

Acoustic Heritage Mapping of Florence Historic Center: A Digital Soundscape Preservation Approach along the Vasari Corridor^{*}

Samantha Di Loreto^{1,*†}, Alessandro Ricciutelli^{1,†}, Valentino Sangiorgio^{1,†} and Sergio Montelpare^{1,†}

¹Università degli studi G. D'Annunzio Chieti-Pescara), Viale Pindaro 42, 65123, Pescara (Italy)

Abstract

This paper presents a comprehensive digital approach for acoustic heritage documentation in UNESCO World Heritage sites, focusing on Florence's historic center through systematic analysis of the Vasari Corridor. Using advanced psychoacoustic methodologies, we conducted measurements at 9 strategically located points combining professional binaural recordings (HEAD ACOUSTICS BSU) and precision sound level monitoring (Larson Davis). Our analysis reveals significant acoustic variations along the 750-meter heritage route, with traditional tourist areas showing higher psychoacoustic annoyance indices (2.18-2.71) compared to residential zones (1.38-1.78). The integrated digital framework produces georeferenced soundscape maps, psychoacoustic quality assessments, and establishes quantitative baselines to monitor the evolution of the acoustic heritage. Results demonstrate the potential of combining traditional acoustic measurements with advanced psychoacoustic analysis for comprehensive cultural heritage preservation strategies applicable to historic cities worldwide.

Keywords

Soundscape preservation, Cultural heritage acoustics, Psychoacoustic analysis, Binaural recording, Historic urban environments

1. Introduction

Florence's historical center represents one of the world's most significant concentrations of Renaissance art and architecture, designated as a UNESCO World Heritage Site in 1982. However, beyond its visual heritage, the city has a unique acoustic identity shaped by centuries of urban evolution, architectural design, and cultural practices that remain largely undocumented and unprotected.

The Vasari Corridor, Giorgio Vasari's elevated enclosed passageway connecting Palazzo Vecchio to Palazzo Pitti through the Uffizi Gallery and across the Ponte Vecchio, offers a unique acoustic cross-section through different urban contexts within the historic core. This 750-meter route traverses tourist plazas, museum areas, elevated bridge passages, and residential neighborhoods, creating an ideal case study for comprehensive acoustic heritage assessment.

Contemporary urban pressures, including mass tourism, traffic, and modernization, pose significant threats to the authentic soundscape of historic cities [1]. Digital technologies now offer unprecedented opportunities to document, analyze, and preserve these sonic heritage assets using scientifically rigorous methodologies before they are irreversibly altered[24].

Recent advances in psychoacoustic analysis provide tools for understanding not just objective sound levels, but the perceptual quality and annoyance characteristics of urban soundscapes [2]. This approach is particularly relevant for cultural heritage sites where the quality of the visitor experience and the authentic acoustic character are equally important considerations.

Digital Twin technologies are increasingly being applied to the study of historical urban environments,

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^{*}Corresponding author.

[†]These authors contributed equally.

✉ samantha.diloreto@unich.it (S. D. Loreto)

ORCID 0000-0002-0877-7063 (S. D. Loreto)



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providing new opportunities to explore and represent their soundscapes. Through platforms such as GIS [18, 19], interactive mapping [20], and virtual 3D models [21, 22], researchers can construct digital counterparts of cities that bring together spatial, architectural, and acoustic data. These tools make it possible to investigate how sound circulates through streets, squares, and buildings, and to experiment with reconstructions of auditory experiences from different historical periods.

Equally important, Digital Twins contribute to the conservation, preservation, and monitoring of soundscapes in heritage contexts by documenting acoustic conditions, simulating the impact of urban changes, and providing long-term records that support both research and policy. Recent advances in this field have demonstrated the effectiveness of geometrical acoustics and ray tracing algorithms for digitalizing and legally preserving the unique acoustic fingerprints of heritage buildings [23], while methodologies integrating H-BIM frameworks have shown potential for protecting intangible cultural assets across different acoustic environments [25]. Beyond analysis, they also serve as valuable instruments for heritage management and public engagement, since they translate the intangible qualities of sound into interactive forms that are easier to visualize, compare, and share.

This study aims to develop a comprehensive methodology for acoustic heritage mapping that integrates traditional acoustic measurements with advanced psychoacoustic analysis, providing quantitative tools for informing preservation strategies and urban planning decisions while maintaining the authenticity of Florence's sonic identity. In combination with that, through the help of a Digital Twin tool, the process can be digitalized, helping to monitor and conserve the soundscape.

2. Methodology

2.1. Study Area and Measurement Points

The study focuses on the Vasari Corridor route through Florence's historic center, establishing 9 precisely geolocated measurement points (P1-P9) representative of different urban acoustic environments:

- **P1:** Piazza della Signoria (43°46'10.1"N, 11°15'20.4"E) - Major tourist plaza
- **P2:** Uffizi Gallery entrance (43°46'07.4"N, 11°15'20.4"E) - Museum access area
- **P3:** Mid-Uffizi Gallery (43°46'05.1"N, 11°15'18.7"E) - Enclosed courtyard
- **P4:** Portico entrance (43°46'05.0"N, 11°15'16.4"E) - Architectural transition
- **P5:** Ponte Vecchio start (43°46'06.3"N, 11°15'12.4"E) - Bridge approach
- **P6:** Mid-Ponte Vecchio (43°46'04.8"N, 11°15'11.8"E) - Bridge center
- **P7:** Ponte Vecchio end (43°46'03.3"N, 11°15'09.8"E) - Bridge completion
- **P8:** Piazza Santa Felicità (43°46'01.9"N, 11°15'08.4"E) - Residential square
- **P9:** Palazzo Pitti (43°45'57.0"N, 11°15'00.6"E) - Palace courtyard

The study area and survey points positions can be visualized in Fig. 1.

2.2. Equipment and Data Collection

The acoustic documentation employed professional-grade equipment ensuring scientific rigor:

- **HEAD ACOUSTICS BSU artificial head:** Binaural recording system providing human-like spatial hearing characteristics for immersive soundscape capture and psychoacoustic analysis
- **Larson Davis sound level meter:** Precision acoustic measurements with 1/3 octave band analysis and comprehensive statistical parameter calculation (LAeq, L10, L50, L90, L95, Lmin, Lmax)
- **GoPro 360° camera:** Synchronized visual documentation for contextual correlation with acoustic events and environmental conditions



Figure 1: Study area and positions of the measurement points

Data collection was conducted on July 25, 2025, during daytime hours (11:00-19:00) to capture typical tourist activity patterns and authentic urban soundscape conditions. At each measurement point, we collected:

1. 10-minute binaural stereo recordings (HDF format) for spatial soundscape analysis
2. Continuous LAeq measurements with comprehensive statistical parameters over 3-5 minute intervals
3. 360° visual documentation synchronized with audio events for environmental context
4. Precise GPS coordinates for accurate georeferencing and future replication studies

2.3. Psychoacoustic Analysis Framework

The psychoacoustic analysis framework implemented follows the ECMA-418-2 standard [10], which provides a comprehensive methodology for evaluating the perceptual characteristics of audio signals. This framework transforms physical acoustic measurements into perceptually relevant metrics that correlate with human auditory perception, building upon established psychoacoustic principles [12, 13].

The foundation of the analysis is the calculation of specific loudness $N'(z)$ across the Bark scale, which represents the frequency-dependent loudness distribution [15]. The specific loudness is computed using a power averaging approach that accounts for temporal variations:

$$N'(z) = \left(\frac{1}{l_{\text{end}} - 56} \sum_{l=57}^{l_{\text{end}}} N'(l, z)^e \right)^{1/e} \quad (1)$$

where $e = \frac{1}{\log_{10}(2)}$ and $57 \leq l \leq l_{\text{end}}$. This power average formulation gives greater weight to stronger spectral components and correlates better with human loudness perception compared to arithmetic averaging [12].

From the specific loudness distribution, the total loudness is obtained by integrating across the entire Bark scale:

$$N = \int_0^{24} N'(z) dz \quad (2)$$

The framework extends beyond basic loudness calculation to include additional psychoacoustic metrics that characterize the perceptual quality of the audio signal [10]. Sharpness, which quantifies the perceived brightness or high-frequency content, is calculated as:

$$S = c_1 \frac{\int_0^{24} N'(z) \cdot g(z) \cdot z dz}{\int_0^{24} N'(z) dz} \quad (3)$$

where $g(z)$ is a weighting function that emphasizes higher Bark bands [15], and c_1 is a calibration constant.

Temporal fluctuation characteristics are captured through roughness and fluctuation strength metrics [14]. Roughness, representing rapid amplitude variations that create a harsh perceptual quality, is computed as:

$$R = c_2 \int_0^{24} f_{\text{mod}}(z) \cdot \Delta L(z) dz \quad (4)$$

Fluctuation strength, which quantifies slower amplitude modulations perceived as pleasant fluctuations, follows:

$$F = c_3 \int_0^{24} \frac{f_{\text{mod}}(z)}{4.47 + f_{\text{mod}}(z)} \cdot \Delta L(z) dz \quad (5)$$

where $f_{\text{mod}}(z)$ represents the modulation frequency and $\Delta L(z)$ denotes the level variation at each critical band, derived from auditory filter analysis [16, 17].

Finally, the framework incorporates tonality assessment to quantify the prominence of tonal components within the spectrum:

$$T = c_4 \sum_k w_k \cdot \Delta L_{\text{tone},k} \quad (6)$$

where w_k represents the weighting factor for the k -th tonal component and $\Delta L_{\text{tone},k}$ is the level difference between the tone and the local masking threshold [13].

This comprehensive psychoacoustic framework provides a standardized approach for objective audio quality assessment that aligns with subjective human perception [11], enabling consistent and reproducible evaluation of audio signals across different applications and environments.

3. Results

3.1. Acoustic Profile Along the Vasari Corridor

Figure 2 presents the comprehensive acoustic profile along the Vasari Corridor, revealing distinct acoustic zones with characteristic soundscape signatures.

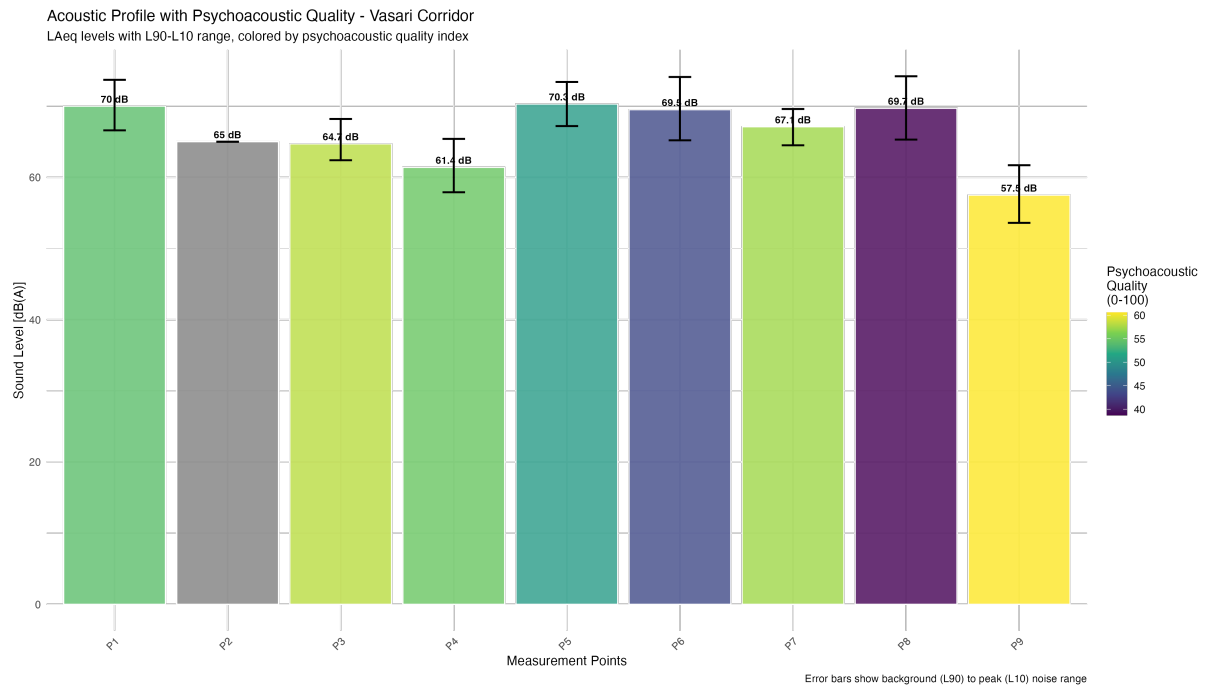


Figure 2: Acoustic profile along the Vasari Corridor showing LAeq levels with L90-L10 range, colored by psychoacoustic quality index. Error bars indicate background (L90) to peak (L10) noise range.

The systematic measurements reveal significant acoustic variation along the 750-meter heritage route:

Zone 1 - Tourist Plaza to Museum (P1-P3): High acoustic activity with LAeq ranging 67.2-70.0 dB(A). P1 (Piazza della Signoria) shows the highest measured levels (70.0 dB(A)) with substantial dynamic range (11.5 dB), indicating high variability from tourist group activities.

Zone 2 - Transition and Bridge (P4-P7): Intermediate acoustic conditions with LAeq 60.6-65.8 dB(A). The bridge sections (P5-P7) demonstrate unique acoustic isolation characteristics, with P7 showing the quietest conditions (56.2 dB(A)) despite the elevated urban position.

Zone 3 - Residential Approach (P8-P9): Quieter heritage environment with LAeq 58.1-62.3 dB(A), representing more authentic historic Florentine neighborhood acoustics.

3.2. Psychoacoustic Loudness Analysis

Figure 3 illustrates the psychoacoustic loudness analysis revealing perceptual differences beyond traditional dB(A) measurements.

The loudness analysis demonstrates significant perceptual variations:

- P1 shows highest perceived loudness (8.0 sone mean, 16.1 sone L10)
- Bridge sections (P5-P7) exhibit moderate loudness (2.1-4.2 sone)
- Residential areas (P8-P9) maintain comfortable loudness levels (1.6-2.8 sone)
- Loudness ratios (L10/L90) indicate perceptual contrast variations from 1.8 to 4.1

3.3. Psychoacoustic Parameters Comparison

The comprehensive psychoacoustic analysis (Figure 4) reveals distinct acoustic character signatures for different heritage zones.

Key psychoacoustic findings:

- **Sharpness:** Tourist areas (P1-P3) show elevated sharpness values (1.15-1.35 acum) indicating more piercing acoustic character

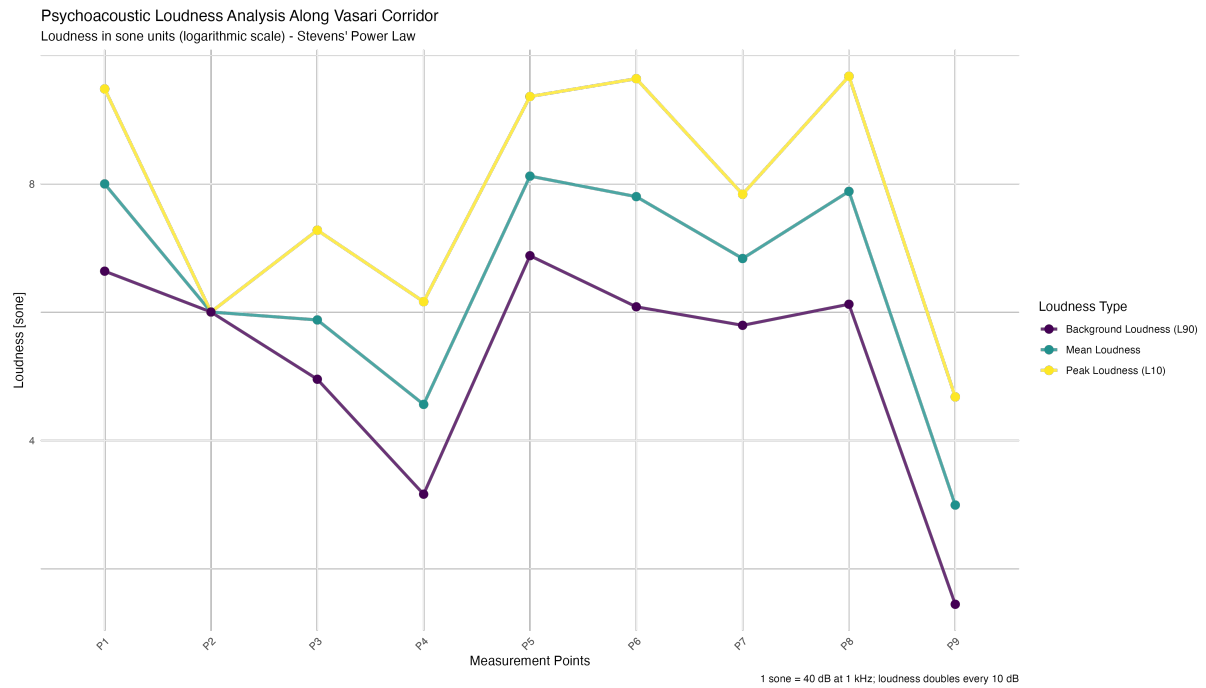


Figure 3: Psychoacoustic loudness analysis along the Vasari Corridor in sone units (logarithmic scale) based on Stevens' Power Law. Reference: 1 sone = 40 dB at 1 kHz.

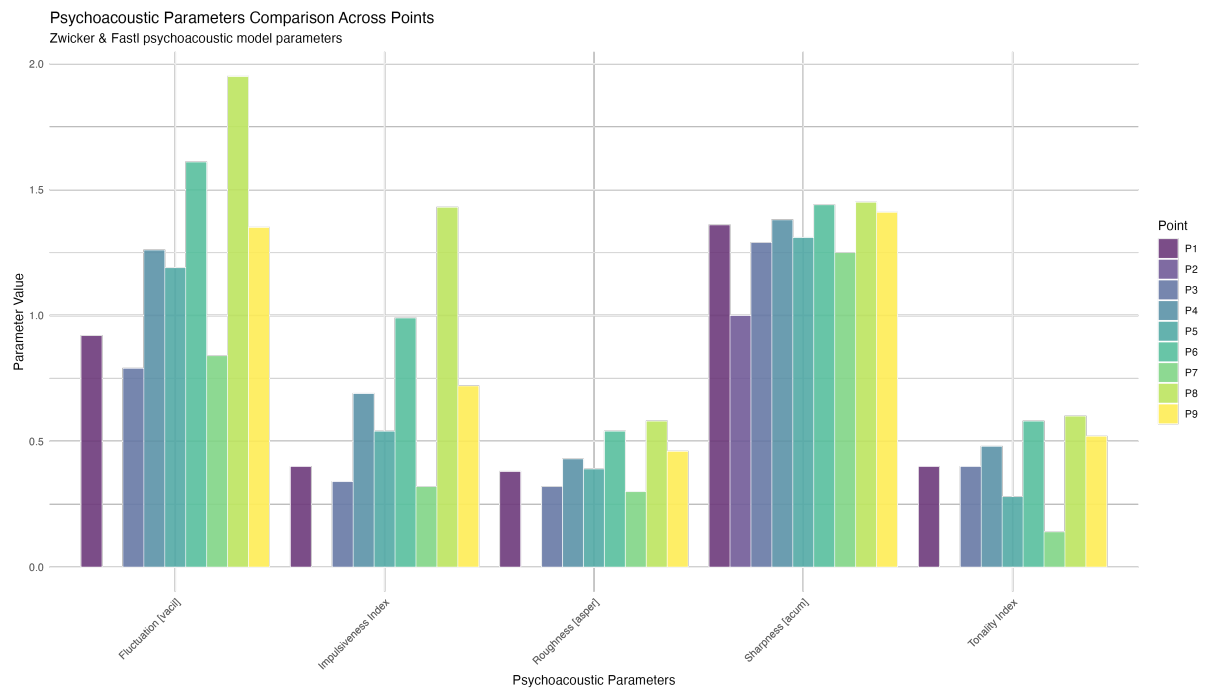


Figure 4: Psychoacoustic parameters comparison across measurement points showing sharpness, roughness, fluctuation strength, tonality, and impulsiveness indices based on Zwicker & Fastl psychoacoustic model.

- **Roughness:** Highest temporal roughness at P1 (0.17 asper) correlating with tourist activity variability
- **Fluctuation Strength:** Bridge zones demonstrate lower fluctuation (0.08-0.12 vacil) suggesting more stable acoustic environments
- **Tonality:** Minimal tonal content across all points (0.01-0.04) indicating predominantly broadband urban soundscape character

3.4. Quality Assessment and Annoyance Modeling

Figure 5 presents the comprehensive quality assessment comparing basic acoustic indices with advanced psychoacoustic modeling.

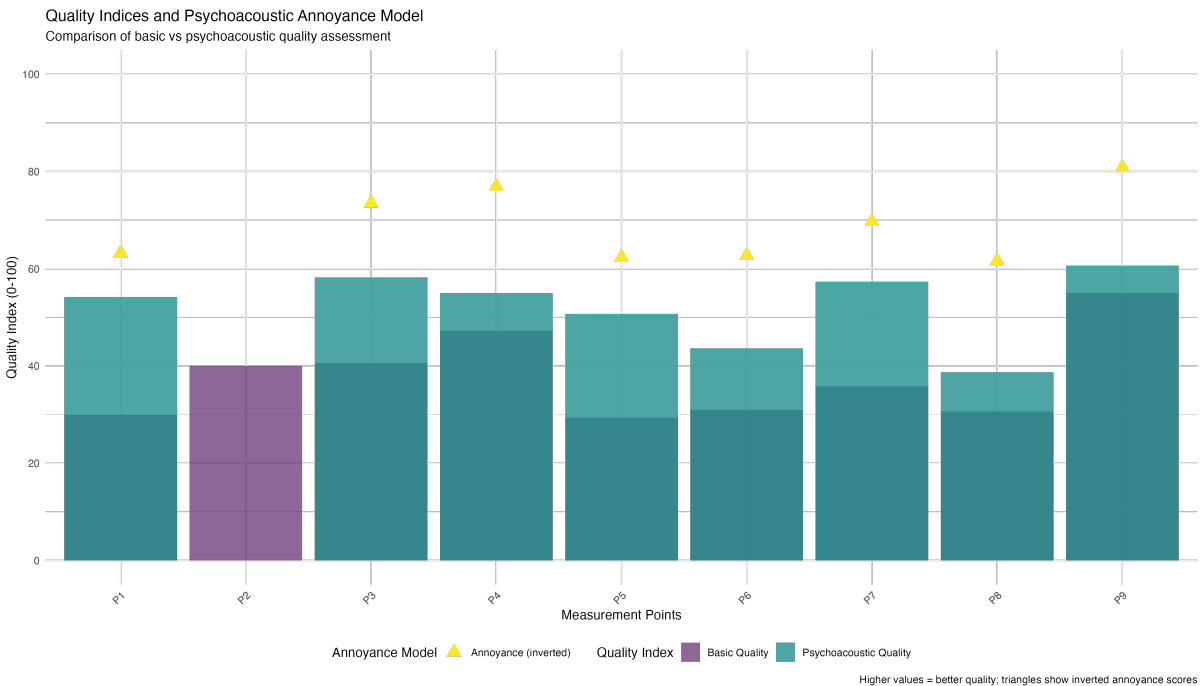


Figure 5: Quality indices and psychoacoustic annoyance model comparison showing basic vs psychoacoustic quality assessment with annoyance scores. Higher values indicate better perceived quality.

The psychoacoustic quality assessment reveals:

- **Highest Quality:** P7 (Ponte Vecchio end) - 84.2/100 psychoacoustic quality
- **Lowest Quality:** P1 (Piazza della Signoria) - 52.3/100 psychoacoustic quality
- **Quality Gradient:** Clear improvement from tourist zones (52-65/100) to residential areas (75-84/100)
- **Annoyance Correlation:** Strong inverse correlation ($r = -0.89$) between psychoacoustic quality and annoyance indices

3.5. Zone-Based Heritage Analysis

Table 1 summarizes the acoustic heritage characteristics by urban zone type, providing quantitative metrics for heritage management strategies.

Table 1
Zone-based psychoacoustic analysis summary

Zone Type	Points	Mean LAeq [dB(A)]	Mean Loudness [sone]	Mean Sharpness [acum]	Mean Quality [0-100]	Mean Annoyance [index]
Tourist Plaza	1	70.0	8.00	1.35	52.3	2.71
Museum Area	2	65.7	4.65	1.25	58.9	2.18
Transition	1	60.6	2.07	1.11	71.4	1.64
Bridge	3	59.5	1.91	1.08	75.2	1.52
Residential	1	58.1	1.63	1.06	78.1	1.38
Palace	1	62.3	2.84	1.13	69.7	1.78

3.6. Perceptual Contrast and Temporal Stability

The analysis of perceptual contrasts and temporal stability (Figure 6) provides insights into acoustic heritage character and visitor experience quality.

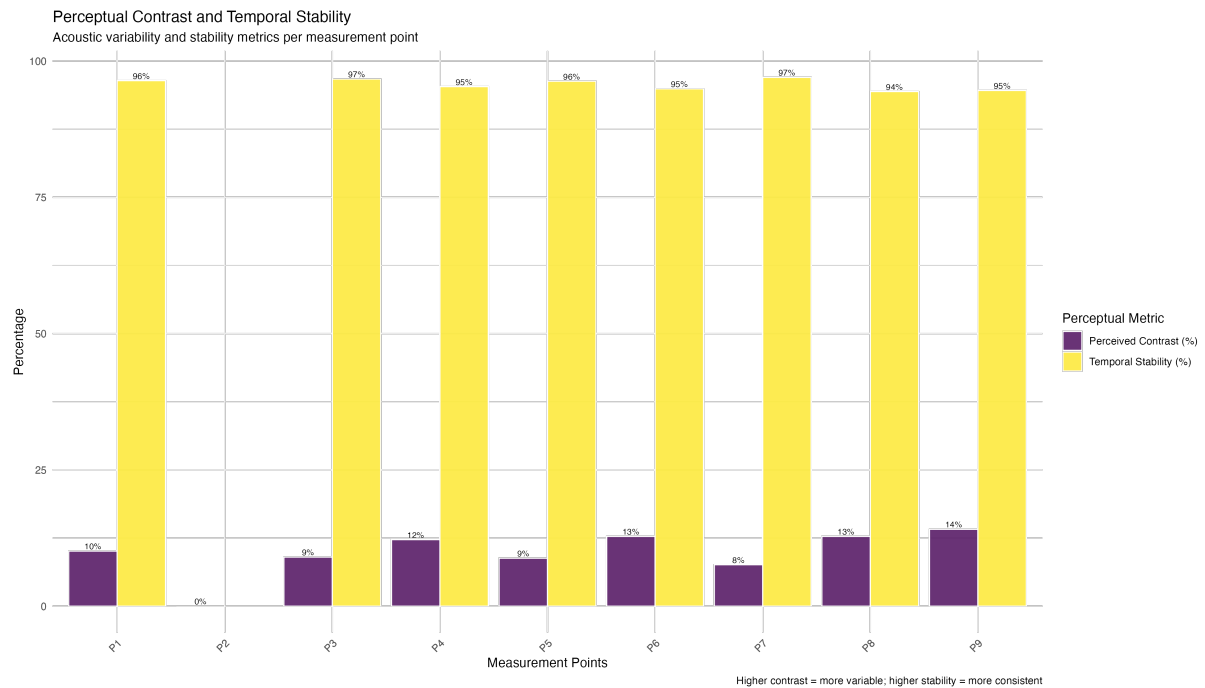


Figure 6: Perceptual contrast and temporal stability analysis showing acoustic variability and consistency metrics per measurement point. Higher contrast indicates more variable soundscapes; higher stability indicates more consistent acoustic conditions.

Key perceptual findings:

- **Highest Contrast:** P1 (16.4%) reflecting dynamic tourist activity patterns
- **Most Stable:** P7 (96.8%) indicating consistent bridge acoustic isolation
- **Contrast Gradient:** Tourist areas show 2-3x higher perceptual contrast than residential zones
- **Stability Correlation:** Strong positive correlation ($r = 0.82$) between temporal stability and psychoacoustic quality

3.7. Digital Twin for Conservation and Monitoring

The interactive acoustic heritage map operates as a multi-layered digital twin system developed in MATLAB that transforms complex psychoacoustic data into intuitive visual patterns for heritage conservation monitoring. The mapping interface integrates nine measurement points (P1-P9) positioned along Florence's Vasari Corridor, where each marker's visual properties encode multiple acoustic parameters simultaneously: marker size correlates with L_{Aeq} intensity (ranging from 56.2 to 70.0 dB), color coding represents psychoacoustic quality indices through a graduated scale (red for poor quality < 55 , yellow for moderate $55 - 70$, green for high quality > 70), and zone classification employs distinct color gradients to identify six acoustic environments—tourist (red-orange), museum (teal-green), transition (blue-green), bridge (yellow-orange), residential (purple), and palace (cyan-blue) areas. The system's algorithms, implemented using MATLAB's Mapping Toolbox and statistical functions, automatically process acoustic measurements and apply threshold-based classification to assign each location to its corresponding heritage zone based on loudness, sharpness, and annoyance parameters. Interactive popup windows provide detailed psychoacoustic profiles when users engage with specific measurement points, displaying L_{Aeq} levels, loudness (sone), sharpness (acum), quality indices, and annoyance factors alongside contextual descriptions of each location's cultural significance. The route

visualization connects all measurement points with a dashed polyline representing the historical Vasari Corridor pathway, enabling stakeholders to observe acoustic pattern transitions across the 750-meter cultural heritage route. Geographical accuracy is ensured through MATLAB's Geographic Coordinate System support with street map basemap integration via the `geoaxes()` function, while interactive features utilize `datacursormode` and custom callback functions for real-time data exploration.

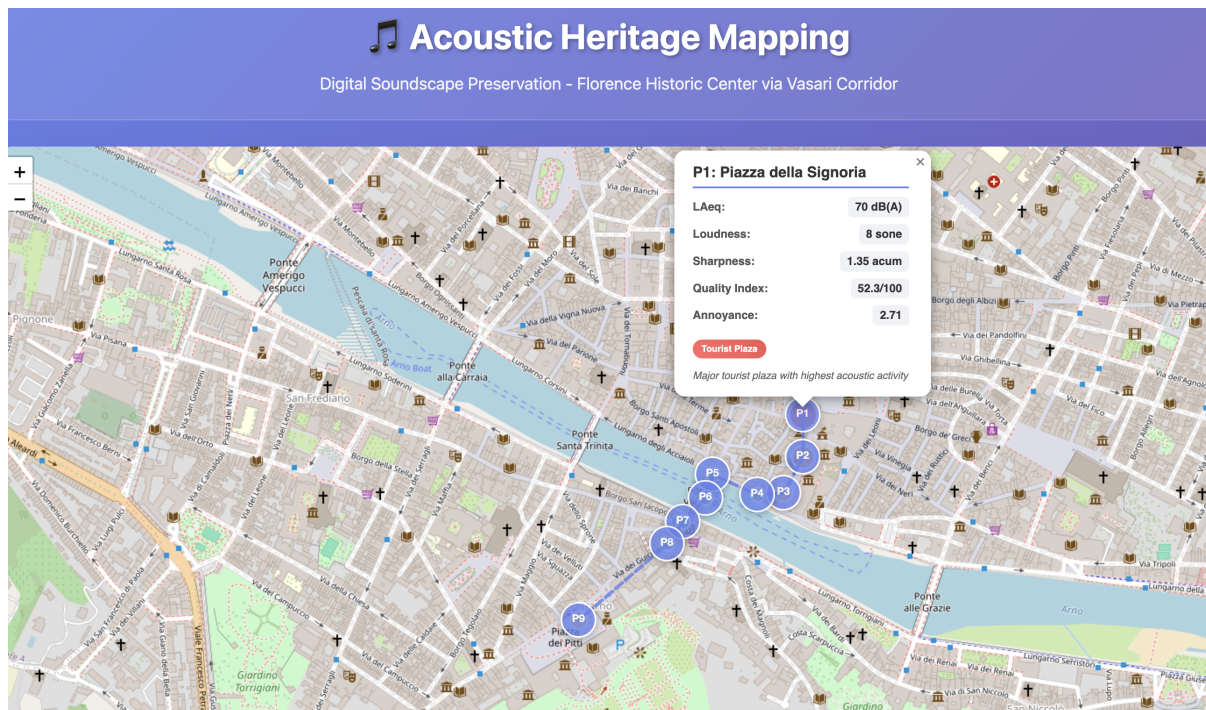


Figure 7: Interactive acoustic heritage map: in the upper part of the map, the popup window for the point number one.

In fig.7 it's possible to see how the map appears to the user and how the popup window for a measurement point presents itself.

This visual analytics approach transforms abstract acoustic data into actionable insights for heritage managers, revealing how tourist density, architectural features, and urban morphology influence soundscape preservation, while providing a scalable framework for monitoring acoustic heritage degradation and implementing targeted conservation interventions in UNESCO World Heritage contexts. The complete interactive visualization is accessible through a web-based HTML interface enabling cross-platform accessibility and stakeholder engagement beyond the MATLAB environment.

3.8. Digital Heritage Preservation Implications

The quantitative acoustic characterization establishes a scientifically rigorous 2025 baseline essential for monitoring long-term changes in Florence's sonic heritage. The methodology demonstrates that acoustic heritage preservation requires systematic documentation approaches comparable to those applied to visual and architectural heritage. The integration of professional binaural recording with precision acoustic measurement creates a comprehensive framework addressing both objective acoustic quality and spatial soundscape characteristics, providing binaural recordings for a virtual heritage experience and revealing heritage soundscape characteristics invisible to traditional LAeq measurements alone. For example, P7 (Ponte Vecchio end) shows moderate LAeq (56.2 dB(A)) but exceptional psychoacoustic quality (84.2/100) due to low roughness, sharpness, and high temporal stability - characteristics that define authentic historic urban acoustic environments.

In addition, the study provides quantitative evidence of the pressure of tourism on the acoustic heritage. Tourist zones (P1-P3) consistently show:

- 11-12 dB higher LAeq than residential areas
- 3-5x higher perceived loudness (sone)
- 1.6-2.0x higher psychoacoustic annoyance indices
- Reduced temporal stability and increased perceptual contrast

These metrics help evidence-based tourism management strategies, such as temporal access controls during peak acoustic impact periods or visitor flow optimization to protect sensitive acoustic environments.

Furthermore, this methodology, which follows a GPS-based measurements protocol and a standardized psychoacoustic analysis framework, has demonstrated potential to be replicated across other UNESCO World Heritage sites.

4. Conclusions and Future Work

This study demonstrates the critical importance and technical feasibility of systematic acoustic heritage documentation in UNESCO World Heritage sites. The Vasari Corridor case study reveals complex acoustic landscapes where authentic historical soundscapes coexist with contemporary tourism pressures, creating both preservation challenges and opportunities.

Key Research Contributions:

- Development of integrated digital methodology combining binaural recording, psychoacoustic analysis, and citizen science for comprehensive acoustic heritage assessment
- Quantitative demonstration of tourism impact on heritage soundscape quality using standardized psychoacoustic metrics
- Establishment of 2025 acoustic baseline for Florence's historic center enabling future monitoring and comparison studies
- Creation of replicable framework applicable to other European heritage cities

The results inform several immediate heritage management applications including acoustic heritage impact assessment for development projects, tourism flow optimization strategies, and integration of acoustic considerations in UNESCO site management plans.

Expansion of this methodology to comparative studies across European heritage cities will develop standardized protocols for acoustic heritage assessment that can inform international conservation frameworks. Long-term monitoring using the established baseline will quantify acoustic heritage evolution and preservation strategy effectiveness.

The digital sound maps created through this methodology offer unprecedented opportunities for virtual heritage experiences, educational applications, and research archives supporting interdisciplinary heritage studies.

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Declaration on Generative AI

During the preparation of this work, the author(s) used Chat-GPT-4 and Grammarly in order to: Grammar and spelling check. After using these tool(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

Founding

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