

Article

Acoustic Investigations of Two Barrel-Vaulted Halls: Sisto V in Naples and Aula Magna at the University of Parma

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Abstract: The percentage of historical heritage buildings in Italy is substantial. Many of these buildings are abandoned or not adequately restored for public access due to safety concerns. However, some are managed by city councils and made available to local communities. These heritage buildings, valued for their historical significance, are now frequently used for live events, including musical performances by ensembles and small groups. This paper deals with the acoustics of two rooms provided with barrel-vaulted ceilings: Sisto V Hall in Naples and Aula Magna at the University of Parma. These spaces are structurally very similar, differing mainly in length. Acoustic measurements conducted in both halls reveal reverberation times of approximately 4.5 s at mid frequencies, resulting in poor speech clarity. This is primarily due to the presence of reflective surfaces, as the walls and ceilings are plastered, and the floors are tiled. To optimize their acoustic properties for functions such as celebrations, gatherings, and conferences, an acoustic design intervention was proposed. Digital models of the halls were calibrated and used to correct the acoustics by incorporating absorbing panels on the walls and carpeting on the floors of the central walk path. This treatment successfully balanced the reverberation time to approximately 1.3–1.4 s at mid frequencies, making speech more intelligible. Additionally, an amplified audio system was analyzed to enhance sound distribution, ensuring uniform coverage, even in the last rows of seating. Under amplified conditions, sound pressure levels (SPLs) range between 90 dB and 93 dB, with appropriate gain control applied to the column array speakers.

Keywords: architectural acoustics; heritage halls; Italian Renaissance; Parma; Naples



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1. Introduction

Italy has a rich architectural heritage, with many historic buildings repurposed for modern uses like conferences, concerts, and exhibitions. However, one of the major challenges of adapting these spaces is their acoustics. Many heritage buildings were designed for different functions: churches for worship, palaces for residence, and theatres for performances, so their acoustics often do not align with the needs of contemporary events, particularly spoken presentations and discussions [1].

In ducal and royal palaces, the people had various ways to submit requests, petitions, or complaints to the sovereigns or their representatives. The petitions could concern pardons, forgiveness, tax reductions, or financial aid. Some sovereigns granted public hearings, during which the people could directly present problems or requests [2]. Therefore, these

palaces were not only residences but also administrative and judicial centers, where the fate of cities and kingdoms was decided.

Regarding speech intelligibility in ancient times, the tone with which the public addressed the sovereign depended on the context, but it was generally a very respectful and formal tone, as the sovereign was considered a sacred and inviolable figure [2].

In private or ceremonial audiences, such as private hearings or official ceremonies, the physical distance between the people and the sovereign could be relatively close, but still somewhat formal. Usually, subjects would kneel or bow as a sign of respect. The physical distance could also be symbolic, with the sovereign positioned in an elevated place, both physically (for example, on a throne) and socially, to demonstrate their superiority. This communication with the sovereign was always codified in a way that reflected the social hierarchy and respect for authority [2].

This research focuses on the acoustics of two important vaulted halls: Sisto V Hall in Naples and Aula Magna at the University of Parma.

Sisto V Hall was more commonly used for official ceremonies and diplomatic meetings rather than for direct audiences with the people, who could access them through their representatives or with presented petitions [3]. One of the most famous state ceremonies held in the Sala Sisto V of the Royal Palace of Naples was the coronation ceremony of Charles of Bourbon as King of Naples, which took place in 1735 [4]. In this hall, Charles of Bourbon was welcomed as a monarch and solemnly crowned with the symbols of royal power. His coronation was not only an act of political justice but also a sign of renewed stability and prosperity for the Kingdom of Naples [5]. The ceremony was accompanied by solemn oaths, chants, and prayers, and was attended by nobles, ecclesiastical dignitaries, and representatives of local institutions.

The Aula Magna, located within one of the historic buildings of the University of Parma, is elegantly decorated with elements that reflect the historical and academic importance of the university. Its functionality is therefore linked to both academic and cultural events, confirming its role as a versatile and symbolic space for the university community [6]. One of the most important ceremonies held in the Aula Magna is the Inauguration of the Academic Year, marking the beginning of each academic year and involving prominent figures at both the academic and institutional levels. During this annual event, the Rector delivers the traditional opening speech, which often addresses topics of great relevance to the university, scientific research, and social challenges. In some cases, the speech may be delivered by distinguished external guests, such as ministers or Nobel laureates. Another major event was the inauguration of the new university headquarters, when Aula Magna was used to celebrate events related to the university [6], with the participation of political and cultural authorities.

These two rooms are studied from an acoustic perspective due to their similarities, featuring the barrel-vaulted ceiling [7]. Their historical importance also remarks on these two halls as representative for ceremonies still ongoing across the year. The acoustic analysis started with in situ measurements to understand the suitability of the halls with respect to their usage and functionality addressed in the rooms. After the analysis of the existing conditions based on the main acoustic parameters, mitigation options are suggested to improve the acoustic comfort within the rooms and enhance the sound quality. The investigations also include the integration of an amplified audio system.

This research addresses the acoustic challenges related to barrel-vaulted rooms, where the focusing effect is a phenomenon dependent on the distance between the source and the curvature rather than curvature radius [7].

Discussions on how to make these historical buildings suitable for modern uses have been addressed, with particular attention given to acoustic treatments to enhance the sound

absorption [8], and the installation of an amplified sound system that improves speech clarity and allows for live streaming network for hybrid events.

2. Acoustic Interest in Vaulted Halls

2.1. Theories and Discoveries in the 17th Century

In section IV of the first book of *Phonurgia Nova* (1673) [9], the Jesuit scholar Athanasius Kircher explored various building typologies, focusing on architectural acoustics based on specific locations [10]. Kircher observed that certain vaulted structures, especially those with elliptical or hemispherical shapes, could transmit whispers over long distances. He documented how sound waves could travel along the curved surfaces of a vault with minimal energy loss [9]. In these cases, he sought to understand the hidden mechanisms behind their unique sound effects.

One of Kircher's notable studies involved the interior of the Palace of the Elector of Heidelberg, where he discovered a room with extraordinary echo effects [9]. He explained that in a particular section of the vaulted ceiling, whispers or soft speech at one point could be clearly heard at specific other locations due to sound reflection patterns. Within the circumference CGEF, as shown in Figure 1, a person speaking at point C could be heard clearly at positions G or F.

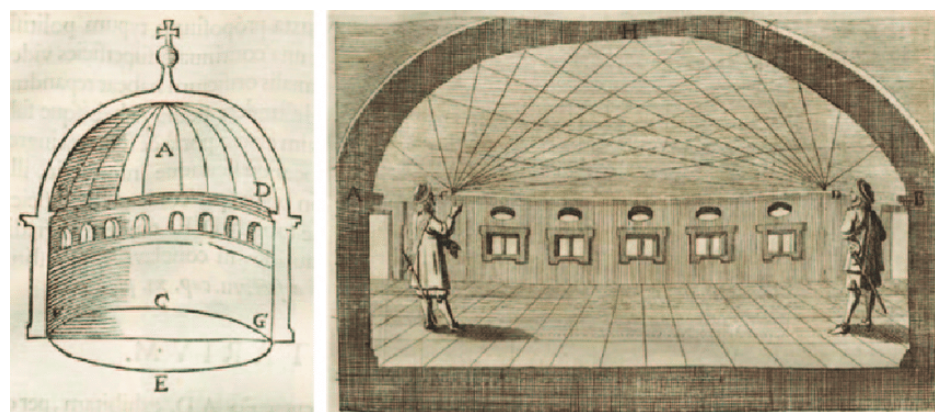


Figure 1. Heidelberg's echo [9].

Kircher proposed that elliptical vaults could be designed intentionally to enhance speech intelligibility in large halls or religious spaces [10]. He theorized that certain ceiling shapes could direct sound waves effectively, allowing preachers or speakers to be heard clearly without artificial amplification. Some of the vaults that Kircher described in *Phonurgia Nova* were purely theoretical or imaginative. Kircher's work influenced later scientists such as Lord Rayleigh and Wallace Sabine.

2.2. Theories and Discoveries in the 18th Century

W. Sabine once described whispers reflected from a giant hemispherical ceiling as creating "the effect of an invisible and mocking presence" [11]. Building on this concept, there is much to be investigated from the whispering gallery geometries. Curved surfaces can generate aural illusions, either by focusing sound waves or by allowing surface waves to skim along the interior of a concave structure [12].

Scientists such as W. Sabine, Lord Rayleigh, and C. V. Raman studied these phenomena extensively. Standing at the right distance in front of a curved surface can cause one's voice to be focused and amplified [13]. The exact auditory experience depends on multiple factors, including the listener's position relative to the curved surface, the curve's size,

curve's profile, as well as the type of sound produced. When a curved surface is farther away, the focused reflections become distinct from the direct sound, creating an echo [14].

Sabine studied large domed spaces where multiple sound reflections blur speech intelligibility and create lingering echoes [11]. He noted that hard, reflective surfaces in domed halls increase reverberation time, making it difficult for listeners to distinguish words [15]. He suggested breaking up smooth, curved surfaces using irregular textures or diffusive elements to scatter sound more evenly.

2.3. Changes in the 19th Century

One of many scientists following Sabine's studies on curved surfaces was Heinz Kuttruff, who provided a more quantitative and predictive framework for understanding sound propagation in rooms with concave walls, domes, and vaulted ceilings [16]. He mathematically demonstrated that parallel sound rays reflect and converge toward a focal point, creating hot spots where sound is amplified and distorting the normal diffusion of sound. While Sabine's formula assumes sound energy is evenly spread throughout a room, Kuttruff proposed modifications to the classical reverberation equation to account for non-diffuse sound fields in such rooms [16]. He stated that sound waves are allowed to reflect smoothly along a concave wall or dome, reinforcing certain frequencies, leading to coloration and intelligibility issues [17].

2.4. Developments in the 20th Century

The sound field serves as a function of the distance of the source from the reflecting surface and the curvature radius ratio, as extensively described by Cremer and Muller, in relation to convex and concave surfaces [18]. In particular, they explain that the dispersion of sound from convex surfaces leads to a reduction in the intensity of reflected sound, as the energy is spread over a broader area. Such surfaces help in achieving a more uniform sound distribution and minimize the risk of focusing sound energy [19]. In contrast, concave surfaces have a tendency to focus sound waves. However, the focusing effect depends on the distance between sound source and surface (d) and the comparison with the radius of the curvature (r). When the $d > r$, the focusing effect is in place, favoring increased sound pressure levels at specific points, potentially causing echoes or uneven sound distribution [20,21]. Cremer and Muller also studied the case of $d < r$, with the source close to the concave surface, and in this case, the sound is diffused as the soundwave hits a convex surface [18,22].

2.5. Historical Relevance to Current Case Studies

Acoustic theories developed from the 17th to the 20th century provide a fundamental conceptual framework for understanding the issues encountered in Sisto V Hall in Naples and in Aula Magna in Parma. Kircher's studies on sound effects in elliptical vaults find direct application in our barrel-vaulted halls, where similar sound focusing phenomena occur. Sabine's observations on domed spaces, where multiple reflections compromise speech intelligibility, are clearly manifested in the high reverberation time values (4.5 s and 3.7 s, respectively) measured in the two halls without any treatment. Similarly, Kuttruff's contribution on the non-uniform distribution of sound energy in spaces with concave surfaces is reflected in the low speech clarity values (C50) detected.

Cremer and Müller's theories on the relationship between source distance (d) and radius of curvature (r) are particularly relevant in our case, as in both halls, the sound source (speaker or musician) is typically positioned at a distance greater than the radius of curvature of the vault ($d > r$), creating the focusing effect that compromises intelligibility. The proposed solutions are based on the practical application of these historical theories, adapted to modern heritage conservation needs.

3. Historical Background of the Halls

3.1. Sisto V Hall in Naples

The Sisto V Hall is part of the Museum of the Opera of San Lorenzo Maggiore in Naples. It dates back to the period of Pope Sixtus V (1585–1590), who played a significant role in the urban and architectural renewal of the city [23]. In 1442, the hall became the meeting place for the Neapolitan Parliament and was the site of notable historical events.

The vault is divided into seven compartments, each depicting one of the Seven Virtues surrounded by four lesser virtues. Nowadays, Sisto V Hall hosts public concerts, including classical, chamber, and solo performances. During a few concerts attended by the composers, some musicians and critical listeners reported complaints about the blurred sound and acoustic discomfort experienced in the hall.

Historically, Sisto V Hall served as the refectory for Franciscan monks, since this grand rectangular hall measures approximately 43.6×9.8 m in plan.

3.2. Aula Magna at the University of Parma

The Aula Magna at the University of Parma is part of a 16th-century palace located in the heart of the city, following the establishment of the Jesuits [7]. In 1564, Duke Ottavio Farnese granted the Jesuits three additional residential properties [24]. The palace was dedicated to teaching and study [24]. However, in 1768, the Jesuits were expelled from Parma, and the palace was subsequently assigned to the University of Parma [7].

The room's geometric composition, featuring a wagon vault, along with the highly reflective surfaces, contributes to poor speech intelligibility. The Aula Magna has a rectangular layout measuring 10.3×22.2 m, with a maximum height of 12 m at the vault's peak, giving it a total volume of approximately 2400 m^3 [25]. The barrel vault runs along the longitudinal axis and intersects perpendicularly with smaller pointed arch vaults [25].

On the long side, eight windows overlook the internal courtyard, arranged with two windows per vault span. The seating consists of historic wooden chairs without upholstery, while bronze sculptures adorn the plastered brick walls. Additionally, carved wooden panels decorate the walls up to a height of 2.1 m, and the floor is covered with marble tiles. The Aula Magna still periodically hosts degree ceremonies, during which students present their final theses.

4. Digital 3D Models and Acoustic Similarities in the Two Vaulted Halls

The digital models of the two case studies have been reproduced with AutoCAD 2024 software, by drawing the surfaces as 3D faces. The two halls are characterized by a single nave, covered by a barrel-vault ceiling, with windows positioned along one side of the longitudinal axis. Table 1 summarizes the architectural features of Sisto V Hall in comparison to the Aula Magna of Parma.

Table 1. Architectural characteristics in the vaulted halls.

Description	Sisto V Hall	Aula Magna Parma
Type of vault	Barreled	Barreled
Longitudinal axis (m)	43.8	22.2
Transversal axis (m)	9.8	10.3
Maximum height at the center of the vault (m)	9.2	12
Total volume approx. (m^3)	3672	2400

Figures 2 and 3 show the plan and sections of the models for the selected vaulted spaces, created from drawings and site measurements. In both halls, the longitudinal axis is intersected perpendicularly by pointed-arched vaults. The primary difference between

the two spaces is their length, with Sisto V hall being nearly twice as long as Aula Magna. A common feature of both halls is the audience arrangement, which is divided into two areas by a central corridor.

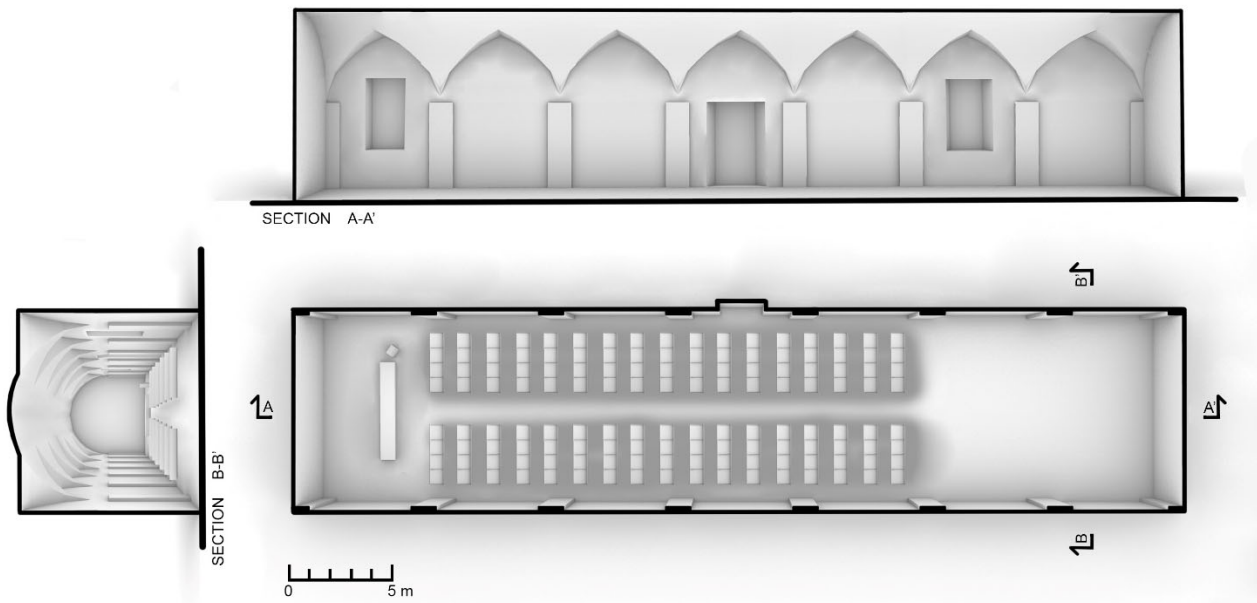


Figure 2. Drawings of the Sala Sisto V Hall, Museum of the Opera of San Lorenzo Maggiore in Naples.

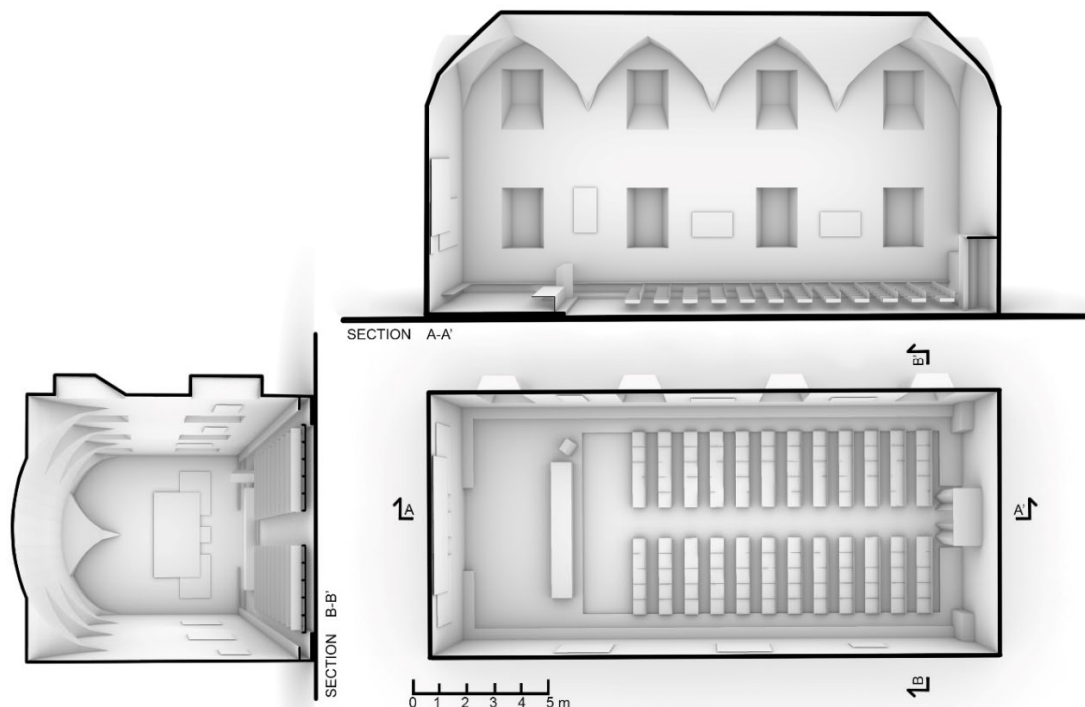


Figure 3. Drawings of the Aula Magna at the University of Parma.

Regarding finish materials, the walls in both halls are made of plastered brick, with frescoes on the ceiling and tiled floors. Aula Magna is provided with a shallow podium in timber (20 cm high), used for conference chairs during student celebrations or congress settings. Sisto V Hall, instead, even if not provided with wooden podium, is used for conferences and classical music performances. In Aula Magna, the basement level is clad with timber boards reaching a height of 2.1 m, whereas in Sisto V Hall, the basement-level

walls are entirely plastered. At the time of site measurements, the chairs in Sisto V hall were made of plastic, while those in Aula Magna were solid wood.

After creating the models, the files were exported in DXF format to prepare them for acoustic simulations, which were carried out using Ramsete 3.13 software [26]. Like many other commercial acoustic software programs, Ramsete is based on ray-tracing computation using a pyramid with a triangular base (instead of conical) propagation, making it suitable for evaluating speech intelligibility within a room.

The first step in the acoustic simulation process involved calibrating the absorption coefficients of the interior material. This calibration was based on on-site acoustic measurements, performed using the following equipment:

For Sisto V Hall: firecrackers as the sound source [27] and a Brahma microphone [28].

For Aula Magna: an equalized omnidirectional loudspeaker (Look Line, Bergamini, Parma, Italy) and an omnidirectional microphone (Bruel & Kjaer 4165, Virum, Denmark).

The Brahma microphone consists of a tetrahedral arrangement of four cardioid capsules that are capable of acquiring the necessary information to synthesize the harmonics of the 3D soundscape related to the first-order Ambisonics (1OA). The omnidirectional microphone, instead, does not allow the reconstruction of a 3D soundscape because it is composed of only one capsule that does not recognize the direction of arrival of a soundwave.

In both spaces, acoustic measurements were undertaken by placing the sound source in two positions: one corresponding to the conference table and the other at the opposite end, representing the public entrance [29].

In Sisto V hall, the receiver was placed in 24 positions, organized in 12 parallel rows evenly distributed to cover all seating areas. In Aula Magna, measurements were taken from 6 positions, with the receiver placed along the room's diagonal axis, as shown in Figure 4. The sound source was positioned at height of 1.6 m above the finish floor, while the microphone was placed at 1.4 m, simulating the ear level of spectators.

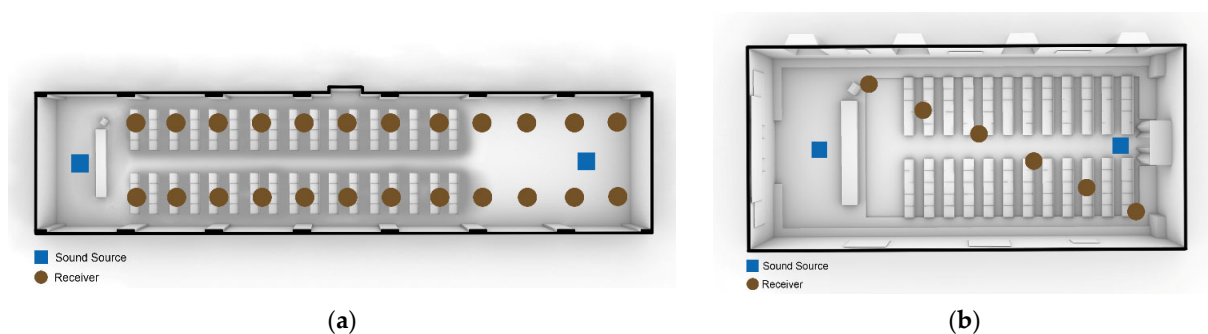


Figure 4. Disposition of the equipment during the acoustic measurements in Sisto V Hall (a) and Aula Magna (b).

The main acoustic parameters, as defined by ISO 3382-1 [29], have been analyzed, with a particular focus on speech intelligibility.

Regarding compliance with Italian regulations [30], for rooms with volumes exceeding 250 m³, the speech transmission index (STI) shall be $STI \geq 0.5$ –0.6, especially when an amplified audio system is in use. Additionally, the optimal reverberation time of these rooms should be 1.0 s for Sisto V hall and 0.9 s for Aula Magna, depending on their respective volumes.

Figure 5 summarizes the measured values of reverberation time and speech clarity in both halls, presented as averaged values across all receiver positions in an unoccupied condition. The analysis was carried out with the 125 Hz to 4 kHz frequency range.

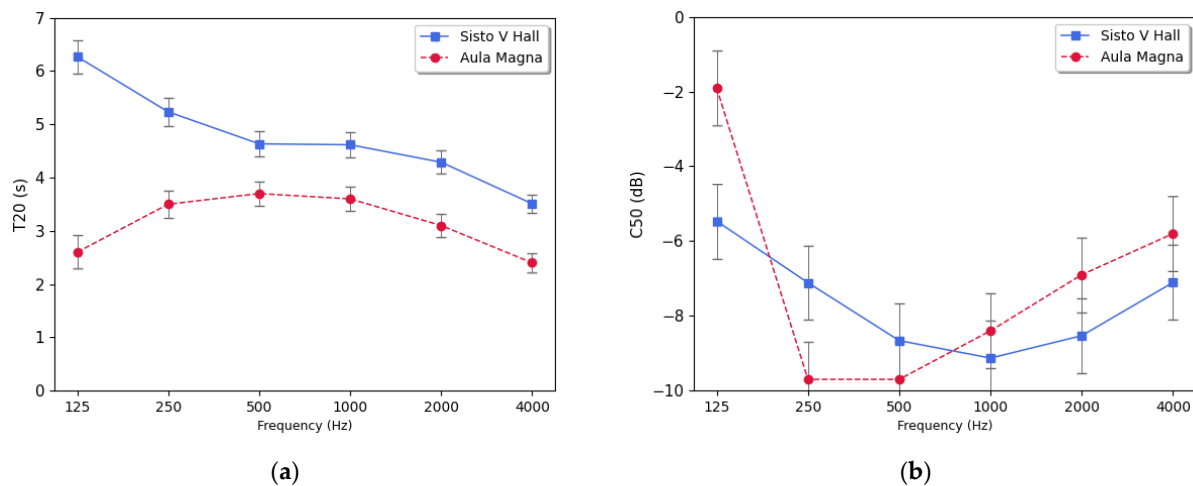


Figure 5. Measured results related to reverberation time $T20$ (a) and speech clarity index $C50$ (b).

Figure 5a shows that the reverberation time in Sisto V Hall is about 4.5 s at mid frequencies, while in Aula Magna it is about 3.7 s. The primary reason for this difference is the room volume, which is nearly twice in Sisto V Hall [31].

In terms of speech clarity, the measured $C50$ average across all seating positions in Sisto V Hall is approximately -9 dB, with an upward trend at very low and very high frequencies, reaching -6 dB, as shown in Figure 5b. In Aula Magna, $C50$ values show the poorest response between 250 Hz and 500 Hz, but improves at 125 Hz (-2 dB) and 4 kHz (-6.2 dB).

It is worth noting that the asymmetrical geometry of the side walls may influence sound perception between the two blocks of seats [32]. This effect is likely more pronounced in Sisto V hall, where one side wall has irregularities, while the opposite wall features large, glazed windows. Additionally, in such a long room, reflections from parallel surfaces play a significant role in shaping the energy response at the listener's position [33].

Overall, the measured acoustics in both spaces present challenges, particularly regarding speech clarity in such reverberant environments. This issue can be further exacerbated when the amplified audio system is in use, potentially causing listening discomfort and reduced speech intelligibility.

5. Calibration of Material Coefficients Within the Digital Models Based on Measured Results

The results from the measurement survey were compared with those obtained by applying absorption coefficients to the surfaces of both digital models. This comparison, known as the tuning or calibration process, involves minimizing the differences between measured and simulated values by adjusting the absorption coefficients in the digital model [34]. The scattering coefficients were assumed to be equal to 0.01 at all frequencies since the surfaces of the halls are smooth and geometrically constructed in the digital models. The scattering coefficients would play a role in case of irregular surfaces that are digitally simplified with a representation of a flat 3D-face.

The primary acoustic parameter considered in this process is the reverberation time ($T20$), as it is more reliable than other parameters such as clarity. This is because $T20$ is less sensitive to the precise position of the receiver. In contrast, calibrating $C50$ is very challenging, as this parameter varies significantly depending on the source and receiver positions.

The tuning was conducted to ensure that the discrepancy between simulated and measured $T20$ values remained within 5% across all frequency bands. However, minor variations between the measured data and the calibrated model are attributed to physical

factors that influenced the survey results. These small discrepancies may be due to environmental elements such as temperature variations [35], which mainly impacts the high frequencies as they are more sensitive to being absorbed when the temperature is low.

Figure 6 shows the comparison between the measured and simulated T20 values for both Sisto V Hall and Aula Magna. The calibration process was iterated until the adjusted values fell within the just noticeable difference (JND), corresponding to 5% of the value.

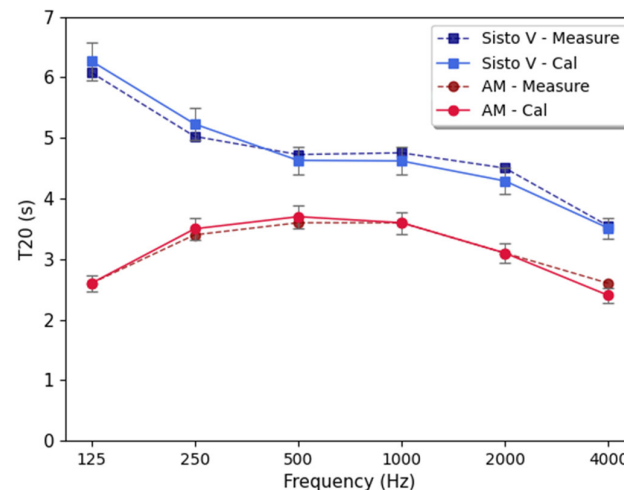


Figure 6. Calibration of digital models based on T20 values.

The values of the absorption coefficients of the final calibration used in both digital models are summarized in Table 2.

Table 2. Absorption coefficients used for the calibration process.

Materials	Octave Band Center Frequency—Hz					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Glass—Window	0.35	0.10	0.05	0.12	0.07	0.04
Solid Timber	0.25	0.13	0.11	0.15	0.13	0.15
Wall Decorations	0.01	0.01	0.02	0.03	0.03	0.04
Furniture	0.28	0.14	0.19	0.18	0.16	0.3
Desk	0.18	0.08	0.11	0.15	0.20	0.25
Floor	0.04	0.04	0.05	0.06	0.03	0.03
Plastered Brick Walls	0.03	0.06	0.06	0.04	0.04	0.04
Wooden Chairs (AM)	0.31	0.16	0.09	0.08	0.09	0.11
Plastic Chairs (SV)	0.23	0.11	0.05	0.05	0.05	0.03

Considerations on the Acoustic Limits of the Two Vaulted Halls

In the plan view, both halls feature long, linear side walls running parallel to the longitudinal axis. Due to the hard brick structure, these walls generate strong lateral early reflections. This volumetric shape is characteristic of certain Baroque churches, which typically have a single nave and a perfectly round vault spanning the entire width, supported by the side walls [36,37].

In the section view, the barrel vaults cause a focusing effect, especially because the sound source (e.g., speaker, presenter) is usually positioned at a distance greater than the radius of the vault's curvature. As a result, a more even redistribution of sound energy across the seating area is necessary to prevent flutter echoes and acoustic zoning with unbalanced sound energy [22]. Additionally, speech clarity should be improved, while reverberation time should be reduced: both essential factors for creating optimal listening conditions closer to the criteria of an auditorium [38].

It is important to note that measurements were carried out in unoccupied conditions, representing the worst-case scenario. Live venues are typically assumed to be at full audience capacity, which significantly affects acoustic behavior. For this reason, acoustic simulations with the proposed design treatments were performed both with and without an audience, as the audience's absorption plays a crucial role in balancing acoustic parameters.

6. Architectural Acoustic Design

As previously mentioned, the two selected vaulted rooms are currently used for celebrations, conventions, and other similar gatherings. The assessment of the current acoustic environment serves as a baseline for designing new mitigation solutions to improve the listening conditions, as this is their primary function [39]. In addition, Sisto V Hall can also be used for classical music performances with a small ensemble of instrumentalists. The treatment of the two halls is discussed separately, as follows.

As previously discussed, the mitigation measures are driven by the existing values of reverberation and speech clarity, aiming to achieve an optimal balance between early and late reflections to enhance the acoustic comfort.

6.1. Sisto V Hall

Given the dominance of the longitudinal axis over the other dimension, Sisto V Hall can be approximated as a shoebox-shaped room due to the linearity of its walls. The intent of the acoustic design is to evenly distribute early reflections across the seating area while avoiding focal echoes from the vault. To achieve this, the insertion of suspended wooden panels above the raised stage is recommended. The panels can be motorized allowing for adjustable orientation and height to create a desired acoustic shell profile [40].

A raised wooden stage, similar to the one in Aula Magna, is recommended at the far end of the hall, where the ensemble or speakers will be positioned. The stage should be elevated to a height of 0.30 m, enhancing sightlines while also slightly deepening low frequency contents by acting as a reduced resonance box [41,42].

To improve sound dispersion and direct sound toward the audience, the walls around the stage should be treated to increase scattering. The proposed solution consists of smooth convex wooden panels, each measuring 2.2 m in height and 1.0 m in width [43]. A similar intervention has already been realized in the Sala della Musica in Parma, Italy, a multifunctional hall used for classic music, conventions, and sound testing.

To optimize the reverberation time, the addition of absorbing material is necessary. Given the historical significance of the frescos on the vault, absorption should be spread on the walls. To maintain the aesthetics of plastered bricks, a product characterized with plaster finish has been selected, which is BASWA phon [44]. This panel is composed of 40 mm glass wool and an external coating of porous plaster.

For the flooring, a carpet running along the central walkway that separates the two seating areas, as well as along the two external walk paths, is proposed to minimize footstep noise from attendees moving during the performances.

6.2. Aula Magna

In Aula Magna, a similar organization has been provided, although the use of additional materials to improve acoustic parameters is less compared to Sisto V Hall. In particular, the bronze relief sculptures on the walls can be replaced with fabric canvas measuring $1.2 \times 2 \text{ m}^2$, mounted on a 20 mm thick wooden frame to create a cavity capable of absorbing low-frequency energy [41]. For additional sound absorption, oversized Caimi wall panels are preferred for installation on the upper portions of the walls above the wooden basement boards [45].

Additionally, the use of a carpet along the central walkway is considered to reduce footstep noise while also increasing sound absorption within the hall.

6.3. Audio System for the Vaulted Halls

Many modern halls are designed with amplified audio systems to deliver high-quality sound. It is recommended to integrate such a system as a supplement to natural acoustics. The primary purpose of the audio system is to ensure speech intelligibility and clarity with uniform coverage [46,47].

One common type of speaker is the linear array, often placed on church columns, where multiple transducers are housed within a single unit and displayed vertically. To be effective, the amplified sound should be approximately 6 dB louder than the background noise, with individual units uniformly distributed across the seating areas [48].

For this study, a linear array speaker system (GF162 by K-array™ PAT®—Pure Array Technology, Florence, Italy) [49,50] has been selected for acoustic simulations. This passive speaker delivers up to 200 W RMS and consists of sixteen 2-inch ferrite magnet woofers. The frequency response ranges from 135 Hz to 20 kHz, with a horizontal directivity of 90° and a vertical directivity of 7°. The speakers are designed to be mounted on the side walls, with three units for each side, constantly spaced 5.0 m apart. This arrangement ensures consistent and uniform coverage across the seating areas.

7. Acoustic Simulations

For Sisto V Hall, two virtual sound sources were placed onto the stage, while 60 virtual receivers were evenly distributed across the seating areas, arranged on a 1.5×1.5 m grid. In Aula Magna, 32 virtual microphones were used.

The characteristics of the materials described in the previous section, which were used for mitigation solutions, are detailed in Table 3, while Table 4 summarizes the features of the digital models. Acoustic simulations were performed both with and without an audience at full capacity.

Table 3. Absorption coefficients of additional materials used for mitigation solutions.

Materials	Octave Band Center Frequency—Hz						Scattering (@500–1k Hz)
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	
Wooden Ceiling Reflectors	0.25	0.13	0.11	0.15	0.13	0.15	0.05
Wooden Stage Floor	0.55	0.50	0.40	0.30	0.30	0.27	0.05
Convex Wooden Panels	0.25	0.13	0.11	0.15	0.13	0.15	0.05
40 mm BASWA phon [44]	0.30	0.73	0.86	0.86	0.8	0.73	0.05
Caimi Oversize wall Panel [45]	0.22	0.6	1.0	1.0	1.0	1.0	0.05
Canvas	0.35	0.38	0.40	0.40	0.46	0.50	0.05
Carpet	0.10	0.15	0.25	0.30	0.35	0.40	0.05
Audience	0.64	0.75	0.80	0.82	0.83	0.83	0.25

Table 4. Characteristics of digital models used for acoustic simulations.

Item Description	Sisto V Hall	Aula Magna
Total number of 3D-faces	2567	1143
Total surface area (m ²)	5318	1338
No. of virtual microphones	60	32

The scattering coefficients were obtained from previous research [20,21], while the absorption coefficients were sourced from acoustics manuals [16,32]. The arrangement of the additional materials within the two halls is illustrated in Figure 7.

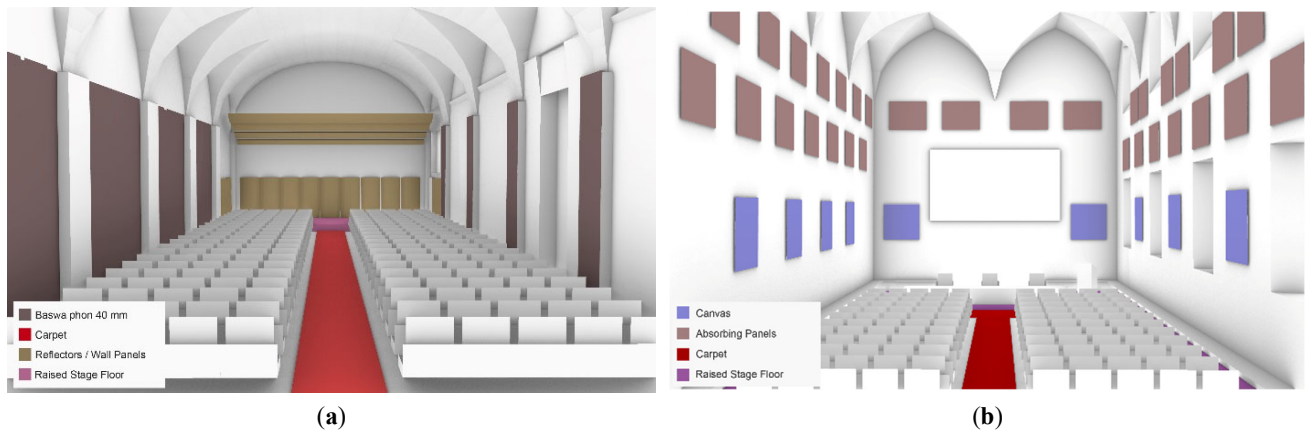


Figure 7. Disposition of the additional materials within the two halls: Sisto V (a) and Aula Magna (b).

8. Outcomes and Simulated Results

8.1. Acoustic Parameters

The analysis of the simulated results considers the optimal range of key acoustic parameters, with particular focus on speech. A graph has been created to represent the reverberation time. Spatial acoustic maps illustrate the distribution of speech clarity, as these values vary depending on the listener's position within the seating area.

Figure 8 summarizes T20 values according to ISO 3382 [29], across frequency bands ranging from 125 Hz to 4 kHz. The graph presents the average results for all virtual microphones used in the models. Simulations were performed under both occupied and unoccupied conditions.

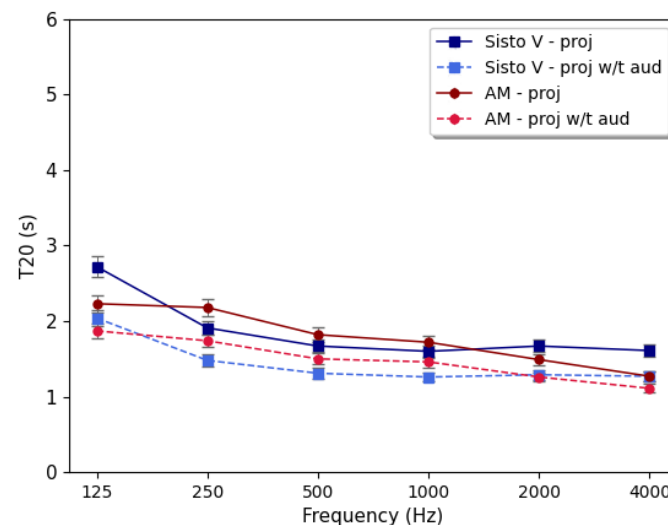


Figure 8. Simulated T20 results related to Sisto V Hall and Aula Magna.

Figure 8 shows that in Sisto V Hall, T20 values decrease from 4.8 s at mid frequencies to 1.7 s when the hall is not occupied. With full occupancy, T20 values drop by an additional 0.5 s, making the environment more suitable for speech understanding [51].

In Aula Magna, T20 values decrease from 3.9 s at mid frequencies without treatment to 1.9 s in unoccupied conditions. When fully occupied, T20 values decrease by another 0.4 s, reaching approximately 1.5 s at mid frequencies.

For speech clarity, C50 values are plotted as acoustic maps in Figure 9, while Equation (1) explains the relationship between the early sound energy within 50 ms and the late sound energy after 50 ms to the end of the impulse response [51]. This equation

explains the importance of balance between early and late reflection and, therefore, the best value is considered 0 dB, with a little tolerance that goes from -2 dB to $+2$ dB [52]. When the early sound energy is dominant (positive values of C50), the listener is more in the case of direct field, meaning that no reflections from the room helps to support the sound content. In contrast, when the late sound energy is dominant (negative values of C50), the listener is in the reverberant field, meaning that the room is very reverberant, and the comprehension of sound content is poor.

$$C50 = 10 \log \left[\frac{\int_0^{50 \text{ ms}} p^2(\tau) \cdot d\tau}{\int_{50 \text{ ms}}^{\infty} p^2(\tau) \cdot d\tau} \right] \quad (1)$$

Figure 9a shows that there is no significant difference in C50 values between occupied and unoccupied conditions in Sisto V Hall, as they are evenly distributed across the room. Under occupied conditions, C50 values increase by approximately 2 dB, ranging from 0 dB to $+4$ dB for seats near the stage, and between -1 dB and -2 dB in the rest of the hall. A similar trend is observed in unoccupied conditions, but C50 values range from -1 dB to $+2$ near the stage and around -4 dB in the rest of the hall. Overall, C50 values in Sisto V Hall with the acoustic treatment fall within or close to the optimal range for speech clarity (-2 dB and $+2$ dB) [32,33].

Figure 9b shows that in Aula Magna, C50 values are around 0 dB and $+1$ dB near the stage under unoccupied conditions, while at the back of the hall, they drop to around -4 dB. With full occupancy, C50 values increase by approximately 1 dB, reaching around $+2$ dB near the stage and -2.5 dB at the back. These values fall within the optimal range for speech clarity [47].

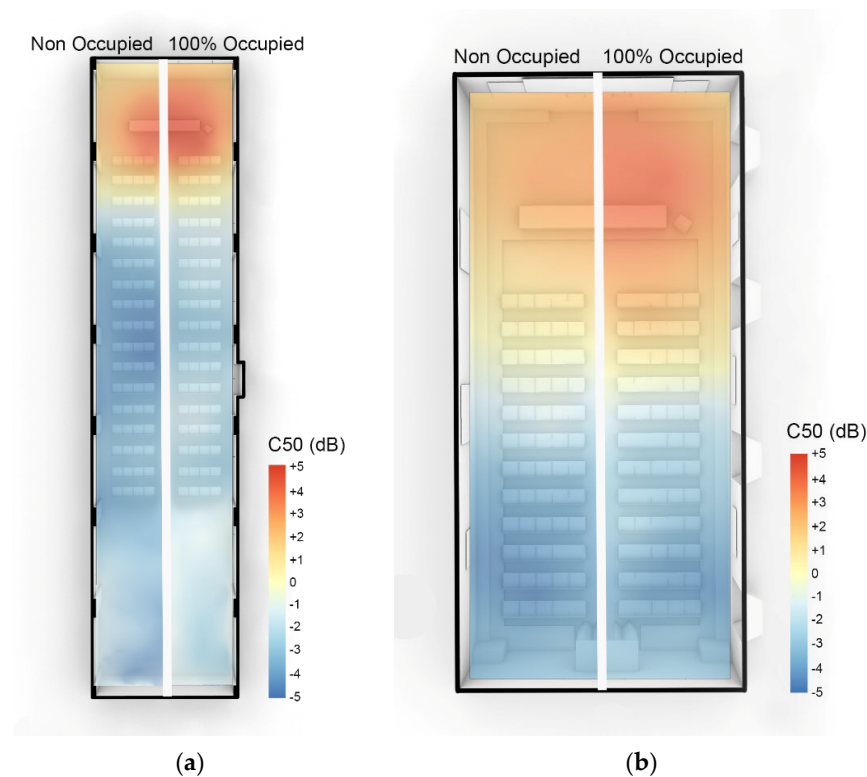


Figure 9. Spatial distribution of speech clarity index (C50) at 1 kHz, with and without audience: Sisto V Hall (a), Aula Magna (b).

8.2. Outcomes from the Amplified Audio System

The simulations for the amplified audio were carried out using K-framework3 software, which is open-source and available online [50].

For Sisto V Hall, the selected column array is the GF162 model by K-array (Florence, Italy), placed at 4.5 m intervals, with a total of four units per side to ensure full audience coverage. To assess the uniformity of sound pressure level (SPL), four virtual microphones were placed at the corners of an audience block, as shown in Figure 10. Each speaker was set with a gain of -15 dB and oriented 30° outward from the wall. The audience area was modeled at a height of 1.3 m.

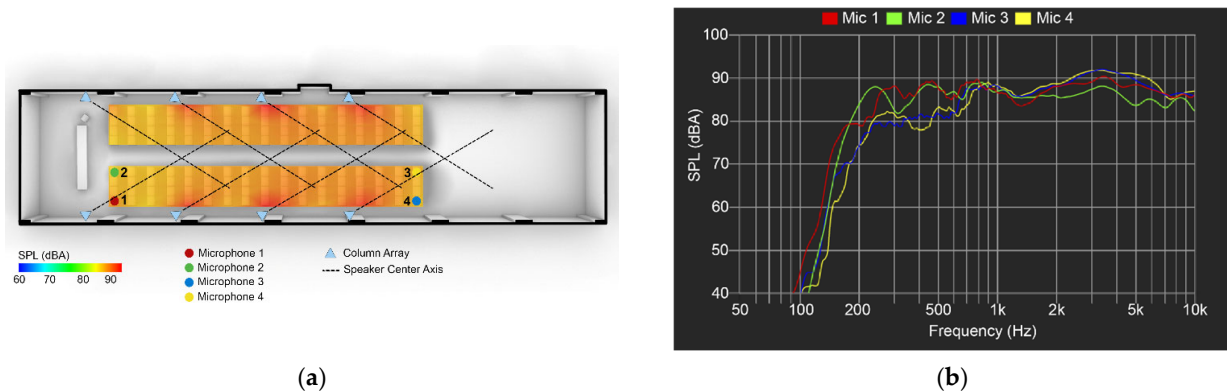


Figure 10. Spatial distribution within Sisto V Hall of SPL in dBA (a) and frequency response of virtual microphones deployed in one audience block (b).

The same column array (GF162 by K-array) was selected for Aula Magna, but with a spacing of 5.0 m between units, resulting in three speakers per side. Similarly, four virtual microphones were placed at the corners of an audience block to analyze SPL uniformity, as shown in Figure 11. Each speaker was set with a gain of -10 dB and oriented 30° outwards from the wall. The gain in Aula Magna was set lower to achieve the same SPL range, as its walls are slightly larger than those of Sisto V Hall. The audience area was also modelled at a height of 1.3 m.

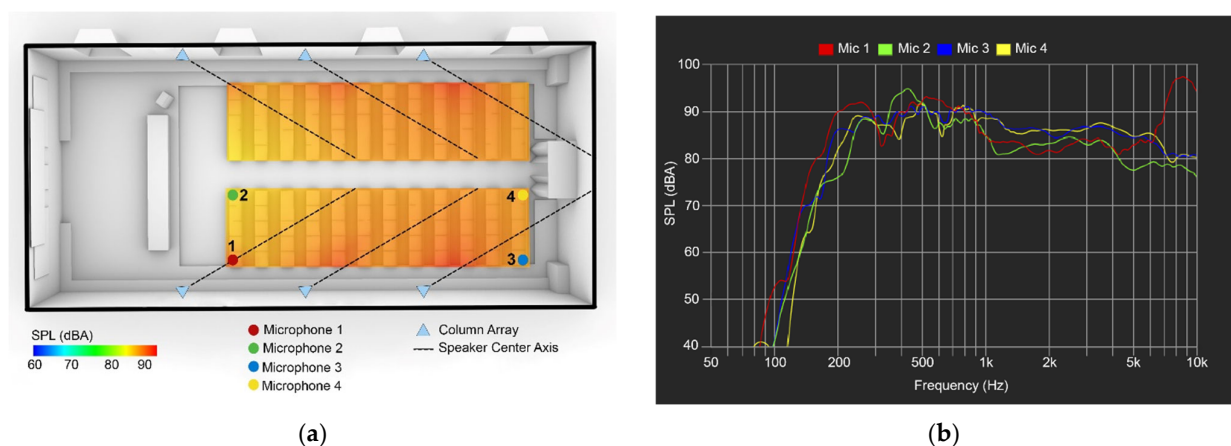


Figure 11. Spatial distribution within the Aula Magna of SPL in dBA (a) and frequency response of virtual microphones deployed in one audience block (b).

Figures 10 and 11 show that, with the amplified audio system and the applied gain adjustment, SPL values range between 90 dB and 93 dB. While low frequencies are not well covered by this speaker array, the octaves relevant to speech are effectively reproduced [52].

This additional analysis of the amplified audio system was carried out to complete the acoustic design for these two vaulted halls, which are used for conferences and celebrations.

9. Discussion on Acoustic Findings

The simulation results demonstrate significant improvements in both halls' acoustic performances. The reduction in reverberation time (T20) from 4.8 s to 1.7 s in Sisto V Hall and from 3.9 s to 1.9 s in Aula Magna, as shown in Figure 8, represents a meaningful compromise between speech intelligibility requirements and the preservation of some acoustic warmth appropriate for occasional musical performances [53]. This balance aligns with recommendations for multi-purpose spaces found in Barron [32] and Kuttruff [16].

The spatial distribution of C50 values, as shown in Figure 9, shows improvement throughout both halls, though some areas (particularly in the rear sections) still present values slightly below the optimal range for speech intelligibility. This spatial variation is consistent with Prodi's findings [49] regarding the challenges of achieving uniform clarity in historical spaces with pronounced longitudinal geometry.

The proposed amplified audio system complements the passive acoustic treatments, with the simulated SPL distribution (90–93 dB) ensuring adequate sound pressure levels throughout the seating areas. The limited low-frequency coverage observed in the frequency response curves (Figures 10b and 11b) is less critical for speech applications but may require consideration for musical performances in Sisto V Hall.

From a conservation perspective, the proposed interventions emphasize reversibility, using suspended elements and movable acoustic treatments that respect the historical integrity of these spaces [54]. The strategic placement of a limited number of acoustic elements yields substantial benefits while minimizing both cost and visual impact.

The simulations for both occupied and unoccupied conditions suggest that these acoustic treatments would perform effectively across varying occupancy levels, addressing a practical consideration raised by Vorländer [34,55] regarding the consistency of acoustic performance in public spaces.

10. Conclusions

This research focused on the acoustic design of two historical vaulted rooms: Sisto V Hall in Naples and Aula Magna at the University of Parma, both located in Italy. Site measurements allowed for an analysis of the rooms in their existing conditions, which were found to be suitable for speech understanding.

The proposed acoustic design strategy includes recommendations for adding absorption panels on the walls and carpeting on the floor to optimize acoustic parameters and bring them closer to the optimal range. With these mitigation measures, the reverberation times in both halls were reduced to 1.2–1.3 s at mid frequencies, which is considered acceptable. However, the installation of column array speakers on the side walls further enhances speech intelligibility, a primary requirement for celebrations and meetings.

The acoustic design solutions discussed in this study can serve as a valuable reference for improving other historical heritage buildings in Italy that are used for gatherings and conferences, particularly in cities where the availability of public buildings is limited.

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