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Topical Issue - The Sound of Ancient Theatres

SCIENTIFIC ARTICLE OPEN ACCESS

Acoustic analysis of a well-preserved Renaissance music space: The Odeo Cornaro in Padua★

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Abstract – The Odeo Cornaro is a remarkable example of Renaissance architecture featuring an octagonal umbrella-vaulted hall surrounded by four adjacent barrel-vaulted spaces. According to the principles outlined by Vitruvius, the central octagonal hall was prized for its acoustical qualities, emphasizing sound propagation and vocal resonance. Due to its remarkably well-preserved condition, the structure continues to serve as a prestigious venue for musical and cultural events. This study investigates the acoustic of this remarkably preserved musical space, employing measurements and numerical models. Finite element analysis and geometrical acoustics models were employed to gain comprehensive insights into sound pressure level distribution across a broad frequency spectrum. The Odeo stands as an outstanding historical music venue due to its capacity to enhance vocal projection while maintaining an intimate ambience during musical performances.

Keywords: Renaissance music space, Central-plan architectures, Modal sound field, Wave-based room acoustic simulations, Geometrical acoustics

1 Introduction

Archaeoacoustics is an emerging field of study enabling the exploration of the significance of sound through different eras and locations [1–3]. The sonic attributes of ancient sites represent an integral component of a society's intangible heritage, and numerous research works have focused on unravelling the acoustic properties of culturally significant spaces, thus enhancing the understanding of their historical use [4–6]. Within the diverse array of ancient cultural spaces under investigation, the architectural and acoustic significance of central-plan designs has an important role [7–9]. During the 16th century, central-plan configurations gained prominence as the Renaissance era rekindled the philosophies of Aristotle and Plato, which associated divine perfection with symmetry [10–12]. Eminent Renaissance architects such as Bramante, Leonardo, Brunelleschi, and Alberti designed and built numerous vaulted chambers featuring rounded corners, a design element believed to enhance sound propagation and musical experiences. The geometric characteristics of central-plan halls are generally able to sustain the voice and the music while preserving a sense of intimacy for the audience [13]. This study introduces a methodological framework for investigating the acoustics of ancient musical spaces, illustrating the approach through a replicable case study. The Odeo Cornaro in Padua, Italy, stands as a well-regarded Renaissance music hall still in operation today, characterised by its central octagonal hall and its historical adherence to architectural design principles. The structure's exceptional state of preservation helped measure the acoustics and collect objective room criteria in accordance with ISO 3382-1 standards. The experimental data are interpreted through computational modelling, a prominent tool for historians and archaeologists seeking to recreate auditory environments of the past [14–16]. Two distinct approaches were employed in the present investigation: a finite element method and a ray-tracing model [17–19]. These methods were used to assess sound behaviour across different frequency ranges. The former was employed in the low-frequency range and the latter in the mid-high range [20–24]. In the course of this study, historical references not only shed light on the intended purposes of the various rooms within the structure but also yielded insights into the materials used in its construction [25, 26]. The present work adds a further case study supporting a methodology applied to examine other historical music spaces [27–29]. It serves as an extension of a conference poster initially presented at the "Acoustics of Ancient Theatres" symposium, which transpired in Verona, Italy, from 6 to 8 July 2022.

★ The present work is an extension of a conference poster presented and awarded as Best Poster during the Symposium "The Acoustics of Ancient Theatres" held in Verona (Italy), 6–8 July 2022.

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Figure 1. Interior views of the central hall's vault (left) and the largest adjacent room (right). Pictures were taken by the authors in February 2022.

2 The case study

The Odeo Cornaro was erected between 1524 and 1534 for Alvise Cornaro (1464–1566), a Venetian patron of the arts and entrepreneur [30]. Around 1539–40, Alvise Cornaro would gather here with his friend Andrea Palladio, when both resided in Padua. Veronese architect Giovanni Maria Falconetto, eager to expand his architectural knowledge acquired during his residences in Rome, had previously been introduced to Palladio. Falconetto was entrusted with the design of Cornaro's villa of delights, which encompassed the creation of two key components: the Lodge, an open-air Roman-style theatrical setting, and the Odeo, a set of fresco-adorned chambers situated adjacent to the Lodge [31]. The Lodge hosted many plays and comedies by Angelo Beolco, also known as Ruzante (1496–1542), one of the earlier actors and playwrights of modern theatre. The Odeo Cornaro distinguishes itself as one of the most notable 16th century Venetian buildings for several reasons. Firstly, it was conceived by Falconetto following his extended sojourn in Rome, during which he gained exposure to classical art and perfected his knowledge of the harmonious proportions associated with central-plan structures. Secondly, the written accounts of the Odeo's use as a performance venue, as noted by architect Sebastiano Serlio, highlight the suitability of the octagonal space for musical events. Serlio stresses the remarkable reception and sustain of sound, attributing them to the concave geometry of the four large niches within the principal hall [32]. Serlio's account substantiates two pivotal aspects: the Odeo Cornaro's use for musical performances, specifically in the central hall, also referred to as ottangulo. Moreover, written records from the same period (1537–1542) indicate the presence of musical instruments and a choir, offering further evidence of the hall's role in sustaining the human voice. The historical documentation effectively highlights the hall's function in amplifying vocal sound [33]. Consequently, within the framework of Vitruvius' four categories delineating the relationship between sound and space (namely, resonantes, consonantes, circumsonantes, and dissonantes), the Odeo unequivocally aligns with the consonantes category of halls. In such spaces, the voice is sustained, ensuring that it reaches the ears of the listeners with clarity and resonance. Given the moderate volume of the ottangulo, it is reasonable to believe that it primarily accommodated intimate gatherings of educated individuals [34, 35]. The adjoining interconnected chambers were evidently intended for intellectual assemblies [36]. One of the Odeo's salient attributes is its impeccable state of preservation, which has helped avoid the need for structural or substantial restoration efforts over the years, except for a refurbishment of interior finishes in the 1970s (Fig. 1). Presently, the Odeo is frequently employed for cultural and musical events, along with its open-air counterpart, the Loggia.

3 Methods and materials

3.1 Measurements

In 2022, the authors conducted an on-site acoustic campaign to quantify the main room acoustic criteria of the Odeo Cornaro [37]. The measurement equipment consisted of:

– a laptop launching the exponential sine sweep (ESS) signals (512 k at 48 kHz),
– a Motu UltraLite AVB audio interface,
– a Crown 2500 W amplifier,
– a custom high-SPL dodecahedron calibrated in reverberation room (ISO 3740) [38],
– a monaural half inch free-field microphone (NTI audio MA220).

The ESS signals have been launched with Dirac version 6, which is the same software employed for the postprocessing phase. The acoustic measurements were performed placing the sound source at 1.5 m and the receivers 1.2 m above the floor, in accordance with the ISO 3382-1 standard [39]. The authors acquired the impulse responses for each source-receiver pair asynchronously, moving each time the dodecahedron and the microphone following the measurements layout shown in Figure 2. Referring to the geometrical arrangement of the architecture, the sound sources and receivers were placed only in the most important halls: the central octagonal space and the largest adjacent room (see Fig. 2). Two source and nine receiver locations were selected in the former; one source and three receiver locations were

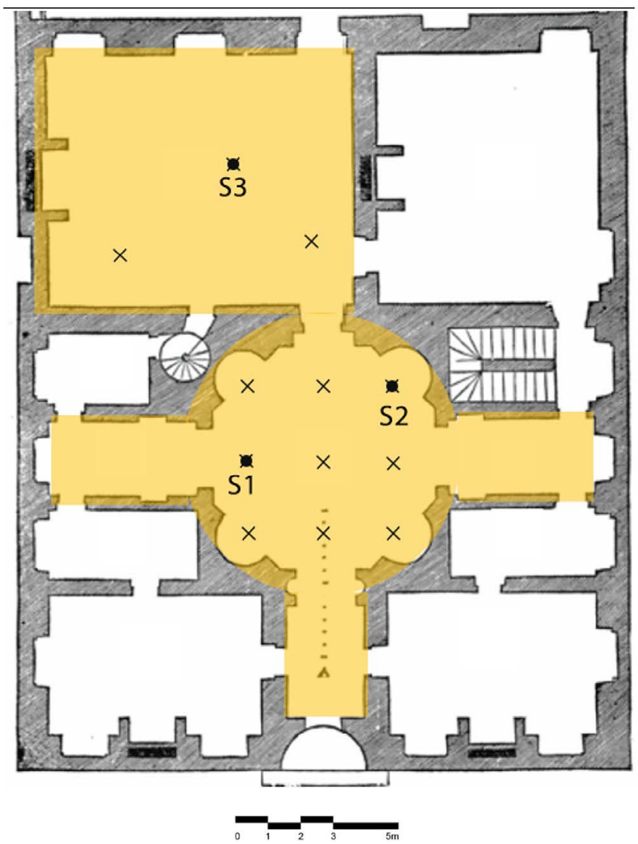

Figure 2. Plan of the Odeo Cornaro with the sound source (S1, S1, and S3) and receiver locations (x) employed during the acoustic measurements.

selected in the latter. The ISO 3382-1 room criteria T_{30}, EDT, C_{80}, T_S, and STI were collected for all the IRs acquired [9]. Table 1 summarizes the experimental results considering the sound source in S1 and all the receivers located in the *ottangulo*, as it is the core of the present study (see Fig. 2).

3.2 Numerical models

In the present work numerical models have been used to analyse the acoustics of the Odeo Cornaro from different points of view. For instance, the sound field behaviour at low frequencies and the spatial distribution of specific room criteria throughout the halls are of interest in order to verify the suitability of the architecture as a multiple performance space (music in the ottangulo and convivial gatherings in the other rooms).

With this purpose, a geometrical survey of the whole building was carried out to verify the dimensions reported in the blueprints found in historical references. These were used to draw a 3D virtual model including the main halls in Sketchup. Similarly to the experimental procedure, only the areas highlighted in Figure 2 have been included in the 3D model, for a total of 350 surfaces approximately. Figure 3 shows the sketch used in the acoustic simulations, with the typical details reduction required [40–42]. Thus, some of the curved surfaces were simplified and drawn as combinations of polygons and no details less than 0.3 m in size were modeled.

The volume of the main octagonal hall is 220 m^3 and the volume of the whole architecture considered is approximately 350 m^3. Since the mean reverberation time at mid frequencies (500–1000 Hz) is equal to 2.75 s, the Schroeder frequency, f_c, falls within the range f_c = 170–225 Hz [43]. Consequently, the modal behaviour strongly affects the sound field at least up to the whole octave band centered at 500 Hz (353–707 Hz), corresponding to approximately three times the Schroeder frequency [44]. For this reason, two distinct simulation approaches are required for tackling the whole frequency range of interest (from 125 Hz to 4000 Hz) [45]. For the steady state reaction under an omnidirectional sound source at low frequencies, a wave-based approach was used (COMSOL Multiphysics). On the other hand, for the analysis of room criteria spatial distribution at mid-high frequencies, a time-dependent ray-tracing method was used (Odeon Room Acoustics).

4 Results

4.1 Low frequency analysis (FEM)

The sound energy behaviour at low frequencies was evaluated using the finite-element modules embedded in COMSOL Multiphysics [46, 47]. The *Pressure Acoustics, Frequency Domain* physic interface, a branch of the *Pressure Acoustics* module, was used to compute the pressure variations within the 3D domain for the propagation of acoustic waves in the air at quiescent background conditions. Since the algorithm solves the Helmholtz equation in the frequency domain, it proved to be suited to all frequency-domain models of pressure field harmonic variations, as the assumption is the linear acoustics described by a scalar pressure variable. Following the same sound source locations shown in Figure 2, the omnidirectional sound sources were introduced as *Monopole point sources* at 1.5 m above the floor, corresponding to the same points employed during the acoustic measurements. Using the linear elastic model, a singular air domain was specified for the entire geometry. The specific acoustic impedance $Z = 10$ MRayls was assigned to all the surfaces involved, replacing the default *Sound Hard Boundary* condition [48–50]. Such value corresponds to the acoustic properties of marble, displaying significantly high acoustic impedance compared to air [43, 51]. The geometry's mesh was created using the rule of thumb of at least 6 elements for the lowest wavelength of concern (f_{max} = 500 Hz in FE analysis) [52].

Figure 4 shows the comparison between measured and simulated frequency responses for the source-receiver pair reported at the bottom right the figure. The simulated frequency response refers to the sinusoidal monopole source ($P_{rms} = 0.1$ W) located at S1 ($x = 0$, $y = 2$, $z = 1.5$) and the receiver located at R1 ($x = -2$, $y = -2$, $z = 1.2$). The frequency range remains in the region where modal peaks are more evident. The shape similarity between the experimental and the simulated results can be detected through the match of the main peaks (in dB) at the same

Table 1. Main experimental results in terms of measured T_{30}, EDT, C_{80}, T_S, STI values in octave bands. The values refer to sound source position S1 (see Fig. 3) and they have been averaged over all the receivers in the *ottangulo*, as it is the core of the present study (see Fig. 2). The standard deviations are provided in brackets.

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
$T30$	4.03 (±0.37)	3.53 (±0.43)	2.88 (±0.22)	2.60 (±0.15)	2.20 (±0.05)	1.66 (±0.03)
EDT	3.07 (±0.27)	2.96 (±0.26)	2.60 (±0.24)	2.40 (±0.14)	2.10 (±0.07)	1.52 (±0.05)
$C80$	−2.6 (±0.6)	−2.4 (±0.7)	−2.1 (±0.7)	−1.3 (±1.0)	−1.2 (±0.8)	0.8 (±0.7)
T_S	225 (±17)	203 (±18)	180 (±17)	162 (±16)	147 (±11)	104 (±6)
STI			0.41			

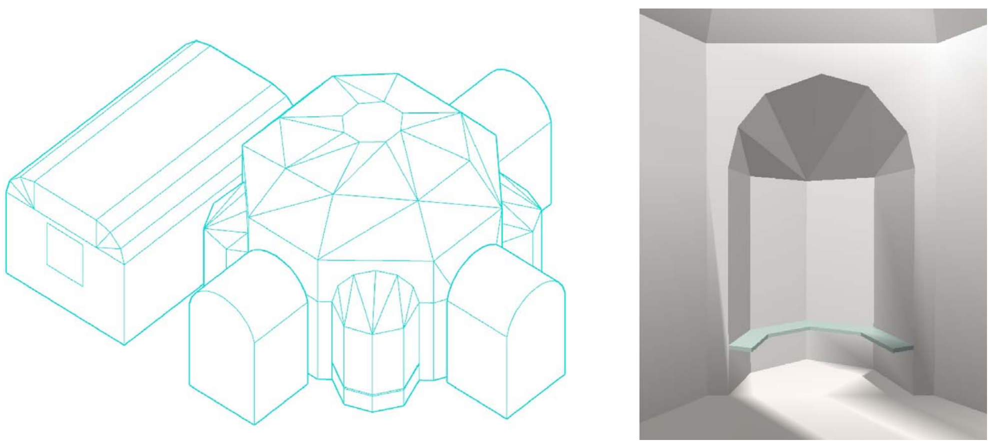

Figure 3. Views of the 3D virtual model of the central octagonal hall (220 m^3) surrounded by the adjacent halls (130 m^3) in Odeo Cornaro's building (overall 350 surfaces approximately): outside and inside views (Sketchup).

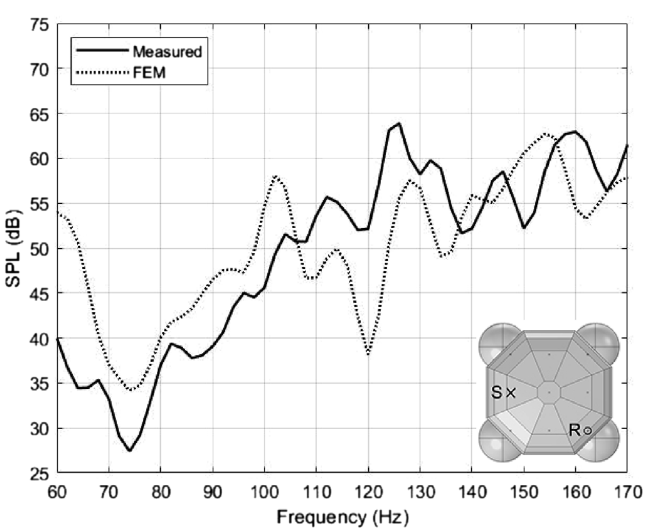

Figure 4. Comparison between measured and simulated frequency responses corresponding to the source-receiver pair shown at bottom right (COMSOL).

frequencies, even though only up to f_c=130 Hz approximately. For higher frequencies, when modes overlapping is increasingly higher, the comparison is indeed more difficult to be assessed. The y-axis shift is caused by the sound power level calibration of the dodecahedron employed during the measurements.

While the match of measured and simulated frequency responses in Figure 4 refers to an effective source-receiver pair taken as an example, the overall sound pressure level distribution is assessed for a general sound source at the centre of octagonal hall. Figure 5 shows the top view of simulated sound pressure level distribution in dB at 180 Hz considering the *Monopole point source* at the centre of the octagonal hall. From the analysis of SPL maps, the three small rooms connected to the octagonal hall seem to be acoustically part of the *ottangulo* (5 dB less on average) due to the large arches of connections. On the other hand, it is possible to notice a considerable drop of sound pressure levels (up to 20 dB) between the *ottangulo* and the largest adjacent room as there were two distinct and separate halls. The area of the connection door is probably too small that the whole geometry acoustically works as two distinct volumes even though they are phisically connected.

4.2 Ray-based simulations (GA)

The 3D model shown in Figure 3 has been imported into Odeon Room Acoustics version 12 through the SU2Odeon plugin [53]. As calculation setup, the transition order (TO) was set equal to 2, as suggested by the manual's guidelines for models with limited number of surface. As a consequence, the first two order of reflections have been computed with higher accuracy thanks to the image source method, whilst all the successive orders of reflections have been handled with a stochastic ray-tracing approach

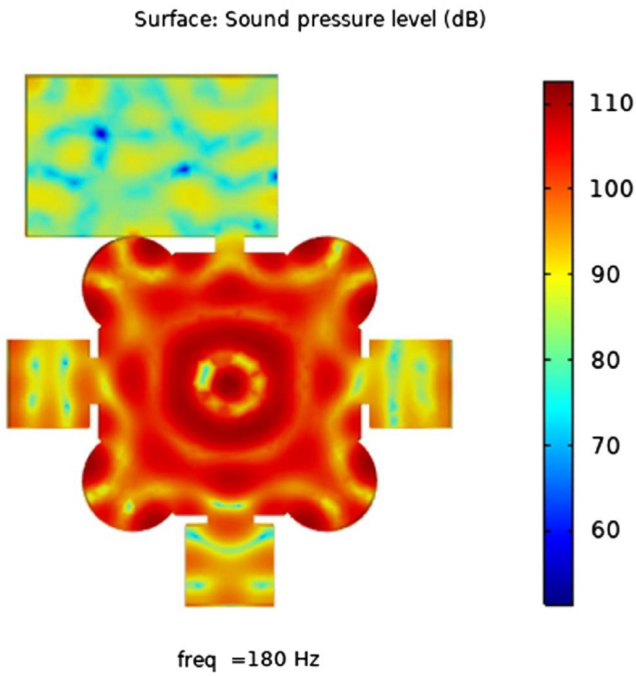

Figure 5. Simulated sound pressure level (dB) distribution at 180 Hz considering a *Monopole point source* at the centre of the octagonal hall (COMSOL).

(40,000 *late rays*). The maximum reflection order was chosen equal to 2000; the temperature and the relative humidity were set equal to 20 °C and 50%. Sources and receivers were placed into the model at the same points of the acoustic survey (see Fig. 2), and adequate boundary conditions were assigned to all the surfaces involved [45, 51, 54]. Table 2 provides the sound absorption and the scattering coefficients given to each material: marble (floor/walls/vault), glass (windows), wooden elements (doors/benches). This study employs Postma and Katz's rigorous system for acoustic calibration, which accounts for stochastic variance of Lambertian acoustic scattering [55]. The acoustic descriptors assessed as calibration criteria are T_{30}, EDT, C_{80}, T_S [56, 57]. Main calibration outcomes are shown taking into account the sound source in S1 and all the receivers in the *ottangulo*. Figure 6 shows the comparison between measured and simulated room criteria in octave bands, along with the tolerance ranges considered in the present work, i.e. 1JND (5% of measured values) for T_{30}, EDT, and 1JND (1 dB and 10 ms) for C_{80}, T_S [58].

Once calibrated, the model has been used as reliable starting point for further evaluations. For instance, the spatial distribution of main ISO 3382-1 room criteria has been investigated. With this purpose, a grid at 1.2 m above the floor, with 0.5 × 0.5 m squares, was set in the model.

Figure 7 provides the distribution of EDT and the C_{80} at 1000 Hz first for the sound source in the octagonal hall. Similarly to FE results at low frequencies, it is possible to notice that even at higher frequencies the three small rooms connected with the central hall through wide arches behave as a unique acoustic volume with the *ottangulo*, as they return the same EDT and C_{80} values. On the other hand, the adjacent room shows a significant increase of EDT values (more than 1 s) and a drop of C_{80} values (more than 4 dB). This acoustic behaviour confirms that space to be acoustically separated from the main hall, due to the narrow connection surface.

5 "Quivi si essercitaranno le musiche"

"Here musicians are to play – this is very suitable since the form is one which tends towards the circular, and the salotto is completely vaulted with brick, a material which has no humidity in it whatsoever. And the four niches, through their concave rotundity, receive the notes and hold them" [33]. This is Serlio's exciting historical description of the Odeo Cornaro's architectural design, providing crucial evidence regarding its intended use. The natural support of singers' voices offered by the hall has been further investigated.

The retrospective analysis of acoustic design for a space considering its use has some notable references in the literature [59, 60]. Indeed, according to historical sources, the Odeo hosted activities related to secular singing and music, and it is plausible to hypothesise that its construction and arrangement, inspired by antiquity, might have been optimised or employed precisely for compatibility with the singing and musical accompaniment of that era. With this purpose, the authors considered an excerpt that could have plausibly performed in the space under study according to historical references. Given the limited availability of anechoic material related to the 16th-century musical tradition, the "Zoia zentil che per secreta via" excerpt from "Canzon villanesche alla napolitana di Messer Adrian Willaert a quattro voci con la canzone di Ruzante" (Venice, Gardano, 1548) [61] was recorded in anechoic conditions in the laboratories of the University of Ferrara [62, 63]. A former professional singer – scholar in acoustics at the time of writing – participated in this study, who was previously familiar with anechoic recordings [64]. The voice chosen for the anechoic recordings is a Tenor because the predominant vocal line ("*Cantus*") was probably assigned to the Tenor voice [61]. Recordings were made with a large diaphragm microphone AT4050, in cardioid configuration, at 1 m from the singer's mouth to avoid proximity effects, as depicted by Figure 8. The microphone was preamplified, and A/D converted with MOTU Ultralite, set at 96 kHz 24-bit.

Figure 9 provides the spectral contents of the anechoic recording up to 700 Hz showcasing the first significant tenor voice's energy contribution in the low-frequencies range (from 110–120 Hz). This aligns with the first signicant SPL enhancement shown in the measured and simulated frequency responses in Figure 4, demonstrating that the hall strengthens the voice signal since its first formants. Moreover, the 125 Hz octave band corresponds to the most extended reverberation time measured in the Odeo Cornaro (see Table 1). All these factors imply that singers' voices are naturally supported by the acoustic environment,

Table 2. Sound absorption (α) and scattering (s) coefficients assigned to the 3D model's surfaces (Odeon).

Materials	α						s
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	707 Hz*
Marble	0.012	0.014	0.023	0.024	0.028	0.034	0.25
Window	0.130	0.060	0.040	0.030	0.020	0.020	0.05
Wooden doors/benches	0.140	0.100	0.060	0.080	0.100	0.100	0.35

* The value is expanded in frequency according to the software algorithm.

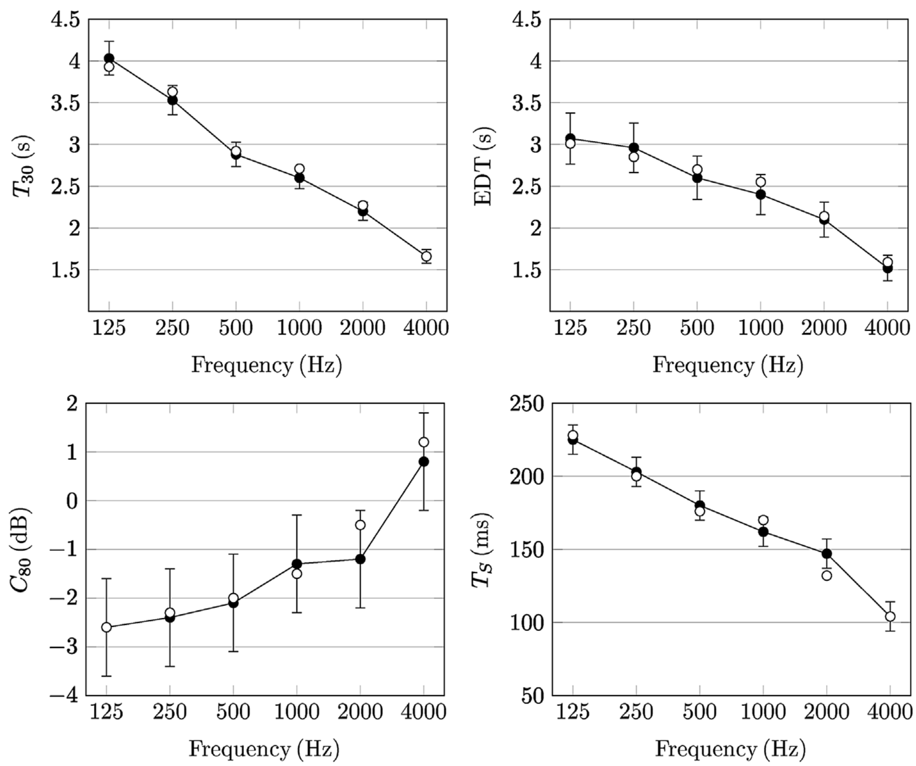

Figure 6. Calibration results: comparison between experimental data (black) and numerical simulations (white) through GA techniques (Odeon). Values have been averaged over all the receivers in the main octangular hall and refer to sound source S1 (see Fig. 2).

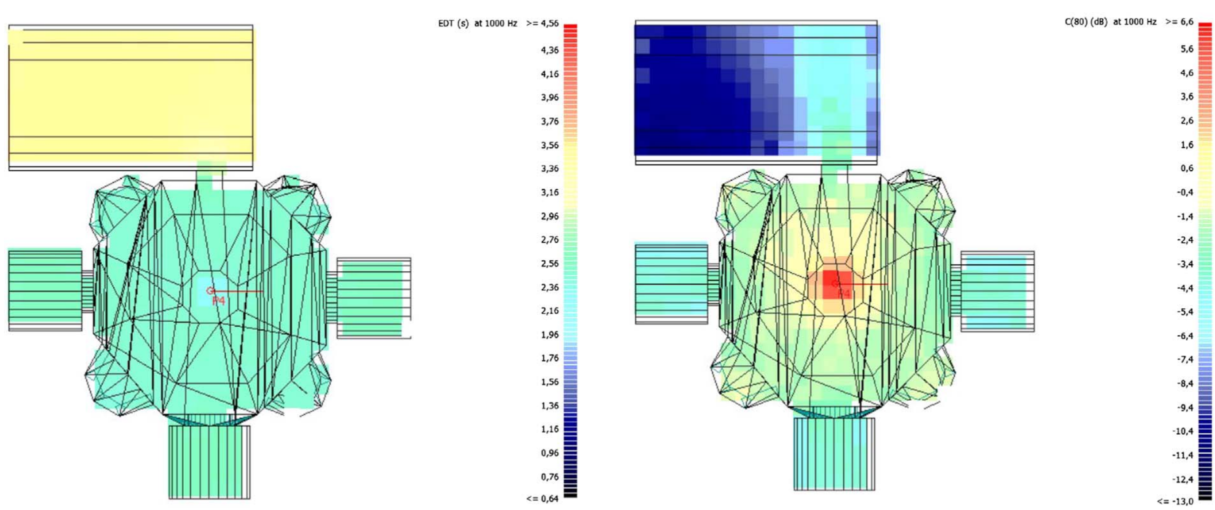

Figure 7. Spatial distribution of simulated EDT (left) and C_{80} (right) values at 1000 Hz considering an omnidirectional sound source at the centre of the octagonal hall (Odeon).

Figure 8. Anechoic recordings of "Zoia zentil che per secreta via" excerpt from "Canzoni villanesche alla napolitana di Messer Adrian Willaert a quattro voci con la canzone di Ruzante" (Venice, Gardano, 1548). Picture taken by the authors in December 2023.

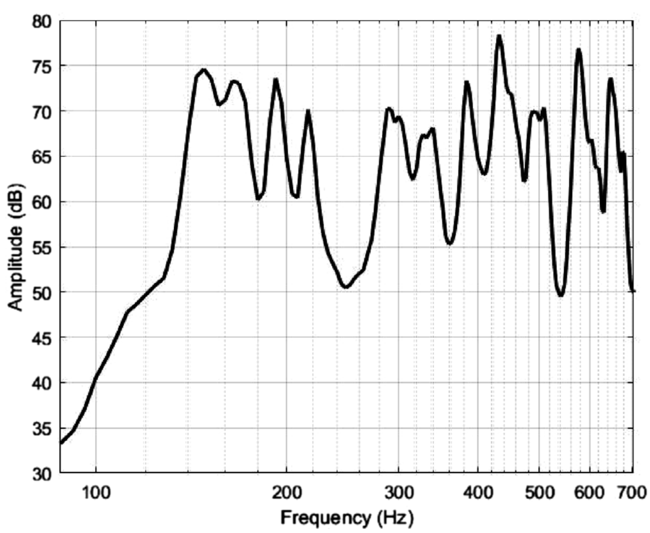

Figure 9. Spectral content of the excerpt recorded in anechoic conditions by a professional singer.

guaranteeing the optimum listening condition for the specific excerpts of that time [13, 26, 65].

Finally, it should be noted that the Odeo, in its current structural and acoustic furnishings, bears significant similarities to the original ones. For example, the masonry structure housing the sliding doors or the arrangement of the furnishings, which are constrained by the dimensions of the niches. This implies that the boundary conditions for low-frequency sound propagation measured are plausibly the same as those that involved performers in the 16th Century. While not claiming that this approach can be exhaustive, it can be asserted that a correlation exists between the space's intrinsic acoustic aspects and the documented use.

6 Conclusions

The present study proposes a multi-step approach to enhance the comprehension and the preservation of ancient places through acoustic investigation. The method here described has been applied to an important Renaissance music space: the Odeo Cornaro. A campaign of acoustic measurements in such a well-preserved architecture allowed to objectively quantify the experimental ISO 3382-1 room criteria. Numerical models pointed out noticeable differences between the sound pressure level and room criteria spatial trend in the different architectural parts of the Odeo's building. The three small rooms with wide arches proved to behave as a unique volume together with the central octagonal hall (intended for music purposes), while the largest adjacent space (intended for erudite symposia) is barely affected by the rest of the sound field. Low-frequency analysis by finite element methods (up to the Schroeder frequency) highlighted 20 dB as SPL drops from the receivers in the *ottangulo* and the receivers in the largest adjacent room. Similarly, geometrical acoustics returned significant differences at higher frequencies, where the 1000 Hz octave band has been taken as a reference. Considering the sound source in the central hall, the EDT values are more than one second longer, with C_{80} values more than 4 dB lower at the receiver in the adjacent space compared to the central hall. Finally, a spectral match between the modal response of the *ottangulo* and the first energy contribution of anechoic recordings of historical excerpts stressed the SPL enhancement to the singers' voice from the octave band centred at 125 Hz onwards. Therefore, the octangular hall in the Odeo Cornaro's Renaissance architecture can be deemed as a suitable space for music and singing.

Materials employed in the present work, including the 3D model, the monoaural measured impulse responses, and the anechoic recording are available in an free repository [66].

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Conflicts of interest

The authors have no conflicts to disclose.

Data availability statement

Data are available on request from the authors.

Ethics approval

No human subjects or animals were involved in the research.

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