensional framework for soundscape assessment proposed in this research.

4.1. Experimental Protocol

The experimental protocol (Figure 4) is based on several successive and complementary methodological steps:

1. An exploratory survey that identified the most significant locations of interest and that reflect places rich in heritage, activities and soundscape: we selected the urban center of the small Tunisian city of Sidi Bou Saïd, which has several very lively urban streets and which conceals a wide variety of commercial and tourist activities that generate a wide range of soundscapes.
2. The deployment of sound and acoustic experimental sensors and their calibration to validate the veracity and accuracy of the results: several locations are carried out on the Sidi Bou Saïd site, and the first audio/video recordings were made to check the feasibility of the operation.
3. A descriptive analysis of the urban space and the sound environment: the development and implementation of the questionnaire by a population panel representative of different user communities.
4. Prospective work in the field that allows sound acquisition and production: recordings of sound facts continuously and for time intervals necessary for the diagnosis of this soundscape.

5. In parallel with phase 4, the collection of questionnaire data and comparative analysis between the analysis of the questionnaire data and the acoustic and psychoacoustic measurements when possible.
6. Establishment of a database to store and process all of the soundscape data.

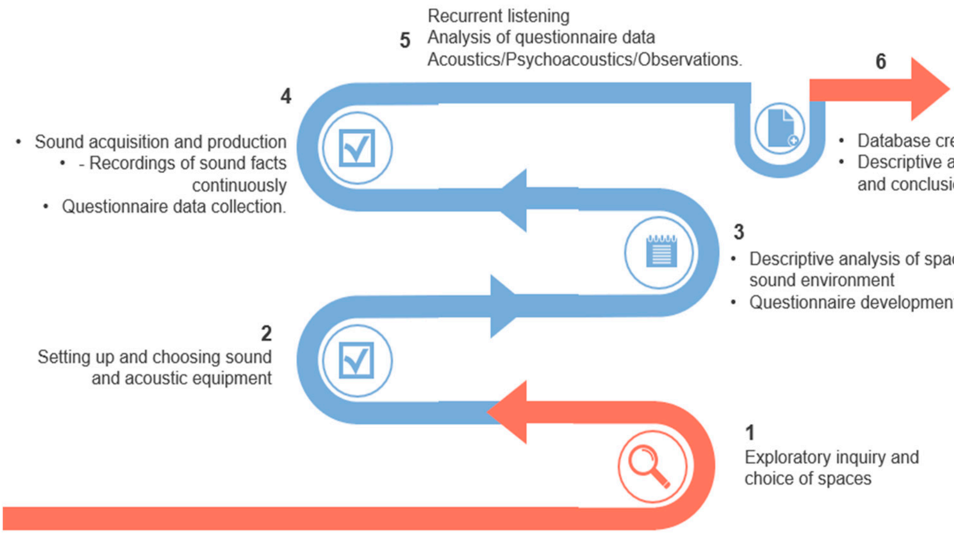


Figure 4. Experimental protocol principles.

4.2. Case Study: Sidi Bou Saïd

Sidi Bou Said is a small city in northern Tunisia 20 kilometers northeast of the capital with about 6000 inhabitants. It is a rich historical place with an urban route that takes place on a progression of alleys including two ancient cafes, a wealth of heritage, several craft shops with hotels and restaurants nearby and a cliff overlooking the sea and the marina; we have chosen 16 measurement and experimentation locations (Figure 5). Before the start of the measurement campaign, several in situ acoustic surveys were carried out over the two days preceding the experiments and measurements, to immerse ourselves in the location. First, 360° videos were made for a realistic reproduction of the place and these routes. Secondly, continuous measurements were taken at the center of the route, which is rich in heritage, that is, two historic cafes and the Zaouïa (place of worship). This experiment was carried out in two days for a total recording time of 19 h and 30 min and 132 sound "accidents" were recorded during the entire investigation period of 1170 min. Our investigation followed the following temporal plan (Figure 6). This preliminary investigation allowed us to highlight the taxonomy and sound characteristics of the urban environment (Figure 7).

Figure 5. Case study locations (16 locations).

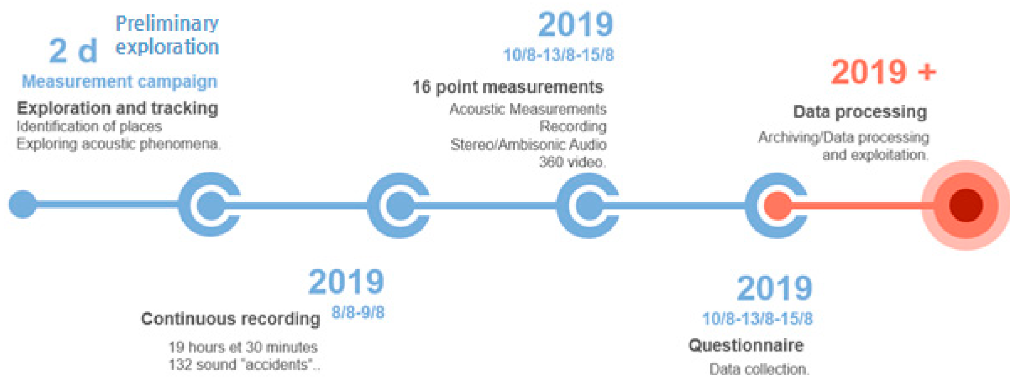


Figure 6. Experiment timeline.

Anthrophonic	**Human**	Hubbub, screams Cocktail effect Child games Movement, step, Laugh, voice Card games (shouting, discussion)
	Artificial - Autonomous	Bus, truck, motorcycle car Mosque loudspeaker: prayer call Ringtone Cell Phones Power generator
	Artificial - Man-made	Road police whistle Crafts – darbuka percussion Craft – plate carving Dishes Suitcases (tourist arrival), Hookah smoking Train whistle Honk Bicycle Municipal equipment
Biophonic	**Wildlife**	Cats Dogs Insects Birds
Geophonic	**Nature**	Wind Wind on the trees. Water flow (fountain)

Figure 7. Soundscape taxonomy and characteristics of the case study environment.

4.3. Data Integration

The detailed methodology behind the soundscape questionnaire is presented in Section 3.2. Here, we describe the protocols for data collection and integration. The data collection campaign is carried out for the 16 places selected for their sound and heritage richness. For each measurement (morning/middle of the day/evening), a continuous recording with a duration of three minutes was performed using the standard ISO 12913-2 [50] to capture the representative sound environment and its morphology. Figure 8 provides an overview of the key steps involved in the soundscape data collection at each location. Before starting the recordings, the equipment is stabilized and calibrated, the precise location mapped, meteorological conditions checked and wind protections set up. The date, time and site heritage significance are documented. The actual recordings are then captured over a continuous 3 min duration, involving simultaneous ambisonic, stereo audio, 360° video and acoustic measurements. Finally, a post-recording check is conducted to verify and annotate the collected data before moving to the next site. This standardized procedure following ISO 12913-2 [50] ensures consistent and comparable high-quality soundscape recordings across all 16 measurement locations in the study area. The soundscape data collected, including audio recordings, acoustic metrics, survey responses and metadata, are stored in categorized files. These files are documented with timestamps, locations, time periods and measurement types. Additional details on the structure and content of these data files are available to enable reproducibility and secondary usage.

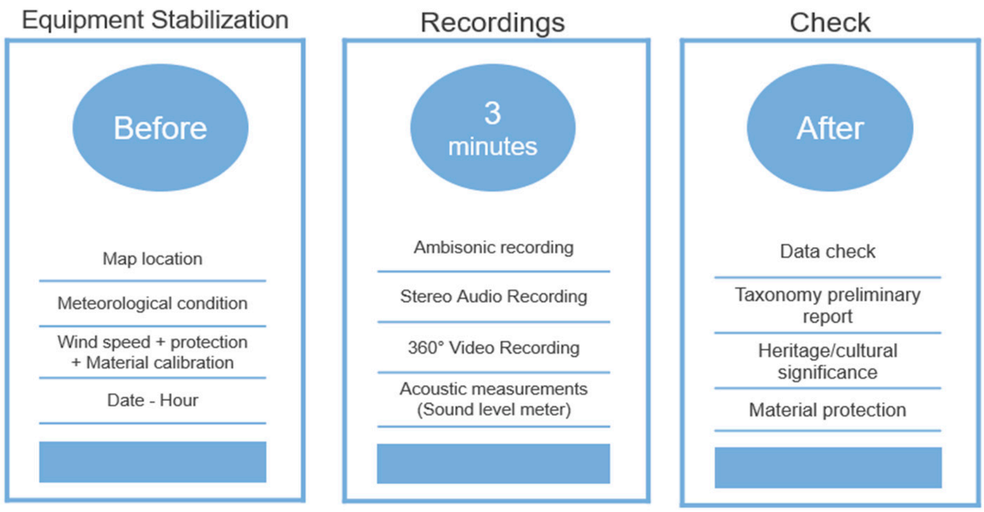


Figure 8. Recording protocols.

The questionnaire collection campaign was carried out in parallel by three people. The panel included 91 men and 81 women aged between 18 and 66 (Figure 9). To evaluate their audibility, a rapid listening test of three frequencies was carried out; the questionnaire written in French required a translation of the terms in the Tunisian dialect for some users. Respondents were divided into three main categories:

- Group A: Experts, i.e., technicians and municipal workers who operate in the urban area;
- Group B: Permanent or temporary Tunisian users;
- Group C: Foreign visitors (tourists).

Nbre	H	F	H+F	%
A	15	20	35	20
B	60	51	111	65
C	16	10	26	15
ABC	91	81	172	100

Age	Nbre	%
1: <18	0	0
2: 18 – 25 ans	28	16
3: 26 – 35 ans	50	29
4: 36 – 50 ans	49	28
5: 50 ans et plus	45	26
	172	100

Age/SD	Age/Mean
13.16	39.41

Figure 9. Survey panel.

The questionnaire for soundscape assessments was developed to correlate it as much as possible with the physical measurements. This questionnaire consists of two sections. The first section includes demographic information, including gender, age and noise sensitivity. The second section is related to soundscape perception. The participants were invited to evaluate the identification of the sound sources at each location and to try to describe the sound experience of the place. The environment at each location was also rated using seven qualitative attributes: boring, quiet, chaotic, hectic, monotonous, pleasant and exciting with a progressive satisfaction scale ranging from 1 to 5, following the guidelines of the standards ISO 12913-3 and ISO 12913-2 [45,50]. The scale used is the Likert psychometric tool [74].

4.4. Results

The experimental principles have been applied to all case study locations. We first illustrate the complete findings of three significant and representative places of interest, before being summarized and discussed.

4.4.1. Location 1: The Garden

The outputs of the first location are presented throughout the three periods: morning/middle of the day and evening (Figure 10). The respective acoustics, psychoacoustics and three-dimensional analysis are given. One can notice that in the middle of the day and the evening, the environment is relatively noisy. At the top of the diagram, one can observe some sound accidents visible with the green color while showing their spatial location. Psychoacoustics gives us additional information, such as for the middle of the day where sharpness denotes an acute environment due to the presence of insects.

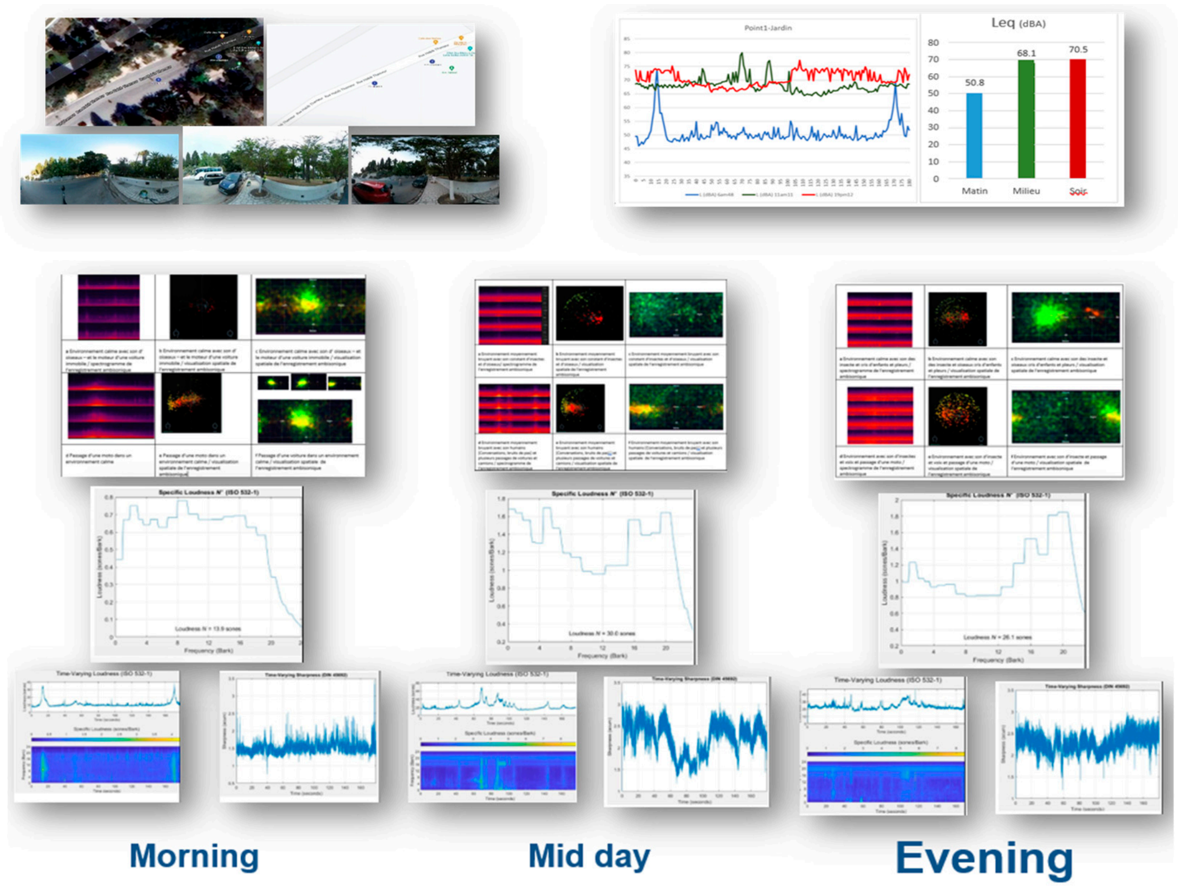


Figure 10. The garden. High-definition version.

4.4.2. Location 2: The Fountain

One can notice that in the middle of the day and the evening, the environment is also relatively noisy, but there are different sound accidents as the fountain water is collected by visitors (Figure 11). The three-dimensional analysis highlights the sound accidents and locates them in space. As illustrated in Figure 12, the location of the sound of the parked car with its engine moving slightly to the left is replicated; indeed, Figure 12 provides a 3D representation of the fountain soundscape, locating specific sound events within the panoramic visual scene and the colors indicate the frequency and amplitude characteristics of the sound. It maps the spatialized placement of the parked car's engine noise detected during measurements. This immersive visualization replicates how the sound was perceived emanating slightly from the left in the physical environment. The ambisonic rendering models the sound field and illustrates auditory event localization.

4.4.3. Location 6: Cafe Sidi Amor

The location 6 Cafe Sidi Amor represents a place with different functions than points 1 and 2. This place is characterized by the presence of two cafes and craft shops. The soundscape environment increases especially at night by its volume; several sound accidents related to craft activity are detected, but the environment is less sharp than the other previous points (Figure 13).

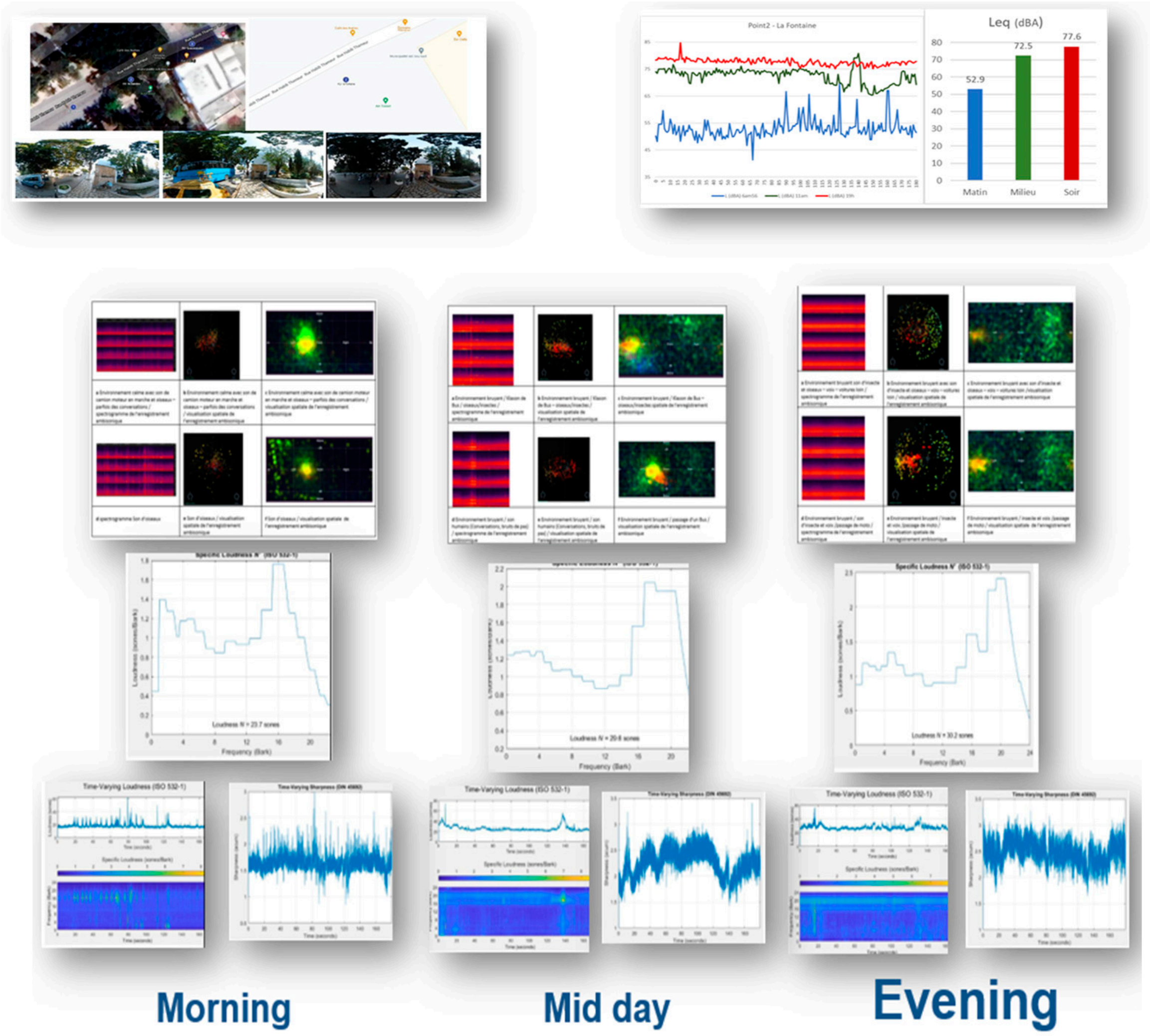


Figure 11. The fountain. high-definition version.

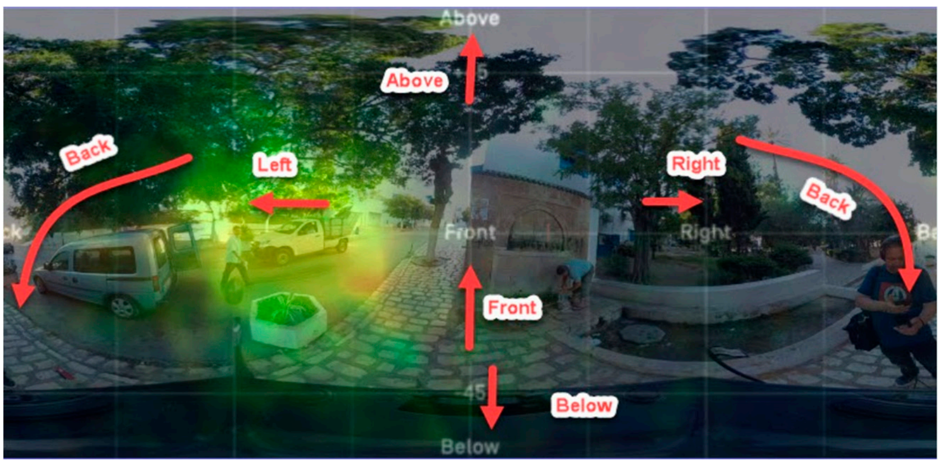


Figure 12. The fountain/sound accident.

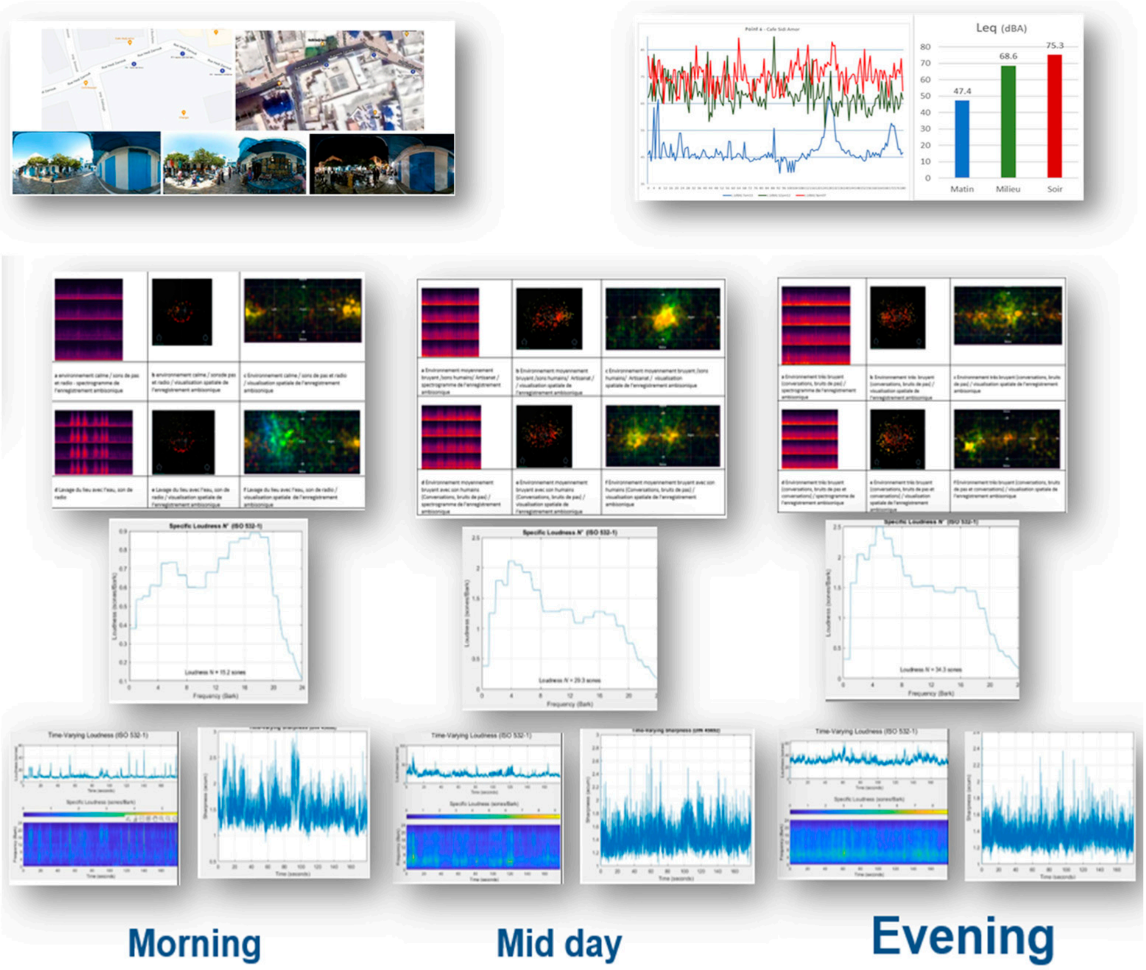


Figure 13. Cafe Sidi Amor. High-definition version.

The 360° video and 3D audio illustrate and identify the evolution of sounds in a three-dimensional and temporal space as things happened when registered (Figure 14).

Immersive analysis Panoramic analysis

Figure 14. Immersive and panoramic analysis (videos: https://youtu.be/tlLhga5xo3o, accessed on August 2019; https://youtu.be/sTUtPowcQyY, accessed on August 2019).

4.5. Soundscape Acoustic Morphology

All the global and local acoustic morphologies of the 16 locations of interest are presented and illustrated in Figure 15 with a histogram visualization that reflects each period of the day. A radar visualization complements the histogram and facilitates the perception of emerging trends and differences. It presents the equivalent continuous A-weighted sound pressure level and characterizes the acoustic intensity by identifying soundscape differences and similarities.

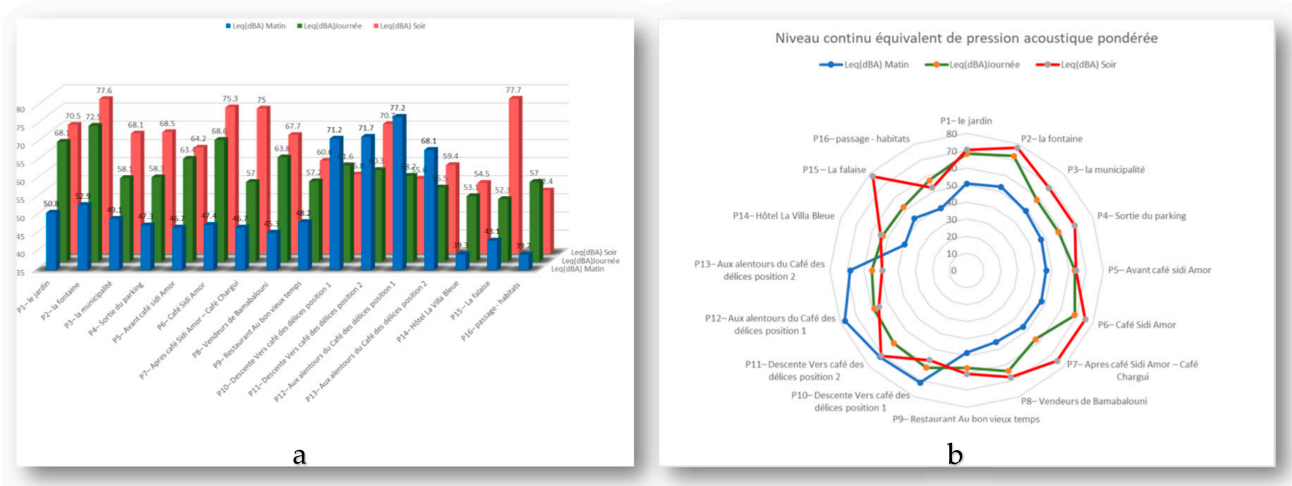


Figure 15. Equivalent continuous level of weighted sound pressure: (**a**) histogram visualization; (**b**) radar visualization. High-definition version.

4.6. Soundscape Psychoacoustic Morphology

Figure 16 presents a visualization of the psychoacoustic morphology of the soundscapes at each location, using (a) loudness and (b) sharpness metrics. This approach provides a more "humanized" interpretation layer of the perceived sound sensations, allowing for the identification of places experienced as loud or sharp. The psychoacoustic patterns show similarities to those detected by the acoustic measurements. However, some differences are noted, such as at location 15 near the cliff, where acoustic measurements indicate high noise levels, but human perceptions characterize it as moderately calm. This discrepancy likely arises from the specific nature of the sound signals related to the users and architecture of these places.

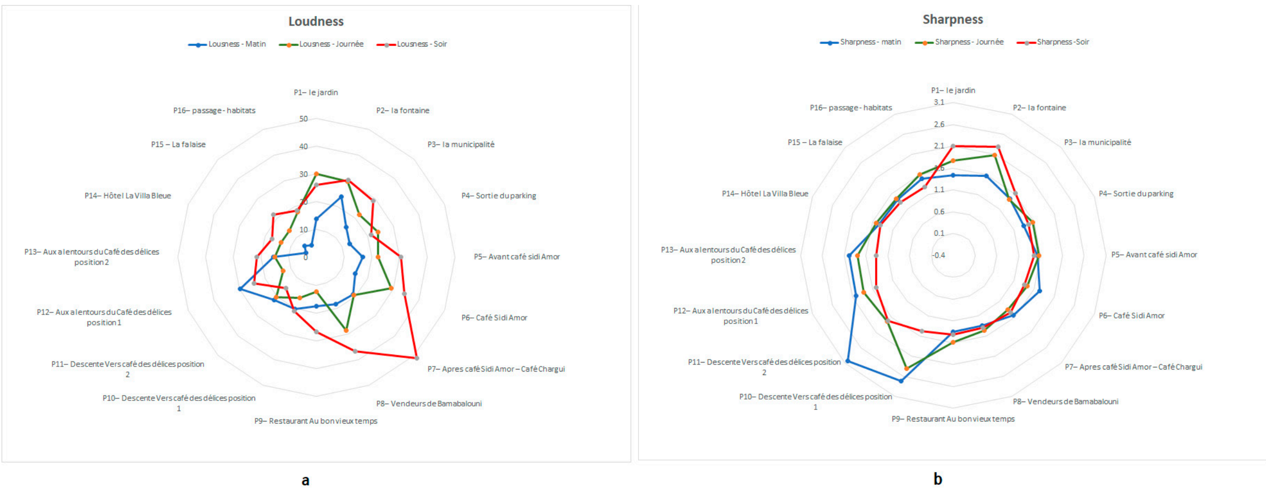
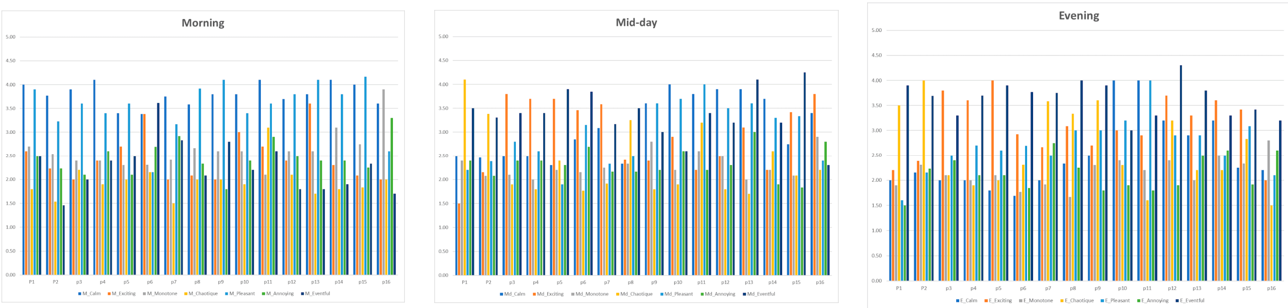


Figure 16. Psychoacoustics of the morning/middle of the day/evening urban environment: (**a**) loudness; (**b**) sharpness. High-definition version.

The cafe in location 7 reflects an important value of loudness in the evening, this being caused by a peak activity. The interest of this psychoacoustic representation is that it provides a global view of the soundscape morphology, cross-analysis of differences and similarities along the different locations of the historical city center and then possible regulation actions.

4.7. Questionnaire Data

The questionnaire supplements the quantitative measurements with a qualitative assessment implemented by a series of attributes that qualify all the soundscape locations during the three periods of the day (Figure 17).



Morning Mid day Evening

Figure 17. Median rating values on a scale of 1 to 5 are plotted for each of the 7 attributes below, based on the questionnaire responses from 172 participants. **Annoying; Calm; Chaotic; Eventful; Monotone; Pleasant; Exciting (Standards (ISO 12913-2 [50]; (ISO 12913-3 [45])**. High-definition version.

As made for the quantitative measurements, differences and even similarities were presented and qualified using the binomials A1, A2, B1 and B2 between the morning, the middle of the day and the evening (Figure 18).

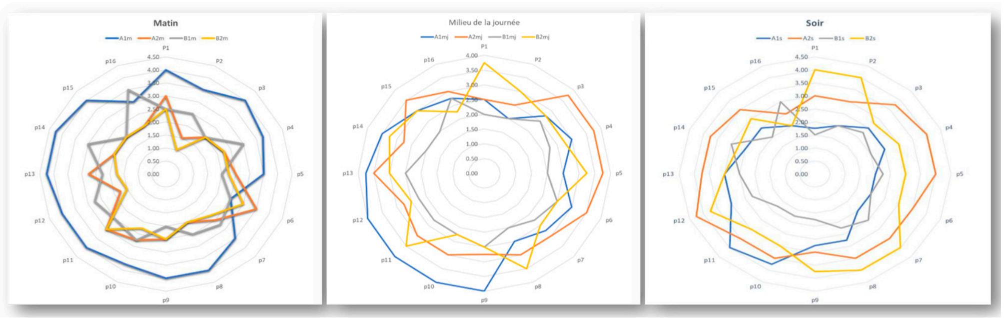


Figure 18. Radar representation of questionnaire responses/sound quality criteria. High-definition version.

This qualitative representation completes the quantitative measurements, by qualifying the different soundscape perceptions by the notions of pleasure and displeasure (Figure 19). This shows that, overall, pleasure is predominant in the majority of the locations except a few ones through the three periods as there is displeasure in the middle of the day and the evening for locations 1 and 2 and in the evening for locations 1, 2 and 7. As revealed by previous studies, local events such as bus and car crossing do not substantially modify the overall positive acoustic perception of an environment [75].

Figures 20 and 21 provide further analysis on the identification of soundscape typologies and the comparison between measured and perceived soundscapes. Figure 20 shows the taxonomy of sounds identified by survey respondents at each location and period. This builds on the taxonomy derived from initial measurements in Figure 7, validating that human perceivers were able to broadly recognize the key sound types constituting the soundscape such as voices, craft noises, music, etc. The importance of these identifiable soundscapes is highlighted since humans can intuitively perceive the typologies, even without conscious knowledge. Figure 21 summarizes the similarities and differences between quantitative acoustic and psychoacoustic measurements and the qualitative soundscape perceptions from the questionnaire.

Figure 19. Questionnaire answers: pleasure/displeasure criteria. High-definition version.

Figure 20. Questionnaire answers/taxonomy of the urban environment.

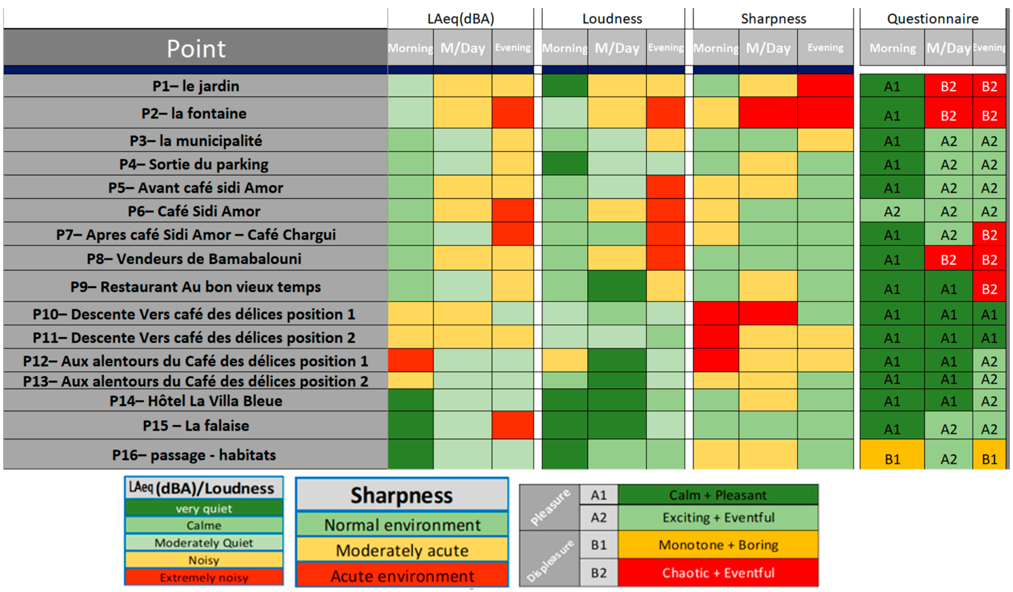


Figure 21. From the measured to the perceived. (color coding allows easy reading of attributes).

4.8. From the Measured to the Perceived (Similarities and Differences)

Soundscape similarities and differences are presented according to the acoustic measurements of the LAeq (dB) and the results of the psychoacoustics, namely the *loudness* and the *sharpness* compared to the questionnaire outputs (Figure 21). While overall trends were consistent, Figure 21 reveals divergences at specific locations and times of day, demonstrating the value of complementing physical measurements with human subjective responses to fully characterize a soundscape. The conjunction of Figures 20 and 21 provides cross-validation between data-driven and perceptual approaches to soundscape classification.

This highlights the differences between the calculated and the perceived, for example, the panelists characterized the location 6 "café Sidi Amor" all day as A2 (Exciting + Eventful), that is to say rich in events and pleasant (Figure 22). For instance, locations P6 and P7 were both measured as extremely noisy in the evening based on objective indicators. However, P6 was rated as A2 (Exciting + Lively) while P7 was rated as B2 (Chaotic + Lively) in the questionnaire results. This difference can be attributed to the distinct sound sources and context of each place. P6 contains lively cafes and artisanal shops, so the loud volume is associated with positive commercial and social activity. In contrast, P7 has amateur musicians and religious prayers in the evening that were negatively perceived by some respondents, especially Group A, leading to a B2 rating despite similar loudness levels. Analyzing the divergent subjective ratings for the equally loud P6 and P7 highlights that soundscape perception depends not just on loudness but also on the type of human activity and personal attributions. The original context and function of a space can shape whether it is interpreted as pleasant or unpleasant. On the contrary, the acoustic and psychoacoustic measurements indicate that the place is quite noisy, but it appeared that all the interviewees should have expected this type of atmosphere for an environment specific to entertainment, which shows the influence of the context and the function of the place in the interpretation of these soundscape environments.

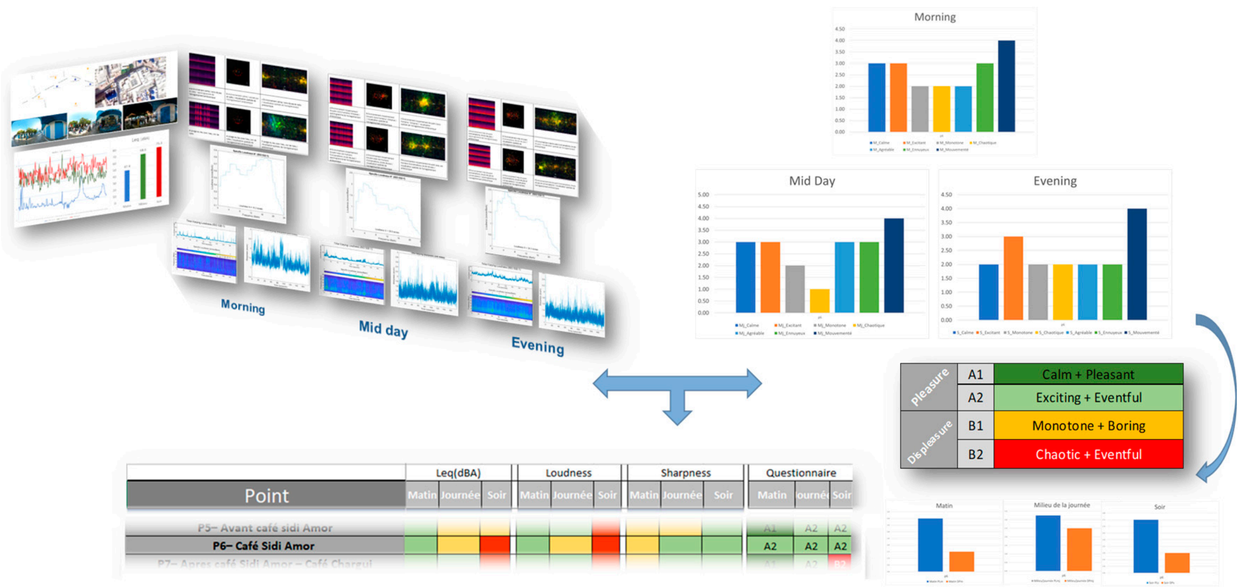


Figure 22. From measured to perceived (similarities and differences). Case of location 6—Cafe Sidi Amor. High-definition version.

5. Discussion

The application of the experimental framework to the case study provides a series of significant findings. First, the whole framework has been applied in a real context and outlines a series of valuable spatiotemporal soundscape properties that reflect the diversity of an urban environment. Not only the physical soundscape peculiarities are identified, but also the associated human and natural behaviors and the whole quantitative soundscape characteristics are identified in relation to the different acoustic and psychoacoustic dimensions. Overall, it exhibits the richness of the soundscapes of Sidi Bou Saïd, its diversity of activities, uses and dynamics.

The multi-faceted methodology encompassing ambisonic recordings, acoustic and psychoacoustic analysis, questionnaire surveys and immersive visualizations provides a comprehensive characterization of the soundscapes. Each component offers complementary insights, from quantifying sound levels to capturing human perceptions. This underscores the importance of a holistic approach integrating both physical measurements and qualitative assessments.

The soundscape morphology is identified by our experimental approach and analyzed according to different spatial, temporal and semantic dimensions. This shows that the physical acoustic measures have most often been confirmed and complemented by the humans' perceptions as reflected by the questionnaires. Sidi Bou Saïd is a diverse environment in terms of atmosphere and events. Despite the low number of locations, the soundscapes are very different. Time, space and the function of the place play an important role in the sound morphology of the place. It also appears that the measured is not always the same as the perceived, and the complementary visual interfaces offer a complete extent of capabilities to interpret the different soundscapes, their complexity, as well as differences and similarities that appear across the whole points of interest.

While overall trends are aligned, this study reveals instances where human subjective evaluations diverged from the objective physical measurements. This highlights the complexities of soundscape perception and the influence of factors like context, activity and place identity. The framework presented supports the analysis of these differences through the multidimensional lens of acoustics, psychoacoustics, questionnaires and immersive 3D visualization. Such an approach provides a more nuanced understanding of soundscapes as perceived experiences. The case study results demonstrate the framework's capabilities for assessing and differentiating urban sound environments across time and space. Additional work could expand to further locations and soundscape types, as well as exploring predictive soundscape modelling based on the collected acoustic and questionnaire data. From a methodological perspective, future research could incorporate other ambisonic, statistical and geospatial techniques for enhanced soundscape mapping and classification. Overall, the experimental framework offers an integrative foundation to advance urban soundscape research, supporting sustainable design and positive human experiences.

6. Conclusions and Future Work

This paper introduces a multidimensional methodology based on complementary three-dimensional analysis tools supported by psychoacoustics and an experimental protocol for qualifying urban soundscape environments. The contribution and findings of this research are summarized as follows:

1. The quantitative experimental approach introduces a quantitative approach that integrates the different acoustic and psychoacoustic soundscape dimensions. It provides a complete framework for the quantitative characterization of urban sound environments. The complementary qualitative study based on a social field survey provides a complementary vision that enriches the experimental component by a cross-comparison of the physical and perceived soundscapes.
2. We developed an experimental environment based on several two-dimensional and three-dimensional sound sensors that together provide a finer characterization of an urban environment soundscape. The combination of 2D and 360° images offers a full range of characterization and understanding of urban soundscapes.
3. The complementary data processing and visualization interfaces support the analysis of sound morphologies across multiple dimensions. This extensively evaluates the acoustic and psychoacoustic perceptions in space and time.

4. A qualitative questionnaire has been tested and experimented with, which highlights some emerging differences and similarities between what has been measured and what has been reflected by humans acting in the urban environment.
5. Overall, the cross-comparison of the physical soundscapes and their association with complementary multidimensional measurement tools can constitute a reference that is both quantitative and qualitative for the characterization of an urban environment. The integration of the measurements with the questionnaire provides a global vision of the urban soundscapes, both qualitative and quantitative. The case study on Sidi Bou Said demonstrates the potential of the framework to capture the complexity and diversity of real-world urban soundscapes. The multidimensional methodology provides a more nuanced characterization than relying solely on physical metrics or human perception.
6. Of course, such approaches will require close collaboration with urban planners and decision-makers. The framework can be applied to the evaluation of urban soundscape environments, even as a simulation system for urban planning developments.

The approach is still preliminary and can be extended in several directions. At the implementation level, the current data integration capabilities can be extended to additional exploratory, ambisonic and statistical techniques. This might provide additional dynamic processing and visualization techniques. Another direction to explore is to identify and categorize different urban soundscape atmospheres, differences and similarities and urban soundscape clusters. Moreover, current soundscape characteristics are locally applied; one can think of extending the concept in relation to navigation activities and displacements to generate soundscape itineraries. This might be a valuable direction to explore, as well as a close integration of all physical and perceived measurements with the wide range of spatiotemporal representation and analysis capabilities offered by geographical information science and location-based services. Finally, while applied to an urban environment, the whole approach might be experimented within diverse urban environments as well as extended toward natural contexts.

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