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Immersive 3D Soundscape: Analysis of Environmental Acoustic Parameters of Historical Squares in Parma (Italy)

Adriano Farina [1], Antonella Bevilacqua [2,*], Matteo Fadda [1], Luca Battisti [1], Maria Cristina Tommasino [1] and Lamberto Tronchin [1]

[1] Department of Architecture, University of Bologna, 40141 Bologna, Italy; adriano.farina3@unibo.it (A.F.); matteo.fadda2@studio.unibo.it (M.F.); luca.battisti5@unibo.it (L.B.); mariacristina.tommasino@unibo.it (M.C.T.); lamberto.tronchin@unibo.it (L.T.)

[2] Department of Architecture and Engineering, University of Parma, 43100 Parma, Italy

* Correspondence: antonella.bevilacqua@unipr.it

Abstract

Sound source localization represents one of the major challenges for soundscapes due to the dynamicity of a large variety of signals. Many applications are found related to ecosystems to study the migration process of birds and animals other than other terrestrial environments to survey wildlife. Other applications on sound recording are supported by sensors to detect animal movement. This paper deals with the immersive 3D soundscape by using a multi-channel spherical microphone probe, in combination with a 360° camera. The soundscape has been carried out in three Italian squares across the city of Parma. The acoustic maps obtained from the data processing detect the directivity of dynamic sound sources as typical of an urban environment. The analysis of the objective environmental parameters (like loudness, roughness, sharpness, and prominence) was conducted alongside the investigations on the historical importance of Italian squares as places for social inclusivity. A dedicated listening playback is provided by the AGORA project with a portable listening room characterized by modular unit of soundbars.

Keywords: soundscape; outdoor acoustics; environmental parameters; Emilia Romagna; Parma

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1. Introduction

In recent years, the study of soundscapes has emerged as a powerful, non-invasive tool in the effort to understand and protect the natural world [1]. A soundscape, defined as the full range of acoustic elements in a given environment, including biological, geophysical, and anthropogenic sounds, offers a unique lens through which to monitor ecosystem health and biodiversity [2]. As natural habitats face increasing pressure from climate change, urbanization, and resource exploitation, soundscapes provide vital insight into the lives of animal species, many of which are at risk of extinction [3,4].

Previous studies demonstrated to be oriented on human perception of soundscape, based on subjective parameters like pleasantness and eventfulness, based on the ISO/TS 12913-3:2019 [5], other research is deep into cross-language pleasantness based on phonemes of different idioms, whose results are scored based on questionnaires carried out by individuals from public spaces [6,7]. Some studies from the literature are determined to categorize audio stimuli based on human activities like traffic noise, construction, industry; this type of evaluation was defined as chaotic, or calm, based on the nature of the signal [8].

Other research on soundscapes is very keen on the localization of sound sources, which developed a cross-correlation algorithm for Time Difference of Arrival (TDoA) used in combination with conventional GPS tracking; this type of application is oriented on animal localization [9,10].

Notably, urban contexts also include green areas and natural parks, where wild fauna is attracted [11]. Another important aspect of soundscape correlates with the detection of changes in species' presence, abundance, and behavior, making it possible to identify early signs of population decline, long before visual evidence is available, enabling conservationists to intervene more swiftly and effectively [12]. Soundscape analysis represents the acoustic fingerprint of a fragile ecosystem that includes birds, insects and other types of animals that may struggle to communicate, reproduce, or survive. Human activities with roads, industrial operations, and aircraft introduce constant background noise that can mask animal vocalizations or drive wildlife away from critical habitats [13].

In a time when fauna extinction rates are accelerating, soundscapes offer a powerful way to listen more closely—to ecosystems, to endangered species, and to the subtle signs of ecological imbalance, warning of anomalous conditions where wildlife should be kept preserved [14,15].

Documenting, analyzing, and reflecting on these sonic characteristics allows for a deeper understanding of a square's historical and cultural role. Moreover, it opens new possibilities for designing specific uses of sound and music that resonate with the character of each space. This vision is fully captured by the project, which aims to bring the experience of these soundscapes to the public, and seeks to combine scientific research, cultural heritage preservation, to elevate sound as both a cultural resource and a tool for civic connection.

Shared spaces such as public squares serve as symbolic arenas for connection, expression, and community building [16,17]. In Italy, and particularly in the Emilia-Romagna Region, these spaces are historically tied to civic life, dialog, and collective identity. Emilia-Romagna has long stood out for its forward-thinking social policies and commitment to fostering active citizenship through inclusive innovation [18].

This paper presents the first milestone of the AGORA project, that builds on this tradition by exploring a new frontier, which is the acoustic identity of public squares. By capturing and enhancing their distinctive soundscapes using multichannel microphones and 3D immersive audio technologies [19], AGORA aims to make these experiences also accessible to a general public, not only experts in acoustics. This initiative is not just about sound reproduction, it is about evoking a sense of place, memory, and belonging through sonic immersion, which can be possible in a virtual environment. The immersive listening experience is captured with a multi-channel spherical array microphone, capable of a directivity at high-order-Ambisonics (HOA). Differently from other research projects, AGORA aims to reproduce the immersive audio-video playback experience in physical and dedicated listening rooms open publicly to visitors. The dedicated listening room is identified with a mono-seat room already existing at Casa della Musica of Parma, or alternatively in another audio technologic space which will be equipped with portable soundbars, as already executed in a previous exhibition at the Creative-Hub in Bologna [20].

2. Italian Squares and Sonic Captures

The public square has long been a central place of gathering, exchange, and collective experience. In the context of Italian urban design, it reflects the civic and cultural identity of the nation, carrying both functional and symbolic significance [21]. Historically, squares have served civic, commercial, religious, and social roles. While their functions may evolve over time, they remain powerful symbols of democracy, open spaces that facilitate dialog and connection [22].

Beyond their visual and historical importance, squares also possess unique acoustic properties shaped by their architecture and spatial configuration. These sound characteristics form an integral part of a square's identity, contributing to its cultural and social meaning. Just as each square has a distinct layout, it also has a unique sonic form, referring to a soundscape that reflects its design and the life that unfolds within it [23].

This acoustic identity exists independently of how the space is used socially. In fact, it is the physical structure itself that shapes how sound behaves, making the square not only a social and civic space but also one with untapped educational and cultural potential [22].

The immersive sound of a square can also become a tool for cultivating a sense of belonging and citizenship. The AGORA project seeks to awaken in all citizens a renewed awareness of the cultural and historical value embedded in the everyday spaces they inhabit. By capturing and transmitting the vibrant, joyful, and socially meaningful sounds of public squares through advanced multichannel audio technologies, the project transforms the act of listening into an immersive cultural experience.

Remarkably, while the acoustics of enclosed spaces like theaters and churches have been studied extensively [24,25], counting on virtual reconstructions and 3D auralization, the soundscapes of historic squares remain almost entirely unexplored. No systematic measurements, recordings, or digital archives exist to preserve these sonic environments, despite their significance. The role of sound in fostering social integration remains virtually unexamined in global academic research.

3. Materials and Methods

3.1. Selected Soundscapes Across the City of Parma

The selected soundscapes for the source localization with the use of 3D mapping are within the city of Parma, specifically in three of many historical squares: Piazza Garibaldi, Piazza Duomo, and Piazzale della Pilotta, as the most representative of various urban contexts [26]. Figure 1 shows the location of the squares within the historical center of Parma.

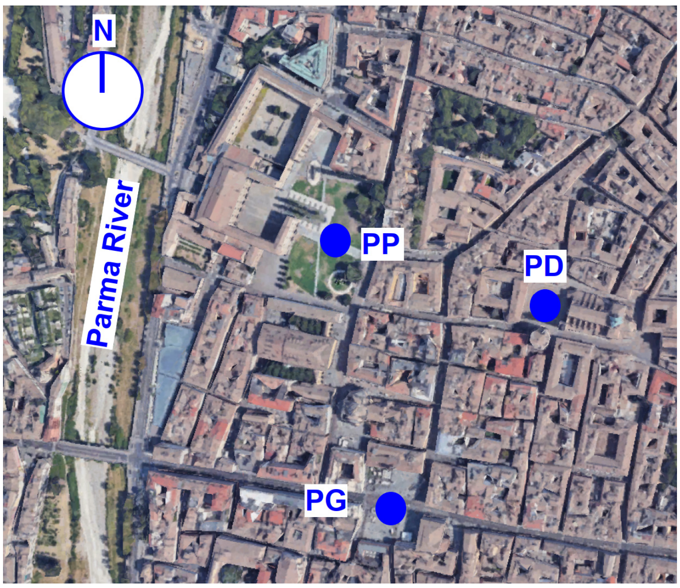

Figure 1. Location of the acoustic survey for soundscapes in Parma: Piazza Garibaldi (PG), Piazza Duomo (PD), and Piazzale della Pilotta (PP).

3.1.1. Piazza Garibaldi in Parma

Piazza Garibaldi in Parma has had deep historical and cultural significance for its rich past since Roman dominion. As the old *forum* due to the cross section of the two main perpendicular roads (*cardo*, *decumano*), it was renamed after Italy's unification after

Giuseppe Garibaldi; the square stands as a symbol of historical memory [27]. The square's development traces back to the medieval era, but it saw substantial architectural changes during the 19th century, reflecting Parma's growth and modernization. It is surrounded by important landmarks, such as the Palazzo del Governatore, which dates back to the 1600s, representing the city's political and administrative core [26]. Other historical buildings are St Peter's church, characterized by the front elevation designed by architect Petitot in 1761, the City Hall Palace (historically known as *Palazzo del Grano*) dating back to 1287, characterized by an arched porch on the ground level and solid brickwork on the upper floors. This city hall is particularly important for the spire (*torre civica*) that was built at the center of the palace, now diminished of its magnificence after the tower collapsed in 1606, destroying the adjacent Palazzo del Capitano del Popolo [26]. Figure 1 shows the position of the squares across Parma.

Another corner of the square is occupied by another palace that was historically used to store wheat, due to which it was named *Portici del Grano*.

Throughout its history, Piazza Garibaldi has been the stage for significant events, from public protests to celebratory gatherings, marking it as a place of civic engagement and social importance, for the presence of bistros, bars, and restaurants. Figure 2 illustrates a view of Piazza Garibaldi.

Figure 2. Aerial view of Piazza Garibaldi in Parma, Italy (from Google Earth).

3.1.2. Piazza Duomo in Parma

Piazza Duomo in Parma is the heart of the city, renowned for its exceptional medieval architecture and rich artistic heritage. At its center stands the Parma Cathedral, a Romanesque masterpiece consecrated in 1106, famous for its interior and frescos of the Assumption of the Virgin by Correggio, a highlight of Renaissance ceiling painting [28]. The cathedral is also noticeable in the square for the presence of its belltower, reaching a height of 67 m and coronated at the top with its golden angel (*angiol d'oro*) having the function of a lightning rod [29].

Adjacent to it is the Baptistery, designed in 1196 by Benedetto Antelami, showcasing the transition from Romanesque to Gothic with its octagonal shape, pink Verona marble, and sculptural decoration. Completing the ensemble is the Bishop's Palace, a more modest but historically significant residence of the bishop and diocesan offices. The square's quiet, harmonious atmosphere and preserved medieval layout reflect the close bond between civic and religious life in Parma, making it one of Italy's most evocative historical piazzas. Figure 3 illustrates a view of Piazza Duomo.

Figure 3. Aerial view of Piazza Duomo in Parma, Italy (from Google Earth).

3.1.3. Piazzale Della Pilotta

Piazzale della Pilotta in Parma holds a deep historical and cultural significance as the monumental forecourt is one of the city's most important architectural complexes. Developed in the late 16th century under the rule of the Farnese family, this piazzale was conceived as part of a grand urban plan to consolidate the family's power and elevate Parma's status as a ducal capital [30]. The name "Pilotta" derives from the game *pelota*, once played in the internal courtyards by soldiers [30]. The square stands as a transitional space between the historic center and the monumental palace, which houses cultural institutions such as the Teatro Farnese, the National Gallery, the Palatine Library, and the Archeological Museum.

Over the centuries, Piazzale della Pilotta has functioned not just as a physical entryway, as it was in the past when entering the old city from the Verdi bridge, but also as a symbolic gateway to power and the arts [30]. The palace was partially destroyed by bombing during World War II, as the vanished St Lorence church is now transformed into a water playground with a series of trees planted instead of the old pillars. Modern restorations have preserved its historical role as a civic and cultural focal point, making it a central gathering place and a testament to Parma's rich ducal heritage. A view of the square is shown in Figure 4.

Figure 4. Aerial view of Piazzale della Pilotta in Parma, Italy (from Google Earth).

3.2. Acoustic Measurements

Different sets of acoustic measurements were carried out across these selected squares belonging to the Emilia-Romagna region, evoking all the historical importance throughout the centuries. The equipment used includes the following:

- 64-channel spherical array microphone (MH-Acoustics Eigenmike) [31];
- 360° video camera (Qoocam3 Kandao 8k) [32];
- Personal computer, connected to both microphone and camera for data storing.

The em64 Eigenmike® spherical microphone array contains 64 omnidirectional electret microphones mounted on a rigid spherical baffle [31]. All electronics are inside the sphere. This ambisonics microphone is designed to decompose the sound field into spherical harmonics of up to sixth-order HOA signals [31]. The em64 is powered by Power-over-Ethernet (PoE+) using CAT5e and uses Audinate's Dante protocol [31]. The em64 Eigenmike® has a flat response in the frequency domain ranging from 50 Hz to 8 kHz, which is sufficient to cover all the urban sounds, while below and above this frequency bandwidth the response registers some harmonic distortions, while the dynamic range is 15–130 dB. The sampling rate of em64 Eigenmike® is 48 kHz and its spatial aliasing cutoff frequency is >12 kHz, corresponding to the diameter of the spherical baffle equal to 84 mm. Figure 5 shows the equipment during the survey and the em64 Eigenmike® microphone.

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

Figure 5. Equipment installed in Piazza Duomo during the survey (**a**), and a 64-channel em64 Eigenmike® microphone (**b**) [31].

The microphone was installed at 1.7 m from the ground, on top of which the camera was placed by ensuring that the vertical axes of both were aligned. For each place, the soundscape measurement was 5 min in duration, executed during daytime, specifically between 11.00 and 17.00 in April, representing everyday acoustic scenarios (e.g., vehicles passing by, conversations). The audio recording captured mainly human activities rather than natural sounds like birds. The external temperature was about 20–24 °C, with a wind speed v_{avge} <1.2 m/s at all sites [33]. A clapping sound was utilized to synchronize audio and video data, at the beginning and end of the measurement.

Due to the temporal variability of outdoor soundscapes at an hourly, daily, and seasonal level (e.g., traffic peaks, construction, road traffic, etc.), one of the limitations of this study consists of its replicability only throughout the controlled playback in laboratories with Ambisonics or Wave Field Synthesis systems. This explains the reason why the immersivity of sounds as captured in specific urban squares is intended to be replicable within dedicated listening rooms.

The measurements have been conducted without any permission from the local authorities since the survey was not intended to impact the existing background, as usually occurs with the presence of a loudspeaker during impulse response measurements. Additionally, the microphone was placed far from commercial realms, like bars and cafeterias, so that no private conversations were captured.

Despite the local regulations in terms of soundscape not being explicit in establishing the criteria for noise parameters, the only current guidance that establishes the noise limits is known as Piano Comunale di Classificazione Acustica (PCCA), which subdivides the territory in homogeneous acoustic zones, each of them with specific noise emission limits.

3.3. Digital Audio-Video Processing

The audio recording was port-processed with Plogue Bidule 9.785 [34], a software dedicated to real-time sound design, synthesis, audio processing, and interactive performance. All VST and other plugins are blocks that can be connected between each other to create audio effects, sequencers, and signal patches. For our case, the multi-channel audio recording uploaded with a player was connected to O3A Flare plugin to detect the directivity of the signal hitting the microphone probe from different directions in real-time [35]. Both 19 and 64 channel signals were transformed to the third-order-Ambisonics (O3A) which can render a very detailed audio spatialization, although the potentiality of a 64-channel microphone is up to higher order Ambisonics [36].

The video recording, instead, is processed with QoocamStudio 2.6.3.4, a software that can elaborate the video, allowing also 3D panning along the horizontal axis and a rotation around the focal point. Audio and video recordings were then synchronized in Adobe Premiere Pro 2024, a software that allows the overlap of audio tracks and video recordings [37]. The result of this audio-video combination is a video overlay that maintains the 3D audio spatialization along with the detection of sound directionality with 3D-color mapping. The colors serve as aids for more easily detecting the sounds that can come from any direction, as it would be in reality.

4. Analysis of Measured Results

4.1. Environmental Acoustic Parameters

Environmental acoustic parameters such as loudness, sharpness, roughness, and tonality are psychoacoustic metrics used to describe how humans perceive complex sound environments beyond the simple sound pressure level (SPL). In particular, loudness refers to the perceived intensity of a sound and depends not only on SPL but also on frequency content and duration; it aligns more closely with human hearing [38], as shown in Equation (1).

$$N = \int_{0}^{24Barks} N'(z)dz \quad (1)$$

where $N'(z)$ is the specific loudness in sone/Bark, and z is the critical band rate (0–24 Bark).

Sharpness quantifies the spectral balance of a sound, with higher values indicating a dominance of high-frequency content, often perceived as shriller [38], as shown in Equation (2).

$$S = \frac{\int_0^{24} N'(z)\cdot g(z)\cdot zdz}{\int_0^{24} N'(z)} \tag{2}$$

where $g(z)$ is a weighting function, z is in Bark, and $N'(z)$ is specific loudness.

Roughness describes rapid amplitude modulations typically in the range of 63–300 Hz, as typical of heavy traffic noise, and is associated with a sensation of harshness or agitation [39], as shown in Equation (3).

$$R \propto\ m^p \cdot f_{mod} \cdot \left(1 - e^{-a\cdot f_{mod}}\right) \tag{3}$$

where m is the modulation depth, f_{mod} is the modulation frequency (15–300 Hz), and a and p are empirical constants (typically $a \approx 3.5$, $p \approx 1$).

Finally, tonality as expressed in prominence indicates the presence of prominent tonal components within a noise, which can make an otherwise broadband sound more annoying [40], as shown in Equation (4).

$$PR = \frac{L_{tone} - L_{mask}}{\Delta L} \tag{4}$$

where L_{tone} is the sound pressure level of the tone, L_{mask} is the masking threshold from surrounding noise, and ΔL is the threshold difference for audibility (typically ≥ 6 dB is audible).

Together, these parameters allow for a more nuanced and human-centered assessment of environmental sounds, aiding in soundscape design, noise control, and acoustic comfort evaluation.

In our three selected squares, the primary noise sources are identified as road vehicles passing by, despite their limited occurrence compared to motorways or high-speed roads, and the secondary source consists of transitional conversations of individuals walking across the squares. Overall, these three squares are very similar to each other in terms of soundscape, as highlighted by the mean values related to different environmental parameters, as summarized in Table 1.

Table 1. Measured results related to environmental acoustic parameters.

Location	Mean Loudness (Sones)	Mean Sharpness (Acum)	Mean Roughness (Asper)	Mean Prominence (dB)
Piazza Garibaldi	1.3	0.2	4.7	1.1
Piazza Duomo	0.9	0.4	1.3	1.4
Piazzale della Pilotta	1.2	0.3	3.2	0.9

The visualization of the environmental parameters in the time domain is shown in the graphs of Figure 6. Specifically, Figure 6a shows that the loudness values in Piazza Duomo were the lowest, while those related to Piazza Garibaldi and Piazzale della Pilotta are more comparable, averaging around 0.9 sones, with the exception of a peak recorded in Piazza Garibaldi that reaching 7.5 sones.

In terms of sharpness, Figure 6b shows that the trendline related to Piazzale della Pilotta is characterized by peaks reaching values around 1.4 acum. This means that there were no particular sound sources with high frequency content, since a sharpness of up to 2 acum is not considerably noticeable.

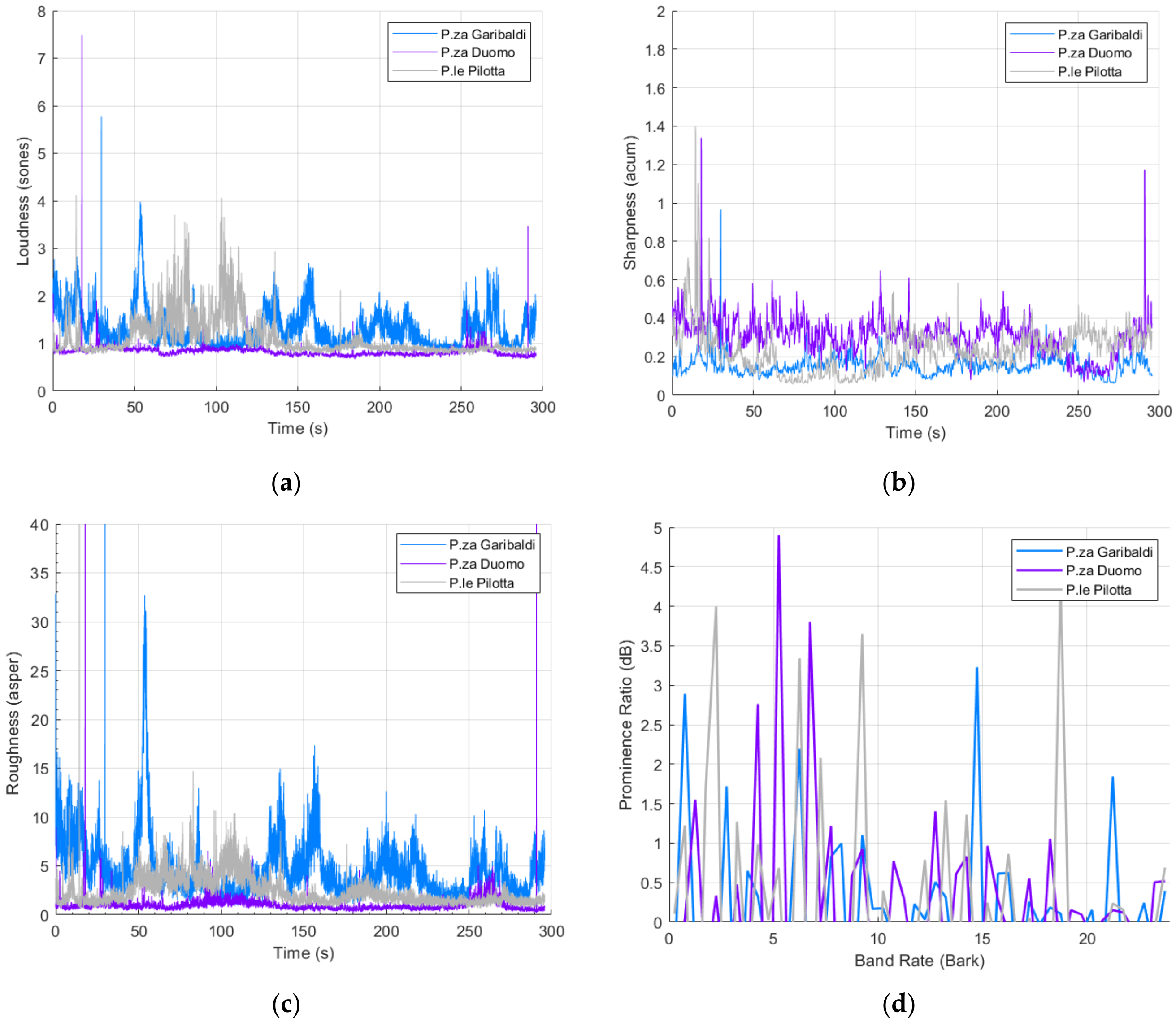

Figure 6. Environmental parameters in the time domain: loudness (**a**), sharpness (**b**), roughness (**c**), and prominence (**d**).

The analyzed values related to roughness were very different among all the squares, as shown in Figure 6c. Specifically, Piazza Duomo has the lowest values, close to zero, meaning that there were no sources with low-frequency content, as the square is in a limited traffic zone with limited access to road vehicles. In Piazza Garibaldi, the values are found around 5 aspers and rise up with peaks around 32–43 aspers, corresponding to cars, buses and motorbikes passing by, as the square is crossed by Via Mazzini by two ways. Similarly, the soundscape in Piazzale della Pilotta was generally between 2 and 5 aspers, slightly below the values in Piazza Garibaldi.

The maximum prominence values, as shown in Figure 6d, do not exceed 5 dB, meaning that they cannot be considered perceivable compared to background noise.

4.2. Three-Dimensional Acoustic Maps for a More Comprehensive Soundscape

A 3D soundscape is necessary to understand the directivity of sound sources in a dynamic landscape. As such, the multi-channel spherical microphone has been used for the audio recording, alongside a 360° camera to capture the panoramic view. The multi-channel audio recording has been processed with Plogue Bidule software to create the colored mapping, highlighting the sound levels by using orange-red colors for high energy and green-blue for low sound energy. The colors follow the sound intensity based on the movement of the sound source in physical space, as illustrated in Figure 7 with some shots from the video overlay.

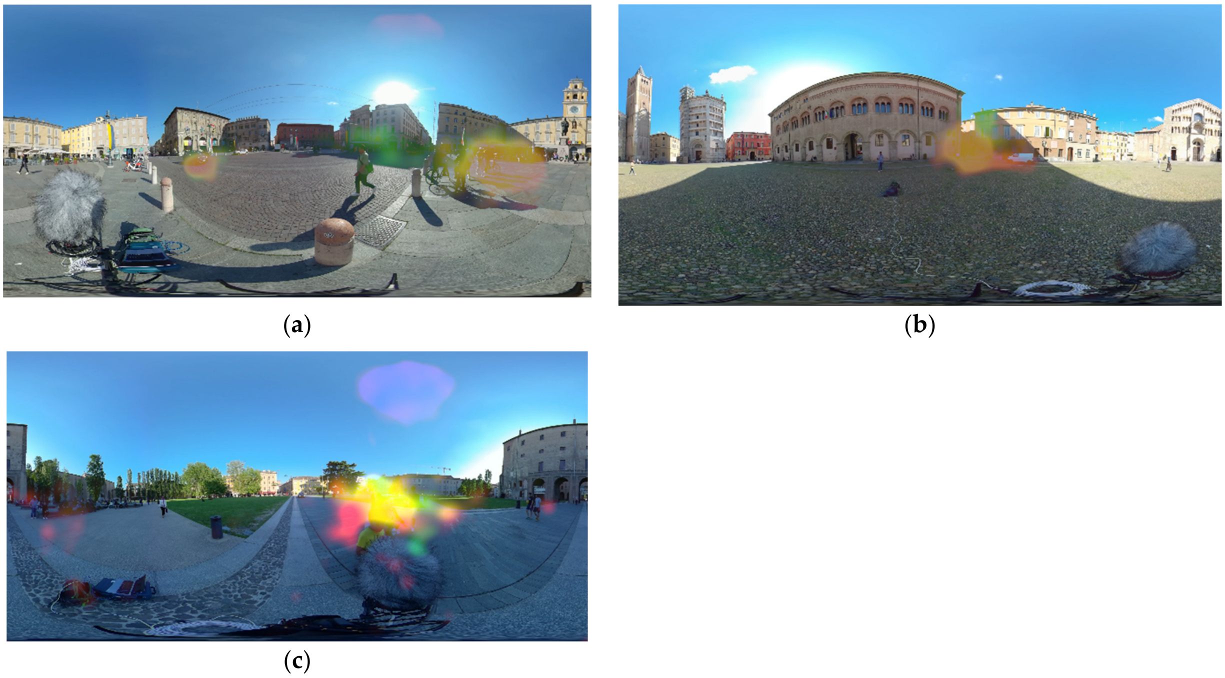

Figure 7. Color mapping of the 3D soundscape in three different squares: Piazza Garibaldi in Parma (**a**), Piazza Duomo in Parma (**b**), and Piazzale della Pilotta (**c**).

In particular, Figure 7a illustrates a moment when individuals talk on the right-hand side, while a car is approaching, as visible in the center-left of the image. Figure 7b illustrates the sound directivity detection in Piazza Duomo, which is another calm environment, where only a conversation has been detected by the microphone, as shown in the orange cloud at the center of the image. Figure 7c illustrates the sound detection of a conversation from individuals close to the microphone. There were no particular sound sources in this pedestrian area, dominated by children playing on the ground and individuals walking across the space.

5. Audio-Video Reproduction

With the advancement of technologies, nowadays there are different solutions for listening to audio. The immediate and common approach is the use of a head-mounted display (HMD) coupled with a pair of headphones and a head-tracking. This solution is relatively inexpensive and is capable of optimal audio-video rendering [41].

The alternative solution consists of a dedicated listening room, which already exists in the Emilia-Romagna region and is called Casa della Musica, located in Parma. It is composed of a mono listening seat placed at the center of an imaginary sphere, where 25 loudspeakers are installed over the spherical surface, as shown in Figure 8. The disposition of the speakers supports up to the 4th order Ambisonics (O4A).

Figure 8. Mono-seat dedicated listening room within Casa della Musica in Parma, Italy.

Another possibility to listen to the 3D reproduction of the recordings is the creation of a portable system capable of delivering high-fidelity, immersive audio experiences. This prototype project is designed for accessibility, durability, and ease of use, allowing users to experience the social and emotional vitality of the square. The portable loudspeakers will be assembled in modular units, capable of different configurations adaptable to any room geometry (e.g., squared or rectangular) [42]. The capacity of this portable system is designed to accommodate 20–28 spectators, who can attend the auralization sessions. This portable and modular audio system will be composed of 8-channel soundbars based on the Automotive Audio Bus (A2B) specifically related to multichannel audio distribution. Each transducer of the soundbar will be a 4-inch RCF loudspeaker, as already designed for a previous exhibition in the Creative-Hub in Bologna [42].

In this way, the AGORA project also addresses a significant gap in research and cultural preservation, which is identified with the digitalization of the acoustic heritage of public squares. The documented soundscapes of urban squares, rich in acoustic diversity, can be accessible to the public by exploring the immersive technology.

6. Discussion

This research study has described the advancement in immersive audio for outdoor soundscapes. While this technology is widely used for indoor spaces, like theaters and concert halls as they represent complex room volumes, the immersive outdoor audio recordings require high-quality technology to remain faithfully documented for future generations. The selection of these three squares is oriented to the similarity of the soundscape in similar historical contexts, as shown by the results of the environmental parameters, except for some transient events.

In addition to the traditional analysis of the environmental parameters, the detection of the dynamic sources in a fully immersive reality helps the listeners to be visually oriented, especially individuals that are hard of hearing. The colors of the 3D mapping use the conventional color scale, going from violet-blue to orange-red, respectively, indicating low to high intensity sound energy.

The availability of audio reproduction open to the public is generally not granted, given the challenge in dedicating a specific place to it. This initiative incentivizes researchers to be closer to the public of different extraction: experts in music, acousticians, but also music lovers, and visitors, who can be beneficial for further research development by releasing their feedback. An appropriate listening test with a perception questionnaire can be a method to complete the soundscape investigation, which will be implemented for future acoustic measurements. A comparison between squares representing the hearth of the social life of various cities can be conducted with sounds instead of traditional methods more oriented to life quality based on the functionality of the transportation network, air pollution level, and traffic flow rate.

7. Conclusions

An acoustic analysis of the outdoor soundscape was conducted by state-of-the-art technology, specifically a 64-channel spherical array microphone. The proposed project, which aims to document sounds related to social activities typically found in public squares, is launching a campaign of digitalization of a very important patrimony. These sound recordings are intended to be presented in the future within a dedicated Ambisonics listening room, open to the public [40].

Future research will focus on collecting additional data and comparing the findings with those from other cities where soundscapes shaped by social activity contribute to the identity of a place, particularly from the intangible perspective of sound. A noticeable shift in the soundscape occurred during the COVID-19 pandemic, when legal restrictions significantly reduced the use of public transportation. As a result, the reduction in noise from aircraft and road traffic massively altered the acoustic environment in cities and public spaces like squares. These audio recordings serve as valuable digital documentation for that transformation.

Collaborations with international centers in audio research are encouraged to implement innovation and develop a unified digital platform for collecting and sharing different urban soundscapes. Looking ahead, advancements in drone technologies, already widely used for filming and photography, may further impact the urban acoustic environment. The prospect of using drones for individual transportation could significantly reshape city soundscapes and contribute to the rapid evolution of urban life.

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