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Acoustic characteristics and objective evaluation of acoustic quality in historical Italian theaters

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ABSTRACT

In order to determine an objective range of acoustic parameters for historical Italian theaters and to recommend ideal values for the primary acoustic parameters reverberation time (T_{20}, T_{30}), early decay time (*EDT*), sound strength (*G*), clarity index (C_{80} and C_{50}), definition (D_{50}) and interaural cross correlation coefficients (*IACC*), an acoustic survey of 24 historical Italian theaters spread over 8 regions of Italy was conducted. In the survey, two distinct acoustic measurements were used: 1. Conventional monaural and binaural measurements under unoccupied conditions. 2. Sound field visualization utilizing a 360° camera and an em32/64 Eigenmike®. The geographic distribution features of the 24 theaters, correlations among parameters, performance of each parameter across various frequencies, and dispersion characteristics were analyzed and quantified through computational methods. The acoustic quality of the theaters was ranked according to the statistical results, giving a range of desirable values for each acoustic parameter. It has been discovered that: 1. Correlation analysis indicates that at 1000 Hz, all parameters exhibit the strongest correlations, with a notably strong negative correlation between reverberation time and both clarity index and definition, and a strong positive correlation between clarity index and definition. These results suggest that data at 1000 Hz may be most suitable for machine learning predictions of parameters affected by measurement distance. 2. Boxplot analysis indicates that *G* is the only parameter without outliers, with variations in other parameters attributed to differences in geographical location, temperature, humidity, theater size, and interior decoration, highlighting the need to consider performance-specific acoustic requirements in evaluations. 3. Objective assessments reveal that most theaters perform best in clarity index values, with Italian historical theaters exhibiting significantly higher *G*-values, possibly due to factors such as reflective surfaces, stage structure, and architectural design features. 4. Theaters such as Teatro Amintore Galli (Rimini), Teatro dell'Opera (Rome), and Teatro Minimo (Atri) demonstrated notable acoustic performance based on the evaluated parameters.

1. Introduction

The acoustic properties and quality evaluation of performance spaces, particularly notable theater buildings, have garnered growing interest from researchers. Jordan [1,2] examined the acoustic characteristics of concert halls and established criteria for assessing acoustic quality. Hidaka and Beranek et al. [3–7] assessed not only several classical concert halls in Europe, the United States, and Japan but also conducted both subjective and objective evaluations of opera house acoustics. Researchers such as Wang, Chourmouziadou [8,9] and Bradley [10,11] have highlighted the importance of advanced computational methods in acoustical analysis, utilizing simulation techniques to predict and enhance acoustic performance. The adoption of these technologies has enabled for more precise and efficient evaluations of theater acoustics. Italian theater acoustics research has also progressively advanced in both theory and practice: Farina performed detailed acoustic measurements and analyses of numerous Italian historical theaters using impulse response measurement techniques and suggested optimal design methods [12–14]; Farnetani and Prodi et al. proposed acoustic standards for modern buildings through historical studies of Italian theater acoustic design [15,16]; Iannace et al. examined the effects of different auditorium and stage designs on sound transmission and audience experience through comprehensive acoustic analyses of several historical theaters [17,18], and also conducted comparative analyzes between modern and historical theaters, emphasizing the application of traditional design concepts to contemporary theaters. Saiki et al. investigated psychoa-

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coustic criteria and their application in evaluating theater acoustics, offering insights into the subjective perception of sound quality [19]. In addition, the database has been enriched with research from numerous experts on the acoustic properties of individual historic Italian theaters [20–25].

Building on previous studies, this article not only presents a holistic statistical and acoustic quality assessment of the acoustic characteristics of 24 historical Italian theaters in eight regions in northern and southern Italy, analyzing the correlation of key acoustic parameters at different frequencies. It also offers a detailed analysis of the causes of variability in the acoustic parameters of these theaters, which were not addressed in previous studies, as well as their characteristics and causes of spatial distribution. In this paper, the acoustic parameters of 24 historical Italian theaters were examined and statistically mapped. First, their geospatial distribution is analyzed, explaining the historical context and necessary conditions for the emergence of theaters in Italy; second, the architectural characteristics of Italian theaters and the measurement methods used in these acoustic investigations are described; the correlations of the main acoustic parameters are analyzed, and the distribution characteristics of these parameters at different frequencies in all the theaters are statistically presented to suggest the reasons for the emergence of dispersal points; subsequently, an objective evaluation of the acoustic quality of 24 theaters is conducted, and objective ranges and ideal suggested values for the acoustic parameters of historical Italian theaters with different volumes are provided.

2. Geospatial distribution and historical background of the theaters

The 24 historical Italian theaters counted are mainly distributed in northern and central Italy. Five theaters in the Lombardy region: Teatro Bibiena (Mantua), Teatro Ponchielli (Cremona), Teatro Social (Soresina), Teatro San Dominic (Crema) and Teatro Grande (Brescia); Teatro Olimpico (Vicenza) in the Veneto region; Emilia-Romagna region eight of them: Teatro Bonci (Cesena), Teatro 1763 (Bologna), Teatro Sociale (Gualtieri), Teatro comunale Pavarotti-Freni (Modena), Teatro Comunale (Bologna), Teatro Masini (Faenza), Teatro Valli (Reggio Emilia), Teatro Alighieri (Ravenna) and Teatro Amintore Galli (Rimini); Teatro della Fortuna (Fano) in Marche; Teatro Monte Castello di Vibio (Monte Castello di Vibio) and Teatro Nuovo (Spoleto) in Umbria; two in Lazio: Teatro Argentina (Rome) and Teatro dell'Opera-Rome (Rome); Teatro Minimo- (Atri) in Abruzzo; two in Campania: Teatro municipale Giuseppe Verdi (Salerno) and Real Teatro di Corte (Caserta);Teatro Eschilo (Gela) in the Sicily region. Fig. 1 illustrates the geographical location of completion of the 24 theaters.

As can be seen from the geospatial statistical map, the majority of these theaters are located in the Pianura Padana (Po River Plain). The Pianura Padana is strategically located between the Mediterranean Sea and the European interior. Its abundant soil and moderate temperature made it a key industrial and agricultural producing location in Europe, helping to drive urban expansion and population growth [26]. Since the Roman period, the Pianura Padana region has served as an important agricultural and commercial center for the Roman Republic and Empire. Its geographical, political, economic, social, and cultural characteristics facilitated the development of culture and art in the region.

These theaters were erected between the 18th and 19th centuries, which correspond with the emergence of the Enlightenment from the mid-17th to the 18th century. In this period in Rome, a variety of thinkers and scholars critiqued and reflected on society, politics, and religion. The time witnessed the advancement of reason and knowledge, the pursuit of individual liberty and equality, and the investigation of democratic institutions and human rights. This was combined with the outstanding achievements of ancient Rome in urban planning and architecture. Many spectacular buildings were constructed, included public theaters, which served as venues for public performances and were one of the city's cultural interchange centers, and the theater was no longer

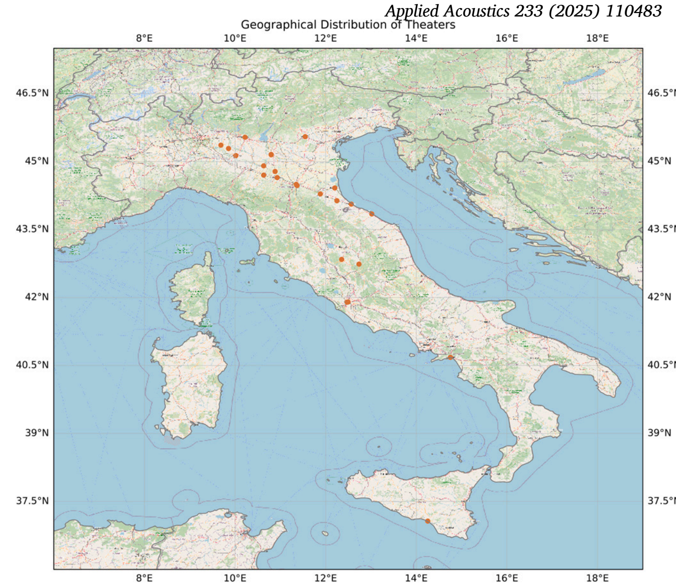

Fig. 1. Geospatial distribution map of 24 theaters.

the exclusive domain of the royal family. The rise of Romanticism and the nineteenth-century revival movement resulted in a higher level of emotion and beauty, while people began to value Italian culture and national identity, and many governments provided funds and resources to support public theaters. All of these historical contexts gave rise to a thriving theater society.

3. Acoustic measurements

3.1. Measurement equipment

All theaters were measured while taking into account the temperature and humidity levels of the space. The following equipment was in use.

- Omnidirectional dodecahedron sound source (Look Line 103)
- Dummy head (Neumann KU100)
- Ambisonic microphone (Sennheiser Ambeo Microphone)
- Omnidirectional microphone (Behringer ECM8000)
- Audio Interface (Zoom F8)
- The 32/64-channel spherical array microphone (em32/64 Eigenmike®)
- The 360° camera (Ricoh Theta V)
- Audio Interface (Orion32)

The em32/64 Eigenmike® and 360° camera are utilized to visualize sound reflections as they hit the surfaces of the theater's inner construction [27,28]. Other devices were utilized to assess traditional monaural and binaural parameters. Fig. 2 illustrates the configuration of the equipment.

3.2. Measurement points

All acoustic parameters were selected from measurements taken when the theater was unoccupied. The excitation signal from the acoustic source was an Exponential Sine Sweep (ESS) with a duration of 15 s. Commonly, Since classical Italian theaters are generally symmetrical, half of the space was selected for acoustic measurements, and a single measurement point in the other half was sufficient to verify the acoustic characteristics of the whole space. Detailed sound maps of the sources and receivers were also created in some theaters with the use of em32/64 Eigenmike® multichannel spherical array microphones and the Rico Teta V 360° panoramic camera. The sound field was visualized

Fig. 2. Equipment setup: sound source (Look Line 103); receiving microphone combination; 360° camera (Ricoh Theta V).

by reproducing the impulse response during the recording with a visual overlay.

It should be clarified that 24 theaters are reported in this article, which were measured over a long period of time, and in some cases the measurements were repeated in different years. Therefore, when measurements were taken in different theaters in different years, the location, height and number of sound sources placed in them were not static, and there may be inconsistencies with ISO 3382-1:2009 (the earliest measurements were taken around 2000, and the specification requirements are different from either 2009 or 2024).

And there are some differences in equipment from the initial period of these measurements until now, due to the evolution of methods and equipment over the years. In addition, in some studies, the experimental design may require exploring different methods to understand how acoustic properties behave under different conditions, and we may intentionally deviate from the standard to obtain more comprehensive data. In other cases, we prefer to focus on particular aspects, such as specific measurement tasks or studies that may involve specific scenes or buildings.

4. Objective evaluation

4.1. Architectural features

Before conducting the objective evaluation, it is necessary to first outline the architectural characteristics of these theaters to provide a foundation for a more comprehensive understanding in the subsequent analysis.

The Italian historical theaters investigated in this article were inaugurated in the Baroque and Classical Periods, with the exception of the Teatro Olimpico, designed by Andrea Palladio, which is of great research and historical importance as the first indoor theater in Italy.

The Italian historical theaters are generally buildings with multi-storey balconies, roof galleries, and horseshoe-shaped layouts. The exteriors were usually built in the classical architectural style, featuring colonnades, arches, and reliefs. The interiors consisted of fine ceilings, frescoes, statues and patterned floors, with ornate lighting. The architectural characteristics of the theaters are statistically shown in Appendix Table 1 (shown in the final pages). The plan layouts of Real Teatro di Corte, Teatro Alighieri and Teatro dell'-Opera Rome are obtained from the official websites (https://www.reggiadicasertaunofficial.it/reggia/teatro-di-corte/, https://catalogo.beniculturali.it/detail/ArchitecturalOrLandscapeHeritage/0800206008#lg=1&slide=15, https://www.operaroma.it/en/). The plan layout of Teatro Aminitore Galli is obtained from the website (https://9hstudio.it/attivita/consulenza-impresa/2012_teatro_rimini/). The re-

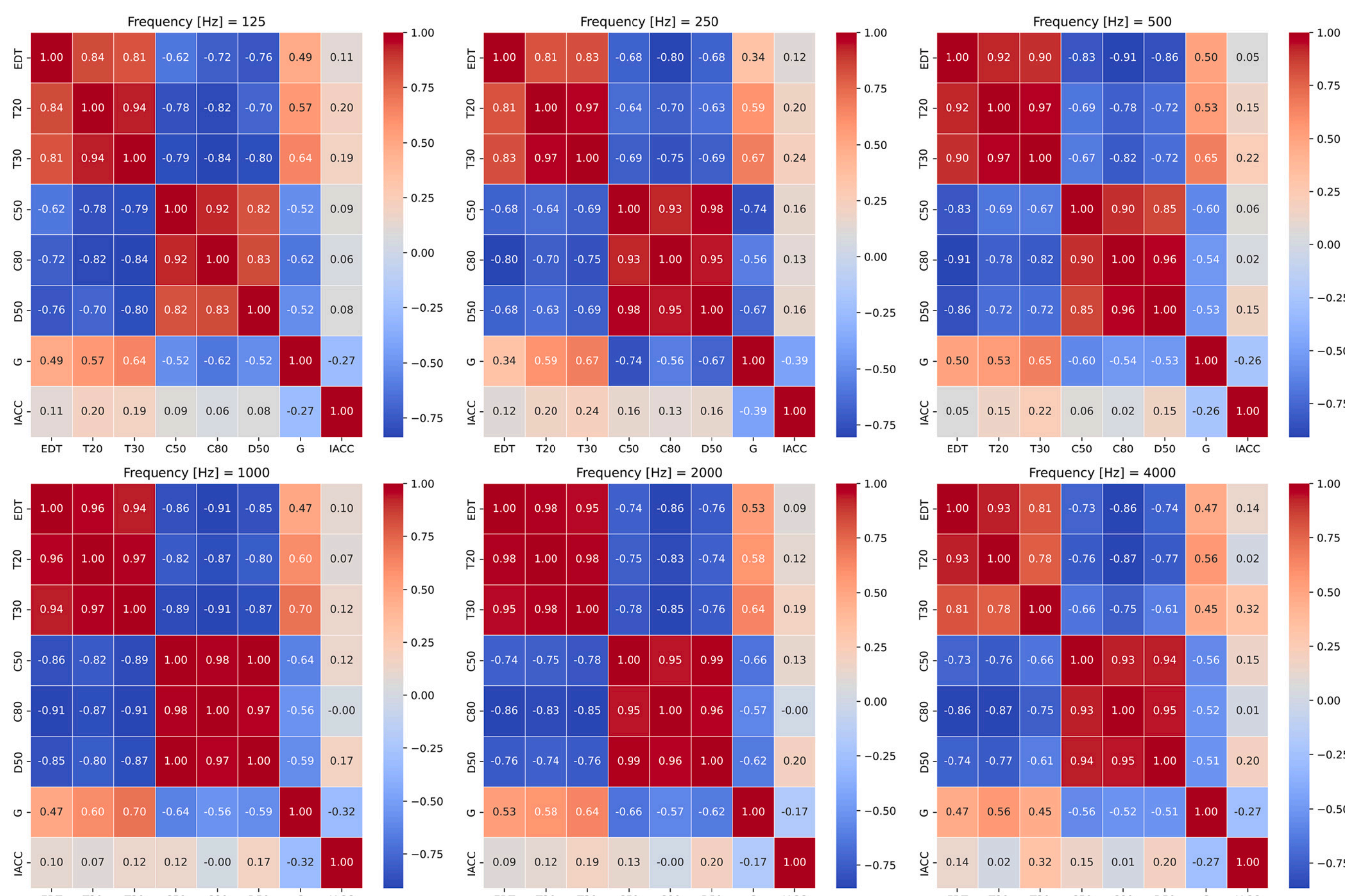

Fig. 3. Correlation heatmaps of the eight acoustic parameters.

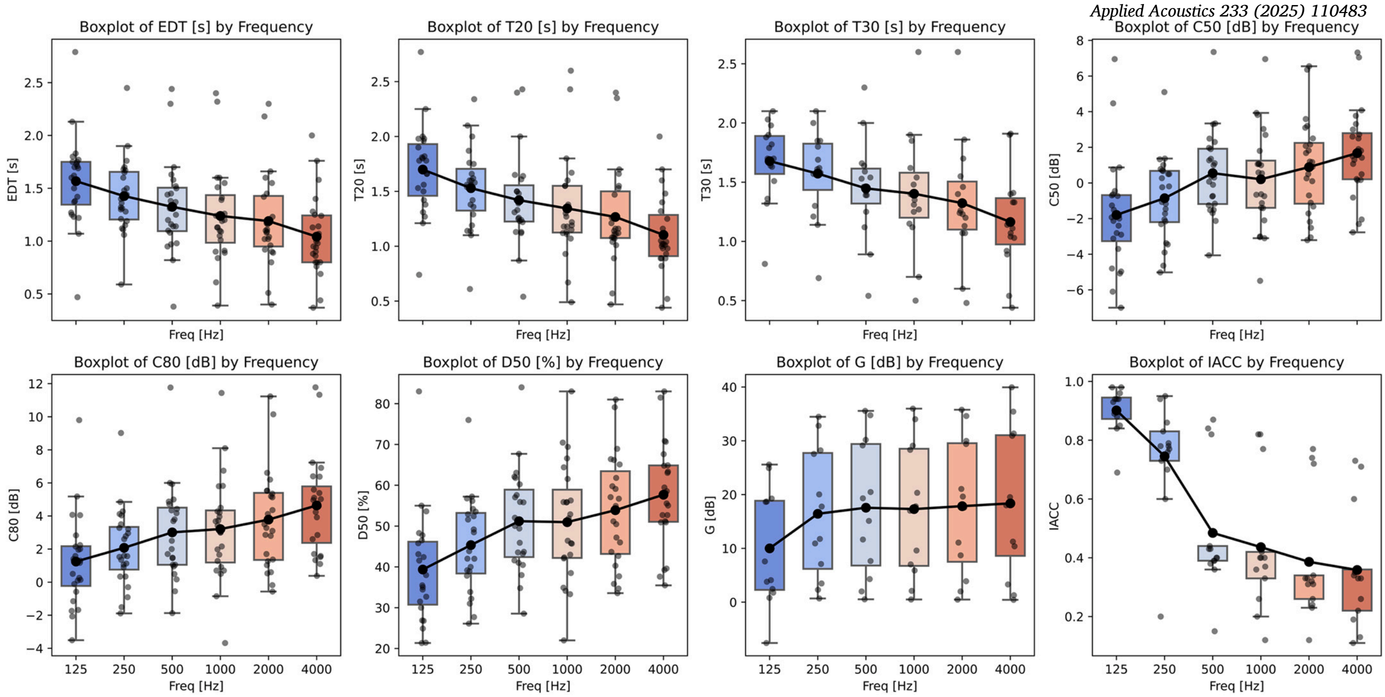

Fig. 4. Boxplots of measurements for eight acoustic parameters by frequency.

maining plans are partially self-drawn by the author and some are from coworkers in the team.

4.2. Correlation analysis

The acoustic parameters obtained from measurements in 24 theaters, including reverberation time (T_{20}, T_{30}), early decay time (*EDT*), sound strength (*G*), clarity index (C_{80} and C_{50}), definition (D_{50}) and interaural cross correlation coefficients (*IACC*), were compiled for analysis. Correlation heatmaps depicting the relationships between these parameters at various frequencies were illustrated in Fig. 3. Darker colors on the heatmaps indicate stronger correlations, while lighter colors signify weaker correlations.

It can be clearly seen that there is a considerable positive correlation between the *EDT*, T_{20} and T_{30} values, with the strongest correlation in the middle and high frequency bands. The same result is observed between C_{80}, C_{50} and D_{50} values; reverberation time (*EDT*, T_{20}, and T_{30}) and clarity index (C_{50} and C_{80}) show strong negative correlations across the full frequencies; The *G*-value shows a moderate positive correlation with reverberation time over the full frequency range, while it has a certain negative correlation with both the clarity index and the *IACC* over the full frequency range; The *IACC* has no significant correlation with the other acoustic parameters across the full frequency range, except for some negative correlation with the *G* value.

4.3. Statistical results of acoustic parameters

The measurements of the eight acoustic parameters for all theaters were plotted as Boxplot on eight subplots according to different frequencies. The black solid lines represent the average values of each parameter in different frequency bands. The statistical results are shown in Fig. 4 and supplemented by Table 1.

Combining the statistical results of Fig. 4 and Table 1:

1. Early decay time (*EDT*), reverberation time (T_{20}, T_{30}) and interaural cross correlation coefficients (*IACC*) show a decreasing trend from low to high frequency bands; clarity index (C_{80} and C_{50}), definition D_{50} and sound strength (*G*) display an overall upward trend. C_{50} and D_{50} slightly decrease from 500 Hz to 1000 Hz, while *G* gradually stabilizes in the middle and high frequencies.

2. Compared to the wider distribution of values for the other acoustic parameters *G*, the narrower distribution of values for *IACC* suggests that these theaters have large variations in *G* measurements at different frequencies, while *IACC* measurements have smaller variations, but the differences become larger in the higher frequency bands. And *G* is the only parameter with no discrete points (outliers).

The presence of outliers in the statistical results may stem from several factors:

1. The considerable variation in theater volumes, along with differences in interior decorative constructions and materials, such as the fly tower, carpets, and seat upholstery in the audience chamber, is a primary reason for the presence of outliers in the data.

The statistical charts of the measured values reveal that the reverberation time, sound strength (*G*), definition (D_{50}), and interaural cross correlation coefficients (*IACC*) of Teatro Monte Castello di Vibio are significantly lower, while the clarity index is notably higher compared to other theaters. This discrepancy is likely attributable to its status as one of the smallest historical theaters in Italy (400 m^3 of main hall), with dimensions and construction markedly different from other theaters. In contrast, Teatro Nuovo, also located in the Umbria region, is the largest theater in this area (5000 m^3 of main hall), accommodating approximately eight times as many spectators as Teatro Monte Castello di Vibio [29,30]. The ample height and width of Teatro Nuovo provide conditions conducive to adequate reverberation. Additionally, unlike the horseshoe plan characteristic of most Italian theaters, including Teatro Nuovo, Teatro Monte Castello di Vibio features a bell-shaped plan. Fig. 5 presents the interior scenes of both theaters.

When it comes to approximate estimation of volumes, measurements can vary considerably from one theater to another, due to the layout of the interior spaces, the decorative structure and the materials used. As an example, the Teatro Monte Castello di Vibio is shown in Fig. 6, which compares the measurements with those of Teatro 1763. The reverberation times measured at Teatro Monte Castello di Vibio are much lower than those measured at Teatro 1763, while the clarity index values are much higher than those measured at Teatro 1763. Fig. 7 illustrates the interior of Teatro 1763, which has a rectangular floor

Table 1
Boxplots quartile distance statistic.

Freq [Hz]	level_1	EDT [s]	T20 [s]	T30 [s]	C50 [dB]	C80 [dB]	D50 [%]	G [dB]	IACC
125	0.05	1.09	1.22	1.17	-5.95	-2.02	21.79	-2.97	0.77
	0.25	1.35	1.46	1.57	-3.27	-0.23	30.75	2.29	0.87
	0.5	1.61	1.78	1.7	-1.96	1.23	38	5.84	0.94
	0.75	1.75	1.93	1.89	-0.68	2.17	46.16	18.84	0.95
	0.95	2.08	2.22	2.05	3.93	5.01	54.86	25.22	0.98
	avg	1.57	1.7	1.68	-1.79	1.25	39.35	10.01	0.9
250	0.05	1.07	1.1	1.01	-4.53	-1.42	28.04	1.58	0.44
	0.25	1.21	1.33	1.44	-2.2	0.76	38.39	6.2	0.73
	0.5	1.38	1.56	1.61	-0.66	1.59	43.86	14.77	0.78
	0.75	1.65	1.71	1.83	0.68	3.34	53.22	27.23	0.83
	0.95	1.88	2.09	2.03	1.36	4.76	57.18	33.55	0.94
	avg	1.43	1.53	1.57	-0.86	2.08	43.35	16.43	0.75
500	0.05	0.84	0.9	0.79	-2.06	-0.44	35.12	1.34	0.28
	0.25	1.1	1.23	1.32	-1.18	1.05	42.4	6.81	0.39
	0.5	1.28	1.33	1.46	0.33	2.8	50.03	17.21	0.4
	0.75	1.51	1.56	1.62	1.92	4.5	58.93	29.4	0.44
	0.95	2.21	2.36	2.09	3.33	5.99	67.24	35.11	0.85
	avg	1.32	1.42	1.45	0.55	3.01	51.2	17.56	0.48
1000	0.05	0.64	0.7	0.64	-3.09	-0.65	33.4	1.38	0.17
	0.25	0.99	1.13	1.2	-1.4	1.19	42.2	6.75	0.33
	0.5	1.16	1.22	1.35	0.32	3.21	51.9	17.41	0.4
	0.75	1.44	1.55	1.58	1.25	4.34	58.92	28.51	0.42
	0.95	2.21	2.37	2.11	3.91	7.9	70.35	34.89	0.82
	avg	1.24	1.34	1.4	0.21	3.21	50.97	17.31	0.44
2000	0.05	0.55	0.6	0.56	-2.97	-0.07	34.81	1.32	0.19
	0.25	0.95	1.08	1.1	-1.16	1.35	43.18	7.51	0.26
	0.5	1.1	1.14	1.24	1.04	3.39	54.93	18.61	0.32
	0.75	1.43	1.5	1.51	2.25	5.4	63.45	29.54	0.34
	0.95	2.1	2.28	2.08	5.94	9.62	78.1	35.13	0.75
	avg	1.19	1.27	1.32	0.89	3.78	53.89	17.85	0.39
4000	0.05	0.48	0.55	0.51	-2.26	1.13	37.78	0.91	0.12
	0.25	0.8	0.91	0.98	0.21	2.38	51.06	8.62	0.22
	0.5	0.97	1.02	1.11	1.61	4.69	58.1	18.24	0.33
	0.75	1.24	1.29	1.37	2.79	5.79	64.85	31.04	0.36
	0.95	1.73	1.69	1.9	6.6	10.71	80.41	37.45	0.72
	avg	1.04	1.1	1.16	1.67	4.64	57.69	18.36	0.36

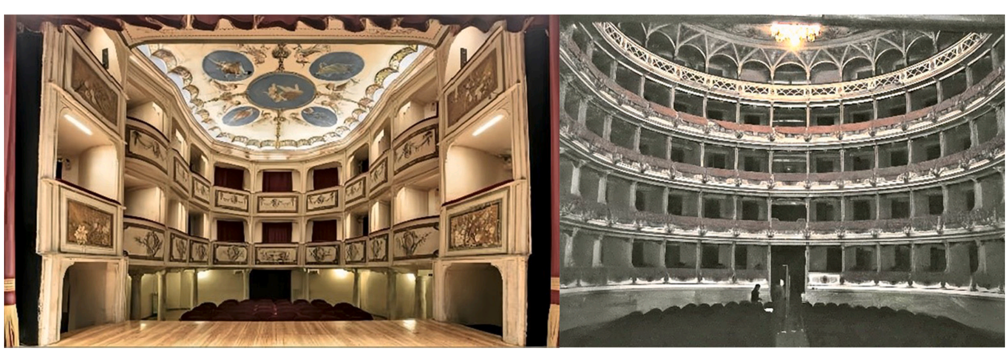

Fig. 5. The interior view of Teatro Monte Castello di Vibio (left) and Teatro Nuovo (right).

plan and an unboxed grandstand structure that is prone to strong reflections, especially in the mid and low frequencies, which are further enhanced by the marble walls, resulting in an increase in reverberation time. The lack of acoustic absorption in the design of the grandstand without boxes, and the marble carved columns without any structural role only for decoration, make the number of sound reflections hitting the construction surface and the arrival time different [31,30], which affects the performance of the C_{50} and C_{80} values. The horseshoe-shaped plan of the Teatro Monte Castello di Vibio facilitates the even propagation of sound waves through the theater, while its higher spatiality helps to reduce the formation of low-frequency standing waves. This design allows for short reverberation times and improves the clarity of the sound. Furthermore, Teatro Monte Castello di Vibio has wooden boxes and velvet seats, both of which have better acoustic absorption properties and reduce reflections, also resulting in shorter reverberation times.

2. Another potential reason for the presence of outliers is the varying temperature and humidity conditions in the regions where these theaters are located at the time of measurement.

Based on our preliminary research [32,33], acoustic parameters such as D_{50}, G, and EDT exhibit significant measurement variability due to temperature fluctuations, whereas other parameters show minimal sensitivity to temperature changes. In contrast, all eight acoustic parameters are influenced by humidity to varying degrees. However, further controlled experiments are necessary to provide a more scientific and robust basis for this explanation.

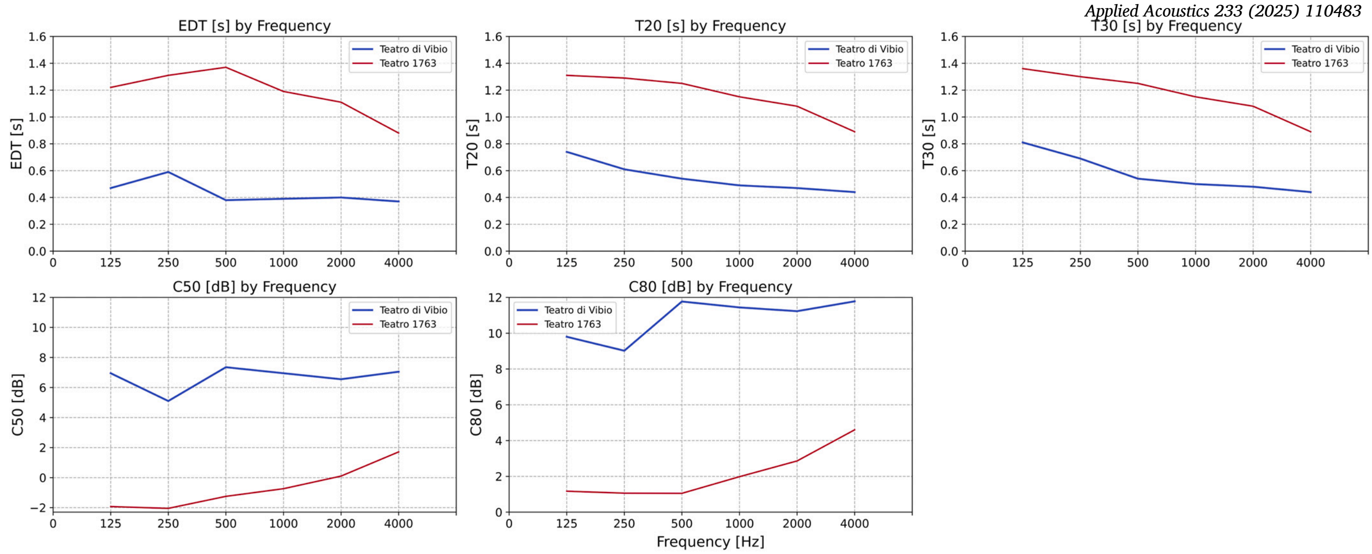

Fig. 6. Results of reverberation time and clarity index measurements of Teatro Monte Castello di Vibio vs. Teatro 1763.

Fig. 7. The interior of Teatro 1763.

4.4. Acoustic quality assessment and recommended ideal values

Fig. 8 presents the average values of the acoustic parameters (*EDT*, T_{20}, T_{30}, C_{50}, C_{80}, *G*, *IACC*) for the 24 theaters at 500 Hz and 1000 Hz. The theaters are distinguished by eight different shapes in three different colors. The gray rectangles indicate the range of "ideal" reference values for each parameter [3,4,6,7,13,34–44].

According to references and published standards, the "ideal" reference range of *EDT* values for theaters is between 1.2 and 1.6 seconds, with nearly 50% of theaters performing well within this range. Reverberation time values should be between 1.4 and 1.6 seconds, with about 20% theaters meeting this standard. For C_{50} values, the ideal range is between -2 dB and +2 dB, with nearly 70% of theaters falling within this range. For optimal acoustics, C_{80} values should be between -1 dB and +5 dB, with nearly all theaters meeting this criterion. *G* values are ideally between 1 and 3.5 dB; The *IACC* value should be as close to 0 as possible and should not exceed 0.4 for a high-quality theater, with approximately 40% of theaters meeting this requirement. The value of D_{50} is not included in the graphs due to its flexibility. For musical performances, the value of D_{50} should be lower than 50%, while for speeches and prose, the value of D_{50} should be higher than 50%.

Different types of performances have requirements for various acoustic conditions, and the proportion of types of performances staged in each theater over the five-year period is counted in Fig. 9.

Statistical data indicate that opera remains the primary repertoire across theaters, with Romantic and Realist operas performed more frequently. These genres require an acoustic environment with longer reverberation times and moderate clarity. Conferences, prose performances, and talk shows also play significant roles in some theaters, where shorter reverberation and high clarity are needed, as seen in venues like Teatro Monte Castello di Vibio, Teatro Nuovo, and Teatro Argentina. Other theaters, such as Teatro Sociale di Gualtieri, present a variety of performances for economic sustainability. In this era, some theaters are also exploring contemporary music and avant-garde performances, as at Teatro Alighieri in Ravenna. Thus, the type of performance must be considered when assessing theater acoustic quality.

By combining Figs. 8, 9, and 4 with Table 1, the ideal value ranges for each acoustic parameter in historical Italian theaters are suggested, as shown in Table 2. The discussions and suggestions regarding the optimal values are based, firstly, on parameter measurements obtained by other researchers in various Italian historical theaters, and secondly, on recognized publications and established regulations. Most importantly, the acoustic parameter values measured in the 24 theaters in this study serve as a benchmark, providing reference values for the main acoustic parameters of Italian historical theaters, which can be used by future researchers.

The value of D_{50} has to be determined according to the different performances to find out what is the best value. And regarding the suggested value of *G*, a value of less than 17.5 dB can be considered as ideal. The statistical results show that the value of the Italian historical theater is much higher than other types of theaters or buildings with the same volume.

Based on the above statistical analysis, the theaters with the best performance in terms of acoustic quality are Teatro Amintore Galli (Rimini), Teatro dell'Opera (Rome) and Teatro Minimo (Atri). The rest of

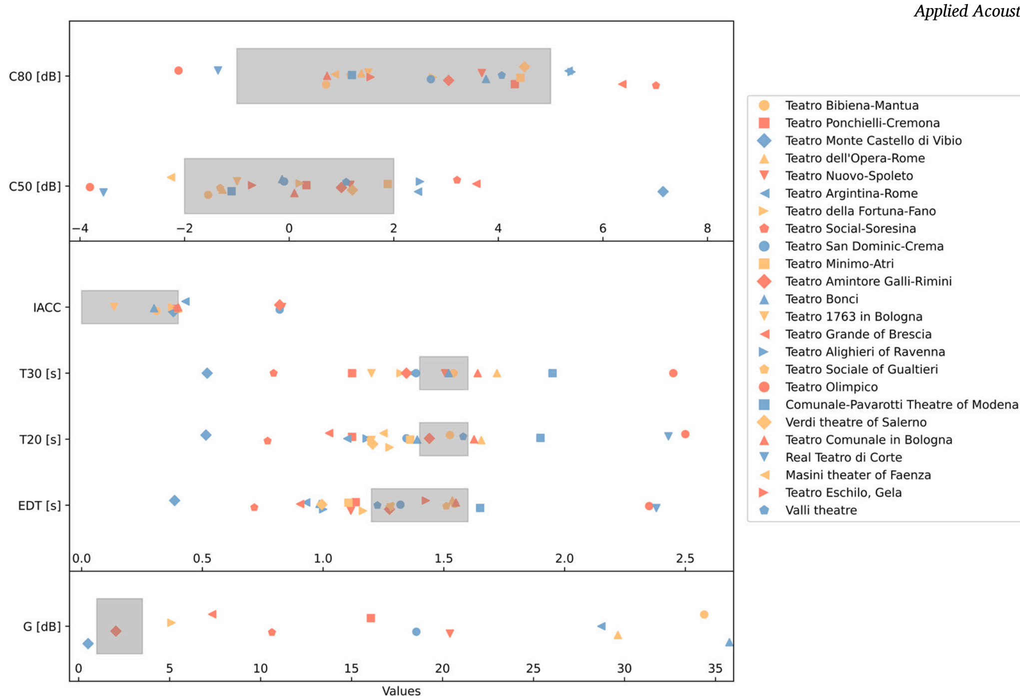

Fig. 8. Comparison of measured average acoustic parameter values (500 Hz and 1000 Hz) across 24 theaters with "ideal values".

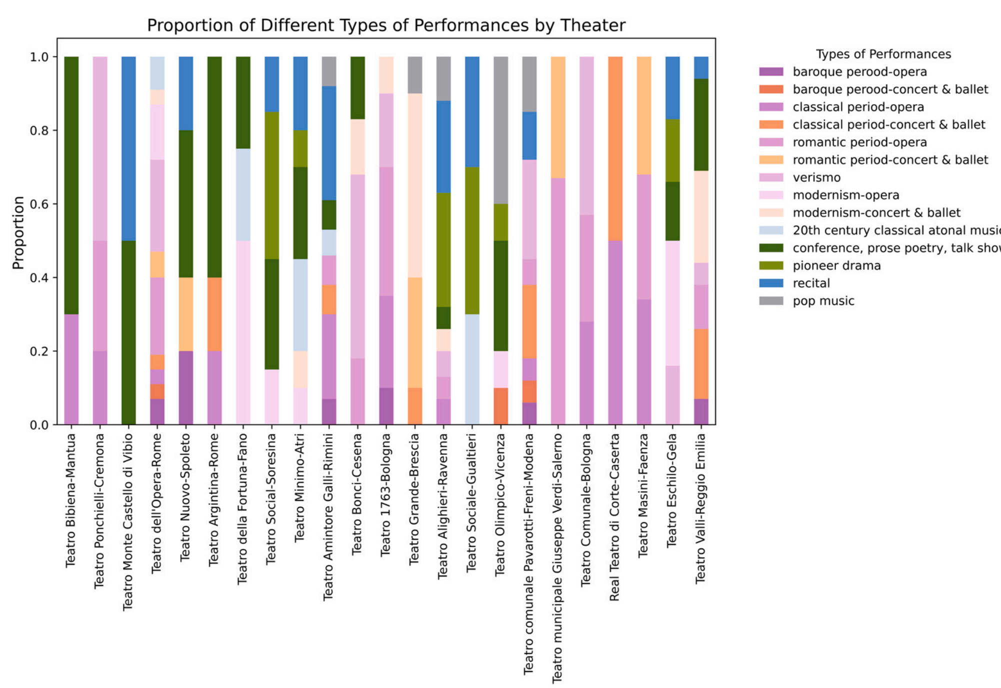

Fig. 9. Proportion of performance types staged in each theater over a five-year period.

Table 2
Range of ideal values for the main acoustic parameters of Italian historical theaters.

Name	EDT [s]	T20 [s]	T30 [s]	C50 [dB]	C80 [dB]	IACC
Small theaters	0.8–1.1	0.9–1.2	0.9–1.3	1.6–2.6	4.4–5.8	< 0.6
Medium theaters	1.2–1.4	1.3–1.5	1.4–1.6	-1.2–1.3	2.2–3.0	< 0.5
Large theaters	1.3–1.8	1.5–1.9	1.6–1.9	-0.5–0.3	1.1-2.6	< 0.4

the theaters will need to make adjustments to the acoustical conditions based on the needs of the performance type.

The selection of Teatro Amintore Galli (Rimini), Teatro dell'Opera (Rome), and Teatro Minimo (Atri) as the top theaters for acoustic quality is supported by two main factors. First, Teatro Amintore Galli and Teatro dell'Opera Rome have undergone recent restoration, while Teatro Minimo has preserved its original structure in excellent condition. This careful maintenance or improvement of the theaters' spatial characteristics has created highly favorable acoustic conditions, in some cases enhancing the original design. Second, the acoustic parameters in each theater are well-matched to its size and primary performance types. Teatro Minimo, a smaller venue mainly hosting spoken-word performances and 20th-century atonal music, has an average mid-frequency reverberation time of around 1.3 seconds, a speech clarity index of about 1.9 dB, and a music clarity index of approximately 4.7 dB. Teatro Amintore Galli, a medium-sized theater featuring Classical concerts, operas, and instrumental solos, has a mid-frequency reverberation time near 1.5 seconds, a speech clarity index of 1 dB, and a music clarity index of around 3 dB. The larger Teatro dell'Opera Rome, primarily used for Romantic and Verismo operas, has a mid-frequency reverberation time of about 1.7 seconds, a speech clarity index of -1.2 dB, and a music clarity index of around 1.1 dB. These acoustic profiles closely align with the requirements of their respective performance types, confirming their selection as the theaters with the most favorable acoustic environments among the 24 examined. If the primary performance types in these theaters were to change, further evaluation would be necessary to assess whether their acoustic environments remain suitable, as this shift could render them less optimal for the new repertoire.

5. Discussion and conclusion

An acoustic survey was conducted in 24 historical theaters distributed in 8 regions of Italy using two different measurement methods. The geospatial distribution of the theaters and the values obtained for the parameters *EDT*, T_{20}, T_{30}, C_{80}, C_{50}, D_{50}, G and *IACC* (unoccupied condition) were recorded, analyzed and plotted. The following conclusions were drawn:

1. In the correlation analysis across different frequencies, while a negative correlation is consistently observed between reverberation time and clarity index (as well as definition), the strongest correlations are found at 1000 Hz. Additionally, the variation in reverberation time (*RT*) and clarity index (C_{50}, C_{80}) across theaters of different sizes and architectural types highlights the influence of structural characteristics, such as volume, materials, and interior design. This foundational analysis will support future machine learning models aimed at predicting acoustic parameters by leveraging more stable parameters, like *RT* at 1000 Hz, which are less affected by measurement distance, to estimate parameters sensitive to distance variations, such as clarity index, definition, and sound strength. Additionally, temperature and humidity are acknowledged as influencing factors in acoustic measurements and will be accounted for in subsequent, more controlled experiments. This data-driven approach offers practical value in applications like acoustic design and spatial optimization, providing more accurate predictions across various environments and measurement conditions.

2. The box plots of the box lines for each parameter yielded that *G* was the only parameter that did not show any discrete points (outliers). There are two main reasons for the appearance of discrete points: the investigated theaters are situated in different geographical locations with some differences in temperature and humidity, which to a certain extent affect the measured values of the acoustic parameters; the theaters differ in size and interior decoration, which makes the measured values of a small number of theaters differ from those of other theaters. However, in the objective evaluation of the acoustical quality of theaters, attention should also be paid to the acoustical requirements of the different types of performances staged in each theater.

3. An objective assessment of the acoustic quality of the theaters results in the fact that most of them perform better in the values of the clarity index compared to the results of the other parameters. The *G*-values of Italian historical theaters are much higher than those of other types of opera houses or architectural spaces of similar volume. This could be an acoustic characteristic of Italian historical theaters and there could be four reasons for the high *G*-values: 1. Design and location of sound-reflecting surfaces: Reflecting surfaces positioned too close to the stage or auditorium—typically hard, smooth materials such as concrete, stone, and metal used in later restorations—are present in these theaters, often leading to excessive early sound reflections and an increase in *G*-values. In theaters such as Teatro Bibiena (Mantua) and Teatro Ponchielli (Cremona), balcony fronts, side walls, and stage surfaces made of hard materials like wood and plaster are positioned within approximately 2 meters of the audience. This close proximity contributes to strong early reflections, raising *G*-values and potentially impacting clarity, especially for spoken performances. 2. Influence of the stage structure: In Italian historical theaters, which are mostly of closed stage design, reflective surfaces within the stage (e.g., ceilings, side walls, etc.) may cause sound waves to be repeatedly reflected and gathered in the stage area. Excessive acoustic reflections may increase the *G*-value by transferring too much acoustic energy to the audience without complete diffusion of the initial sound waves. 3. Aggregation of acoustic energy due to dome and arch designs: The design of domes or arched structures in theaters can focus sound waves to specific locations, resulting in unusually high *G*-values in certain areas. For instance, in Teatro Olimpico (Vicenza), the arch positioned both above and relatively close to the audience intensifies sound energy in central seating sections, creating elevated *G*-values. Teatro Bibiena (Mantua) features a dome with a relatively shallow curvature, with a radius of approximately 20 meters, which concentrates sound around the audience and stage, particularly amplifying reflections in the central stage area. In Teatro Alighieri (Ravenna), the dome's smooth plaster and stone surfaces enhance sound reflection, further contributing to higher *G*-values in adjacent regions. 4. Influence of the number of spectators: In this article, only measurements carried out in the case of an empty theater are counted, and the lack of sound absorption by human bodies in the theater may lead to high *G*-values. Combined with the previous analysis, we propose ideal values for each acoustic parameter of Italian historical theaters.

CRediT authorship contribution statement

Ruoran Yan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lamberto Tronchin:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT in order to check grammar and improve language. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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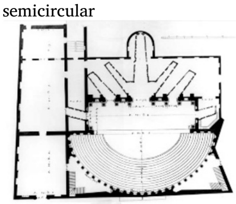
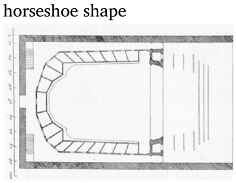
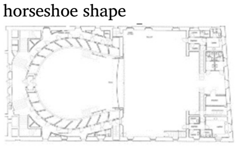
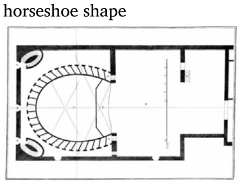
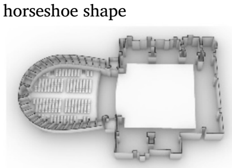
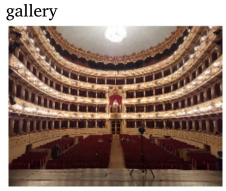
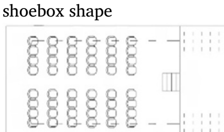
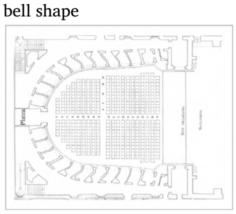
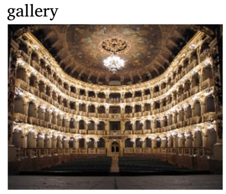
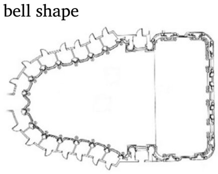
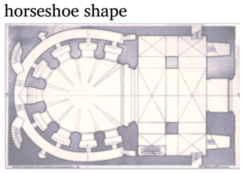
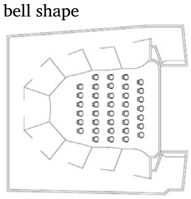
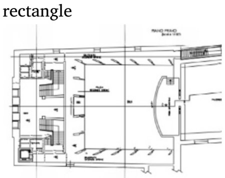
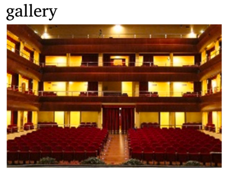
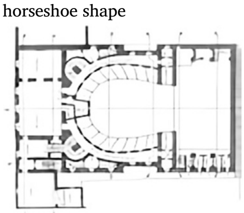
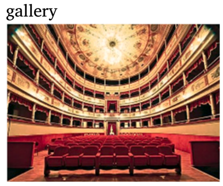
Appendix

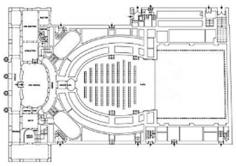
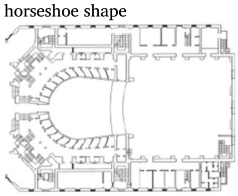
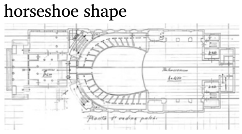
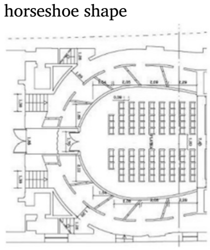
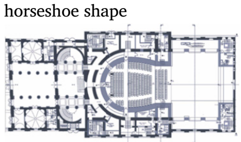
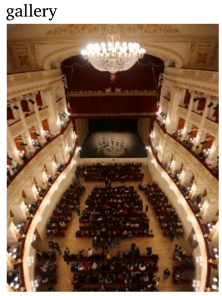
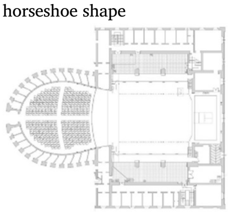
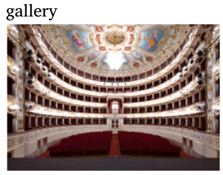
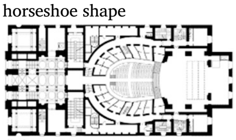
Appendix Table 1
Statistics on the architectural features of the 24 historic Italian theaters.

Name	Year of inaugu-ration	plan layout	structure	stage dimension (m) [L × W]	fly tower height	total capacity (no. of seats)	main hall volume (m^3)	seat volume (m^3/seat)	architect
Teatro Olimpico-Vicenza	1585	semicircular 	stepwise 	10.5 × 7.5	8.0	470	2000	4.3	Andrea Palladio
Teatro della Fortuna-Fano	1676	horseshoe shape 	three order balconies + top gallery 	16.4 × 13.8	14.0	600	2500	4.2	Luigi Poletti
Teatro Masini-Faenza	1726	horseshoe shape 	three order balconies + top gallery 	20.0 × 12.0	20.0	520	2330	4.5	Giuseppe Pistocchi
Teatro Argentina-Rome	1732	horseshoe shape 	six order balconies 	22.5 × 12.4	15.0	720	5500	7.6	Gerolamo Theodoli
Teatro Ponchielli-Cremona	1747	horseshoe shape 	four order balconies + top gallery 	21.0 × 16.0	15.0	800	3600	4.5	Luigi Canonica
Teatro Sociale-Gualtieri	1750	horseshoe shape 	three order balconies 	10.0 × 8.0	12.0	300	1050	3.5	Gabriele Ricci
Teatro 1763-Bologna	1763	shoebox shape 	two order balconies 	9.0 × 4.0	-	80	1150	14.4	Francesco Tadolini

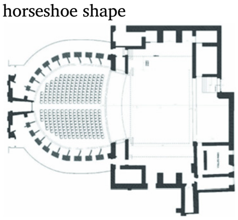
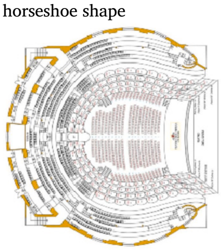
Appendix Table 1 (*continued*)

Name	Year of inaugu-ration	plan layout	structure	stage dimension (m) [L × W]	fly tower height	total capacity (no. of seats)	main hall volume (m^3)	seat volume (m^3/seat)	architect
Teatro Comunale-Bologna	1763	bell shape 	four order balconies + top gallery 	21.0 × 15.0	20.0	1034	4500	4.4	Antonio Galli
Teatro Bibiena-Mantua	1769	bell shape 	three order balconies 	12.9 × 5.7	11.0	300	2050	6.8	Antonio Galli
Real Teatro di Corte-Caserta	1769	horseshoe shape 	five order balconies 	11.3 × 16.7	12.4	400	1400	3.5	Ferdi-nando Fuga
Teatro Monte Castello di Vibio	1808	bell shape 	two order balconies 	8.0 × 6.5	6.0	99	400	4.0	Giuseppe Valadier
Teatro Grande-Brescia	1810	horseshoe shape 	four order balconies + top gallery 	18.5 × 26.0	16.0	931	3650	3.9	Luigi Canonica
Teatro Eschilo-Gela	1832	rectangle 	two order balconies + top gallery 	15.0 × 12.0	-	300	2500	8.3	-
Teatro Social-Soresina	1840	horseshoe shape 	three order balconies + top gallery 	14.2 × 9.1	15.0	900	3000.	3.3	Carlo Visioli

Appendix Table 1 (*continued*)

Name	Year of inaugu-ration	plan layout	structure	stage dimension (m) [L × W]	fly tower height	total capacity (no. of seats)	main hall volume (m^3)	seat volume (m^3/seat)	architect
Teatro comunale Pavarotti-Freni-Modena	1841	Ellipse shape 	four order balconies + top gallery 	18.5 × 22.0	12.0	350	3800	10.9	Francesco Vandelli
Teatro Bonci-Cesena	1846	horseshoe shape 	four order balconies + top gallery 	13.0 × 10.0	18.0	930	4000	4.3	Vincenzo Ghinelli
Teatro Alighieri-Ravenna	1852	horseshoe shape 	four order balconies + top gallery 	13.0 × 10.0	15.0	830	3000	3.6	Tommaso Meduna & Giambattista Meduna
Teatro Minimo-Atri	1857	horseshoe shape 	three order balconies + top gallery 	10.0 × 8.0	-	320	1000	3.1	Niccolò Mezucelli
Teatro Amintore Galli-Rimini	1857	horseshoe shape 	three order balconies + top gallery 	7.4 × 9.3	-	573	2250	3.9	Luigi Poletti
Teatro Valli-Reggio Emilia	1857	horseshoe shape 	four order balconies + top gallery 	20.5 × 31.2	20.0	1122	8300	7.4	Cesare Costa
Teatro Municipale Giuseppe Verdi-Salerno	1863	horseshoe shape 	four order balconies + top gallery 	15.0 × 22.0	26.0	650	4262	6.6	Antonio D'Amora & Giuseppe Menichini

Appendix Table 1 (*continued*)

Name	Year of inauguration	plan layout	structure	stage dimension (m) [L × W]	fly tower height	total capacity (no. of seats)	main hall volume (m^3)	seat volume (m^3/seat)	architect
Teatro Nuovo-Spoleto	1864	horseshoe shape 	four order balconies + top gallery 	25.0 × 12.0	16.0	800	5000	6.3	Ireneo Aleandri
Teatro dell'Opera-Rome	1880	horseshoe shape 	four order balconies + top gallery 	50.0 × 24.0	35.0	2200	11250	5.1	Marcello Piacentini

Data availability

Data will be made available on request.

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