acoustics

Article

The Bell-Shaped Opera Houses Realised by Antonio Galli Bibiena: Acoustic Comparison between the Communal Theatre of Bologna and the Scientific Theatre of Mantua

Antonella Bevilacqua [1,*] and Lamberto Tronchin [2]

[1] Department of Industrial Engineering, University of Parma, 43100 Parma, Italy
[2] Department of Architecture, University of Bologna, 40120 Bologna, Italy; lamberto.tronchin@unibo.it
* Correspondence: antonella.bevilacqua@unipr.it

Abstract: Many acoustic studies have been carried out in the Italian theatres built during the 17th and 18th centuries. Along with the development of technology, acoustic measurements become increasingly more accurate, able to capture the faithful acoustic conditions of these cultural heritage buildings that are considered icons for representing the house of sound. Although considered controversial for their innovative geometry and shape, the plan layouts proposed by the architect Antonio Galli Bibiena for the theatres placed in Bologna and Mantua were remarkable and appreciated by the audience given the florid artistical program run over the seasons. Site were undertaken in order to analyse the acoustic response of the main halls. From the recorded impulse response, both monoaural and binaural acoustic parameters were compared between the two theatres, where the analysis separately considered the stalls and balconies. The historical background of the selected theatres was detailed to understand the acoustic behaviour of the main halls.

Keywords: architectural acoustics; acoustic measurements; cultural heritage; opera theatres; Galli Bibiena

Citation: Bevilacqua, A.; Tronchin, L. The Bell-Shaped Opera Houses Realised by Antonio Galli Bibiena: Acoustic Comparison between the Communal Theatre of Bologna and the Scientific Theatre of Mantua. *Acoustics* **2023**, *5*, 586–600. https://doi.org/10.3390/acoustics5020036

Academic Editor: Haydar Aygun

Received: 10 May 2023
Revised: 4 June 2023
Accepted: 12 June 2023
Published: 20 June 2023

1. Introduction

The dynasty of Galli Bibiena dominated the architectural style of the 17th and 18th centuries. Their taste for the Baroque style inspired some members of the family to realise memorable sceneries for theatres, considered an important place for the community due to their functionality of diffusing art, culture, and literature in a representative way [1–5].

Belonging to the second generation of the family, Antonio Galli Bibiena carried out the design of bell-shaped theatres, as testified by two masterpieces erected in northern Italy, which are still at the core of live artistic performance: the Communal Theatre of Bologna [6] and the Scientific Theatre of Mantua [7]. The dispute that took the architect to propose this innovative shape to the local authority, compared with the horseshoe shape so popular for the opera theatres and the shoe-box geometry, was not straightforward [8]. The acoustic measurements undertaken inside these two selected theatres demonstrate that the theories supported by A. Galli Bibiena for the bell-shaped geometry have been scientifically verified to have acoustics suitable and optimal for their room function [9,10]. In addition, the aesthetic *finesse* of the interior design in combination with the particular geometry has always impressed architects, experts of constructions, and visitors of these cultural heritage buildings, which assists artistical performances [11–13].

A comparison between the different types of plan layout that was widely discussed during the 18th century has been reviewed, along with the sightline requirements and the necessity of fulfilling the seating area for widening the total capacity of the theatre [14–20].

After a brief excursus relating to the historical background of the two theatres, the geometry design of the two selected theatres was analysed along with the measured results of the main acoustic parameters, both monoaural and binaural, as outlined by ISO 3382-1 [20–22]. The measured results were compared with the optimal range set by the literature for Italian theatres [23–25] in relation to both monoaural and binaural parameters [26–37].

2. The Galli Bibiena Family

Three generations of supremacy in the specialty of art is considered quite exceptional in Europe. Originally from Florence, the dynasty of Galli Bibiena established their centre of art in Bologna, where the school of painting was at the top of the list among similar schools established in other Italian cities, from Renaissance to Baroque [1]. The Bibienas are well known for the creation of a new iconography for the theatrical stage [2].

The first family members to be famous were the brothers Ferdinando (1657–1743) and Francesco (1659–1739). Then, the art passed to Ferdinando's sons, who were Alessandro (1686–1748), Giuseppe (1695–1757), Antonio (1697–1774), and Giovanni Maria (1700–1777). The other component of the family was Francesco's son, Giovanni Carlo (1713–1760) [2]. Their handwriting and draftsmanship were very similar to each other such that the identification of drawings is sometimes confusing [3,4]. The variety of their sketches ranges from stage sets to architecture and even highly finished design details.

At the beginning of the 18th century, the Bibiena also operated in the Hofburg theatre of Vienna, a construction built for Emperor Leopold I that was destroyed in 1747. The Hoftheatre's architecture has greatly influenced the theatre design in Germany and Austria [5]. Another masterpiece to be mentioned, designed in the same period by Giuseppe, is the Bayreuth Theatre. By 1739, only Giuseppe and Antonio remained in the Austrian capital city, because Ferdinando and Francesco had left earlier for Italy [5].

Some drawings and sketches are still debated regarding the attribution to a member of the Bibiena family, but from the already assigned paternity, Antonio's preference was oriented toward curves for the volutes and decorative elements such as urns. It should be remarked that A. Galli Bibiena was also a set designer rather than simply an architect; this means that attention to details, colours, and visual aspects was also constantly present in his architecture.

Several drawings have been engraved, which represent, in many cases, the only records of their works. Some sketches were destroyed, such as some related to the Teatro Filarmonico of Verona and to the Nancy Theatre built for Leopold, Duke of Lorraine [5]. Fortunately, other drawings are preserved in museums and art galleries. The unicity of the Bibienas' perspective drawings, demonstrating how to develop shapes in space, is subject to admiration due to the inherited aptitude developed by a constant family collaboration. In line with the rules of the Baroque style, considered the age of illusion, the Bibienas were capable of creating new illusions of the architecture by merging solid buildings with perspective enlargements.

3. Historical Background of the Constructions

3.1. The Communal Theatre of Bologna

The Communal Theatre of Bologna was built after the ruin of the Teatro Malvezzi, which burnt down in 1745. This was one of the reasons why the local authority commissioned a new theatre in Baroque style to be built with a brickwork structure to prevent the risk of further fire [7]. The decision to design a bell-shaped plan layout, as shown in Figure 1, was much criticised by other architects because it was considered a geometry not suitable to satisfy acoustic requirements [8]. Contemporary research studies have demonstrated that this thesis is not true, and the bell-shaped plan is suitable for acoustics: it has also been adopted for the Aleksandrinsky Theatre of St. Petersburg. The arguments by A. Galli Bibiena for its innovative design was supported by the new outfit desired by musicians and spectators, repeated for the Scientific Theatre of Mantua. The Communal Theatre opened on 14th May 1763 with the performance of *Il trionfo di Clelia* by Gluck.

Figure 1. View from the stage of the Communal Theatre of Bologna.

Bologna is a city visited by different artists and musicians, including Mozart, Rossini, Verdi and Toscanini, to name a few, given its strategic location in the centre of northern Italy; nowadays, the theatre still hosts the most famous opera singers, such as M. Freni. During the 20th century, the Communal Theatre was restored especially in the orchestra pit and in the trussed roof to meet fire standards [9–11]. In 1931, the theatre experienced a fire that burnt down the stage and the curtain. After this disaster, the theatre reopened in 1935. The most recent event to have caused a temporary closure of the theatre is World War II, with the first performance following the war held in 1946 [12].

3.2. The Scientific Theatre of Mantua

The Scientific Theatre of Mantua was built between 1767 and 1769. The architectural design was commissioned by count Carlo Ottavio from Colloredo, who was the lead of the Academy of Timidi, to Antonio Galli Bibiena, son of the well-known scenographer Ferdinando [13]. The aim was to build a place dedicated to scientific committees; in addition to this main activity, recitals and concerts could be performed.

The theatre is part of the Gonzaga family's palace, where Ferrante I used to live.

In only two years, the architect A. Galli Bibiena supervised the construction works by following his drawings and painted numerous frescos inside the boxes with monochrome configurations [2]. The main elevation was instead realised by the architect Giuseppe Piermarini. The theatre officially opened on 3rd December 1769. The balance of the architecture between movement and elegance was the right architectural combination that A. Galli Bibiena was able to contribute at the end of the 17th century in Europe, as shown in Figure 2.

A few months later, in January 1770, the young W.A. Mozart exhibited a memorable concert with his father Leopold during his first tournee in Italy. The theatre is the headquarters of the Accademia Nazionale Virgiliana di Scienze Lettere e Arti, the most ancient and prestigious cultural institution of the city.

Figure 2. View from the second order of balcony of the Scientific Theatre of Mantua.

4. Architectural Characteristics

4.1. Geometry Selection during the 18th Century

Different scholars have studied the optimal shape for opera theatres based on the theory regarding the trajectory of sound inside different room volume types. The discussions have mainly focused on the elliptical, bell-shaped, and the horseshoe-shaped plan layouts, in combination with the direct sightline that should be satisfied for all the seating positions.

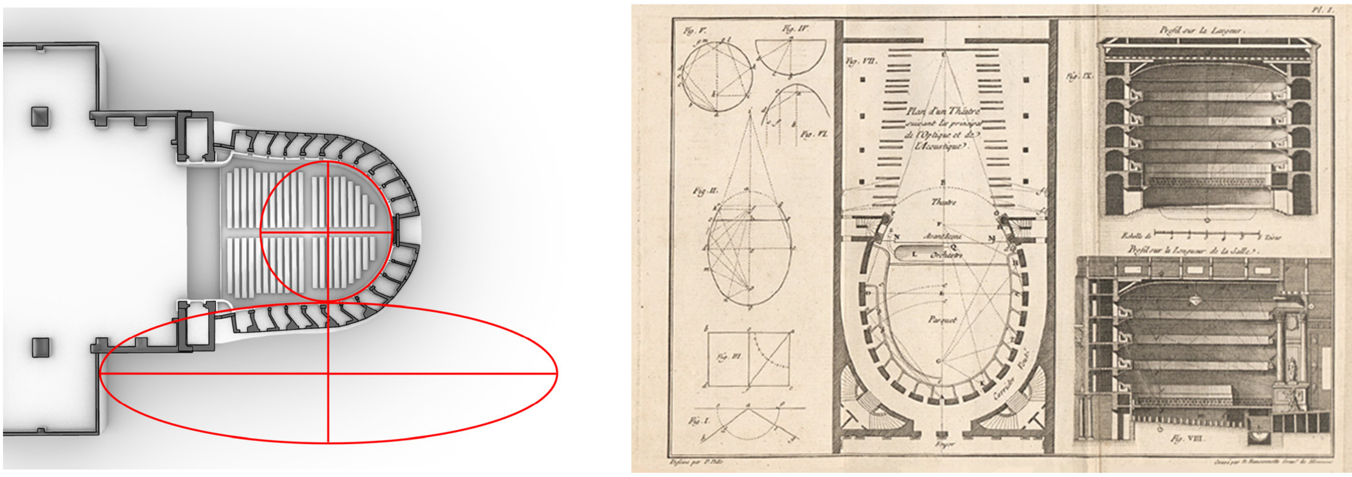
The architects of the 18th century inherited different theories through the previously written treatises and essays. One of the most recent treatises for that time was the Seven book of Architecture by Sebastiano Serlio (1475–1554) [14], who focused on the perspective of theatres and scenography, adding to the valorisation of the proscenium arch under both acoustic and perspective studies. From an acoustic perspective, the proscenium arch represented the architectural element that enhanced the lateral reflections from the stage and the orchestra, in addition to being the division line between the audience and the representation area.

Independent from the different geometries, the main elements of an opera theatre were the boxes at different levels, arranged in order to increase audience capacity; the stage, extended toward the audience to increase the intelligibility of the soloists; and the orchestra pit placed between the stalls and the stage. It should be remembered that the earnings from the paid tickets heavily influenced the determination of the theatrical structure.

The bell-shape plan was purely created by the Galli Bibiena family, although no treatises have been written by them so that it could be possible to fully understand the reasons and the theories behind this unique geometry. The realisation of the bell shape is given by a circumference and an ellipse added to a tangent, having a minor axis equal to the diameter of the first curve [15], as indicated in Figure 3a.

The bell shaped was criticised by F. Algarotti in his essay on the opera in music [16], especially for visibility reasons, but he considered the ideal shape for the voice strength. Algarotti was in favour of the use of masonry for the structure to prevent the risk of fire and the use of timber for the indoor cladding because it is the most suitable material that allows the vibration of sound.

In the same period, the French architect P. Patte published his essay on theatrical architecture (1792) [17]. Patte had carefully studied numerous theatres; and, although he never built one of his own, his book included a model design, as shown in Figure 3b. Patte stated that a building's interior surfaces must be shaped to reflect sound toward the audience in a highly efficient way, recognising in the ellipse shape as the ideal geometry to satisfy his three criteria for a natural-surrounding room: uniformity, audio–visual coordination, and intimacy. Nowadays, with the help of developed science, the sound bouncing off the curved walls of an elliptical shaped theatre has been found to be nonuniform over the audience area.



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

Figure 3. Geometry-based plan: shape for the Communal Theatre of Bologna (**a**) [17] and the elliptical shape proposed by P. Patte (**b**) [18]. Contents of (**b**) are in French.

The other geometry supported by F. Milizia was circle-based, as widely adopted in the ancient Roman and Greek theatres, where the stage is placed along the diameter of the circle and the spectators being equidistant to the spectacle, guaranteeing the same perspective for each attendee in the audience [18]. In addition, in his drawing of Teatro Ideale, Milizia replaced the separated boxes with open galleries, supporting the principle that no social division should exist during the performance with no partitions in the elevated orders to shield the free diffusion of sound within a space [19].

Revisiting the U-shape plan as built in 1610 for the Farnese Theatre in by the architect Aleotti, the definitive geometry representing the Italian-styled opera theatre became the horseshoe shape, which was adopted by many architects for the construction of theatres in Italy and in other European cities.

4.2. Geometry of the Communal Theatre of Bologna

The Communal Theatre of Bologna has a total capacity of 1176 seats distributed as 644 in the stalls and 532 on the balconies. The main axes of the hall are 22.4 m (L) and 15.4 m (W), as shown in Figure 4; the maximum height is equal to 16.9 m [6]. The main hall is composed of four orders of balconies plus a gallery located on the top level. Another characteristic of the Communal Theatre of Bologna is the floating floor of the stalls, where wooden mechanical systems beneath the wooden planks can regulate the height of the sitting area [11].

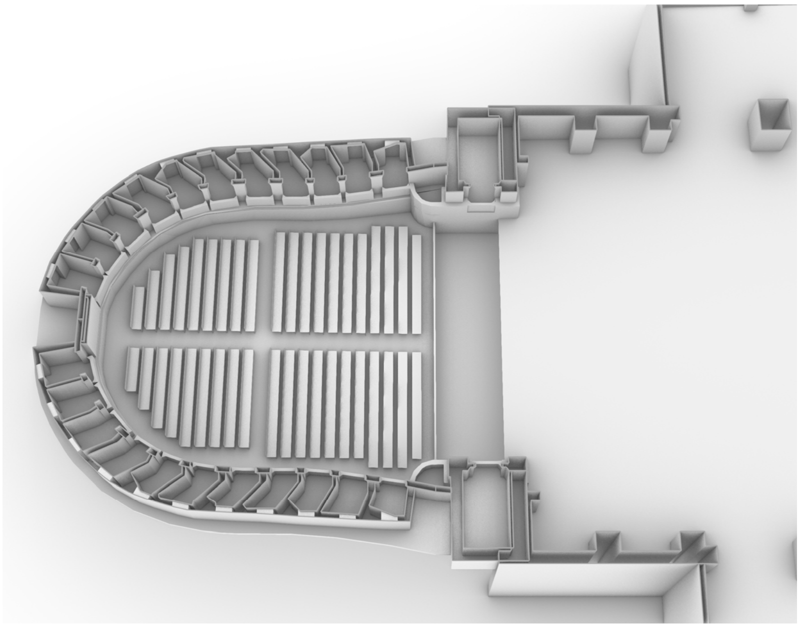


Figure 4. Plan layout of the Communal Theatre of Bologna.

4.3. Geometry of the Scientific Theatre of Mantua

The plan geometry of the Scientific Theatre is a bell shape, a very common design by A. Galli Bibiena. The main hall is characterised by four orders of balconies realised with a wood frame structure, while the ceiling is painted with a decoration representing holes framed by a balustrade [7]. The total capacity of the Scientific Theatre is 363 seats. The plan at the stalls level is 14.7 m along the main axis, measured between the main door and the beginning of the stage floor. The dimensions of the minor axis are variable, but the maximum height of the main hall is approximately 13 m.

The stage is decorated and has a fixed elevation, composed of two orders of serlian arches subdivided by niches occupied by statues having human dimensions; the four statues are the most representative of Mantua: Virgilio the poet, P. Pomponazzo the philosopher, and B. Castiglione and Bertazzolo the architects. The dimensions of the stage are 12.8 × 6 m (L × W). Figure 5 shows the plan layout of the Scientific Theatre of Mantua.

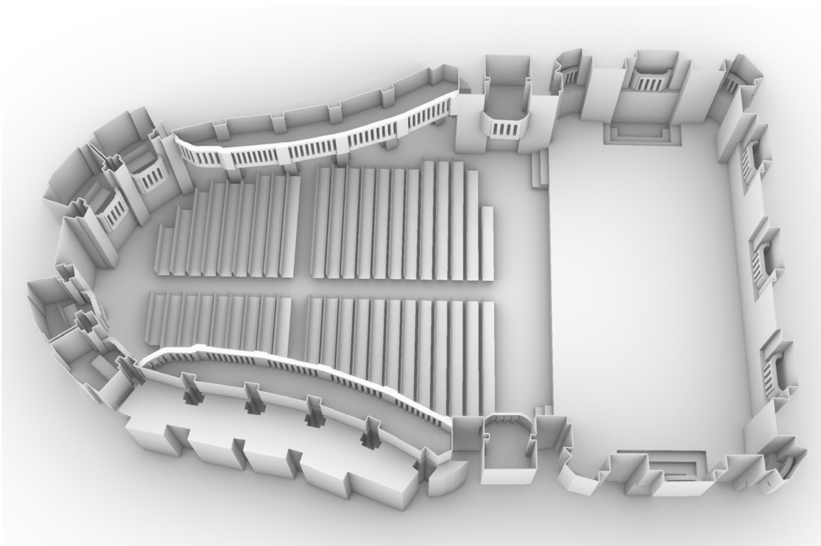


Figure 5. Plan layout of the Scientific Theatre of Mantua.

Table 1 summarises the architectural characteristics of the two theatres.

Table 1. Architectural features of the A. Galli Bibiena theatres of Bologna and Mantua.

	Description	Communal Theatre (Bologna)	Scientific Theatre (Mantua)
Main hall	Inclination of stalls (%)	2	-
	Major axis (m)	19.6	14.7
	Minor axis (m)	18	9
	Maximum height (m)	16.5	13
	Levels of boxes	5	4
	Volume (m^3)	Approx. 5190	Approx. 2100
Scenic arch	Width (m)	15.3	10.8
	Maximum height (m)	12	9.4
Stage	Inclination (%)	2	1
	Length (m)	23	12.8
	Width (m)	24	6
	Height (to the reticular wooden structure) (m)	13	11
Fly Tower	Volume (m^3)	Approx. 8370	890
Hall + Fly Tower	Volume (m^3)	13,560	2990

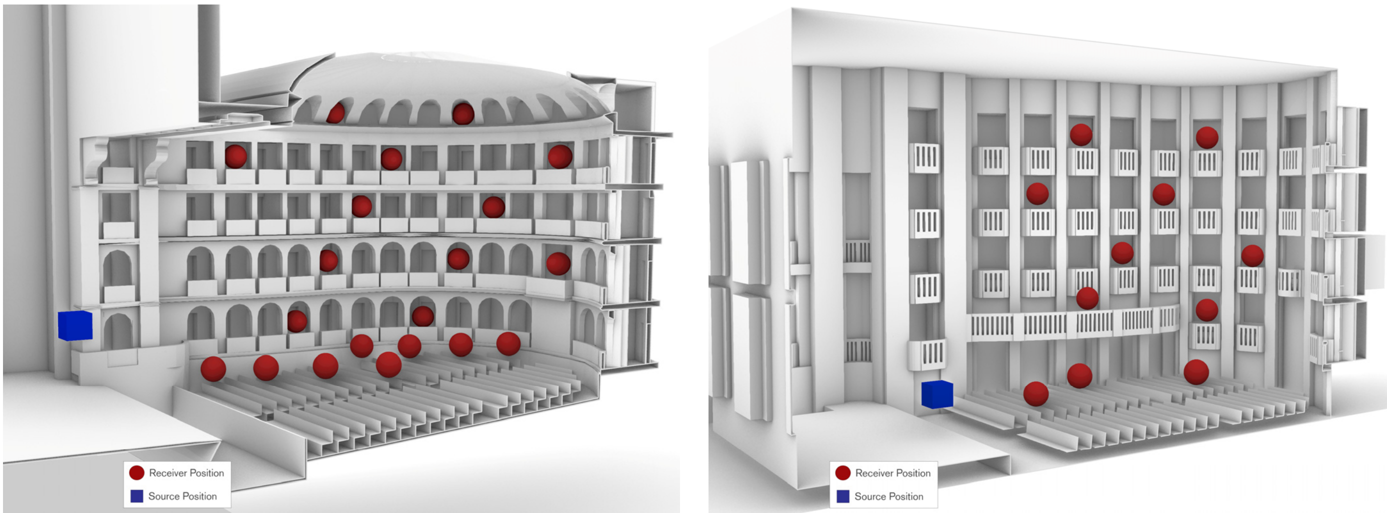
5. Acoustic Measurements

Two campaigns to record acoustic measurements were carried out in the two selected theatres in accordance with the requirements outlined in ISO 3382-1 [20]. The thermo-hygrometric variations were considered during the survey, precisely related to a temperature ranging between 14 °C and 16 °C, a relative humidity of 67–69%, and with the mechanical ventilation turned off. The equipment utilised inside both theatres included the following:

- Equalised omnidirectional sound source (LookLine Kit 103);
- Omnidirectional microphone (B&K 4165);
- Binaural dummy head (Neumann KU-100);
- B-Format microphone (Sennheiser Ambeo);
- Zoom (F8n Pro).

The sound source was placed at a height of 1.6 m on the stage, while the receivers were moved across the stalls and placed in a few selected boxes at all levels of balconies, to be at the height of human ears at a sitting position, approximately 1.2 m from the finished floor level. The height of both the source and receiver was selected based on a person standing while singing or seated on a chair, for any spectator. Because of the axial symmetry of the volumes, only one half of the theatre was measured, which was considered adequate to describe the acoustic responses.

The excitation signal employed to feed the sound source was an exponential sine sweep (ESS) [21] with a duration of 15 s at a uniform sound pressure level between 40 Hz and 20 kHz. The measurements were recorded in unoccupied conditions. Figure 6 indicates the location of the equipment installed during the acoustic measurements inside the studied theatres.



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

Figure 6. Schematic positions of the equipment during the acoustic measurements: Communal Theatre of Bologna (**a**) and Scientific Theatre of Mantua (**b**).

6. Acoustic Results

6.1. Criteria and Optimal Values of the Acoustic Parameters

The optimal values of the acoustic parameters related to opera houses differ [22]. Before the analysis of the measured results, some definitions and literature references are necessary in order to ensure a correct evaluation. These were conducted in line with ISO 3382-1 [20] along with the guidelines proposed by the International Centre of Acoustics and Music Research [23] and previous acoustic investigations by authors inside other Italian opera houses [24].

The early decay time (EDT) is the initial phase of sound decay, specifically referring to the exact amount of time it takes for a sound to decay 10 dB after it is cut off. In relation to opera theatres, the EDT values are more indicative of the acoustic quality of symphonic music compositions, usually characterised by notes that follow each other very rapidly [25].

In terms of reverberation time, Sabine formulated an equation by considering the sound energy in function of the room volume. His theories describe the influence of the volume in the determination of energy decay, where the bigger the volume, the higher the value of reverberation, even if the absorption coefficients of the finish materials are considered constant between two volumes. The second factor determining the optimal value of reverberation in a room is the destination use, because certain frequencies (usually 500 Hz and 1 kHz frequency bands) can be sufficient to explain the adequacy of a room if speech is predominant [26]; in contrast, opera singers (both women and men) are performers, so lower and higher octaves are required for determining the acoustic behaviour of a room during acoustics analysis [27].

The clarity index is defined as the ratio of the sound energy arriving within 50 ms (for speech) and 80 ms (for music) and the energy arriving in the following instants of the decay after the impulse signal. Reichardt stated that the optimal speech clarity occurs for values more than +3 dB; by calculation, the optimal value would be 0 dB, with a tolerance of $\pm$2 dB, which was the threshold considered in this study [28].

"Definition" is a synonym of "clarity", referring to musical quality. The definition can be considered in two forms: horizontal, related to tones played in succession; and vertical, when the tones are played simultaneously [25]. How a piece of music is communicated to the audience is strictly related to the degree of definition. This acoustic parameter reflects the annoyance and the delay of the late reflections of the sound energy bouncing in a room. For speech and prose, the optimal definition values are between 50% and 100%; for music (both symphony and opera), the values fall between 0% and 50% [29].

In addition to monoaural parameters, there are also binaural acoustic parameters that are more related to sound perception in a specific environment and the direction of arrival of lateral reflections. On this basis, the lateral energy fraction (LF) is defined as the ratio between the late energy coming within 25 ms from lateral directions and the total omnidirectional sound energy. For opera theatres, the optimal values of the lateral fraction range between 0.5 and 1.0, which are strictly related how the sound is blended in a room due to a certain degree of diffusiveness [30].

The interaural cross correlation (IACC) is a binaural parameter that highlights the sense of envelopment and spaciousness of listeners inside concert halls. It is a pure number between zero and one, considered the normalised correlation coefficient for the first 80 ms (for music) of the sound pressure measured during the impulse response measurement [31]. When reflections arrive laterally, the sense of envelopment is stronger and therefore the value of the IACC is lower; reflections arriving symmetrically at both ears of the listener (e.g., reflections from the ceiling or from the floor) contribute to increases in the value of the IACC, which is not good since the sound comes frontally and the sense of envelopment is not perceived [32]. The optimal values of the IACC are around 0.2–0.3.

Strength (G) is the acoustic parameter that indicates the sound pressure perceived at the listener's position as a function of the power level emitted by the sound source in a room. According to theory, the G value indicates the difference between the sound pressure level produced by an omnidirectional sound source and the sound level produced by the same source at a 10 m distance in free-field conditions.

Other acoustic parameters can be considered for assessing an opera theatre; some of these parameters are subjective; however, the evaluation of performers' experiences was beyond the scope of this work.

Composers and performers use the reverberation of a room to produce a specific musical effect by taking advantage of the quantity and quality that the reverberant sound to fill the space between played notes [25]. This concept is known as fullness of tone, which musicians may employ or restrain. This sound effect is required more for choral and liturgical music, whether the choirs are inside large cathedrals or small chapels.

The concept of resonance is related to the natural vibration of every object/body at a certain frequency. When the vibration is maximised at the same frequency of the sound source, the resonance phenomenon occurs [25].

Acoustic intimacy can be compared to visual intimacy to fully understand the concept on which it is based: similar to when people in a room see objects relatively nearby, when sound is "intimate", it seems to originate from nearby surfaces. Acoustic intimacy depends on the delay of the reflected sound arriving to the listeners with respect to the direct energy; the time in between determines the initial time delay gap (ITDG). When the ITDG is small, the room sounds intimate [25].

The warmth of music is directly related to whether the bass sounds are clearly audible when a piece of music is played. In other words, it is related to the strength of the bass tones [25]. A room can sound more or less warm depending on the material used for finishes.

6.2. Analysis of the Measured Results

The main acoustic parameters were analysed for the bandwidth between 250 Hz and 4 kHz. The values were averaged for the receivers placed in the stalls and in the balconies for both the Scientific Theatre of Mantua and the Communal Theatre of Bologna. Figures 7 and 8 include the graphs of the selected acoustic parameters: early decay time (EDT), reverberation time (T_{30}), the clarity indices (C_{50} ad C_{80}), definition (D_{50}), lateral energy fraction (LF), and interaural cross correlation (IACC). Neither opera theatre was not occupied at the time of measurement.

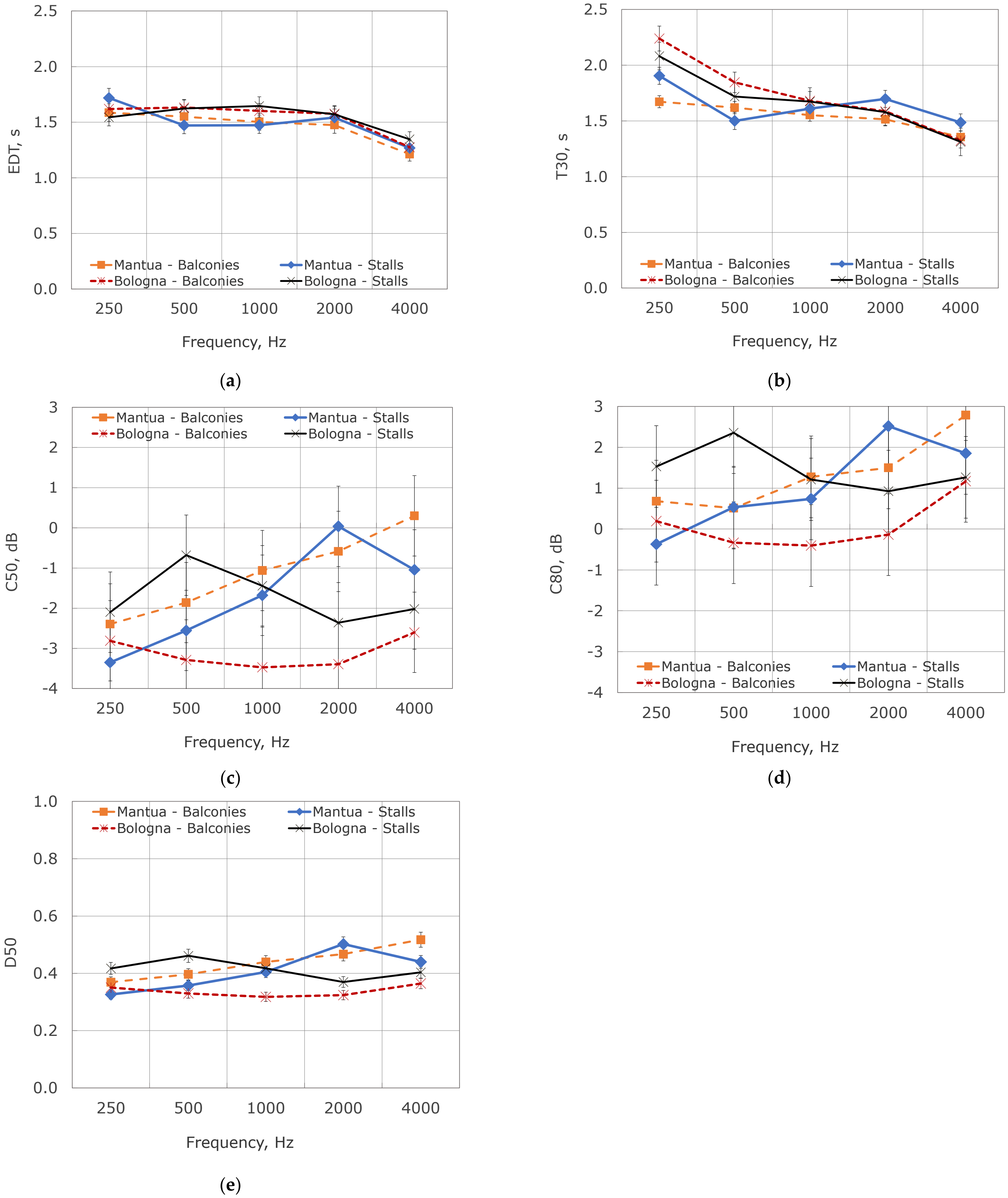


Figure 7. Measured results of the monoaural acoustic parameters: early decay time (**a**), reverberation time (**b**), speech clarity index (**c**), music clarity index (**d**), and definition (**e**).

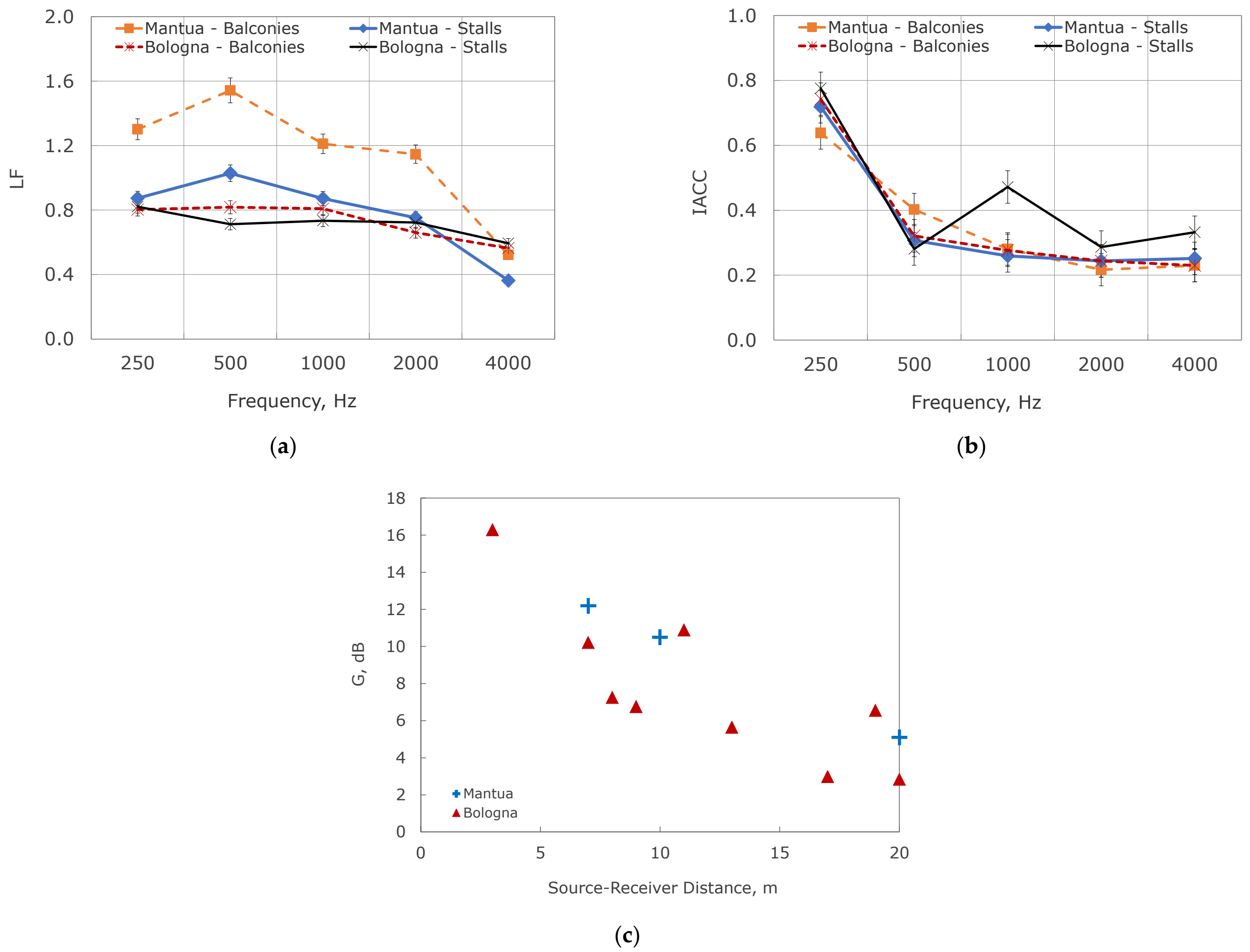


Figure 8. Measured results of the binaural acoustic parameters: lateral energy fraction (**a**), interaural cross correlation (**b**), and strength (**c**).

The EDT results, shown in Figure 7, indicated an acoustic response fluctuating around 1.5 s across the considered bandwidth, with a shortfall at 4 kHz. This means that the values are slightly below the lower optimal range limit, but both theatres produced a very similar response despite the different room volumes. In addition, the difference between stalls and balconies was minimal, falling within the just noticeable difference (JND), with the exception of the values at low and middle frequencies measured in the stalls of Mantua, but it could be considered a negligible difference from the other values.

In terms of $T_{30,}$ the difference between the two theatres was larger at low frequencies, up to 1 dB at 250 Hz and out of the JND flexibility percentage; at high frequencies, this difference was smaller, up to 0.2 s and around 1.5 s, and only the values related to the stalls of Mantua were slightly outside of the JND tolerance. Overall, the reverberation time of the theatres, fluctuating around 1.5 s, could be considered suitable for both symphonic and opera music [33].

Regarding the speech clarity index (C_{50}), the difference between the stalls and balconies was larger in Bologna than in Mantua, being up to 2.5 dB at 500 Hz but always within the JND ranges. Generally, all the values were slightly below the lower range limit, especially at 250 Hz; the values in the other octaves were within the optimal range, with the exception of the results related to the balconies of the Communal Theatre of Bologna [34].

All the C_{80} values were shifted almost 3 dB compared with the trendlines of C_{50} and ranged between −0.5 dB and 3 dB. At low frequencies, the clearest values were found for the stalls of the Communal Theatre of Bologna, especially at 500 Hz; the values found in the balconies of the Communal Theatre fluctuated around 0 dB, found to be 0.5 dB outside of the JND values. In the Scientific Theatre, the C_{80} values were similar between stalls and balconies, being clearest at high frequencies, around 2.5–3.0 dB, slightly above the upper range limit, which is commonly found in other Italian opera theatres [35]. The difference between stalls and balconies in Mantua was within the JND values.

The responses in terms of definition (D_{50}) were similar for the two theatres, fluctuating around 0.4 (40%), meaning that the definition is good for music and slightly less for speech performance. The trendlines were found to be slightly outside of the JND, because a small tolerance of 5%is given to this acoustic parameter.

In terms of binaural acoustic parameters, the lateral fraction values, as shown in Figure 8, were within the optimal range, with the exception of the balconies of the Scientific Theatre, which were slightly higher, between 1.0 and 1.6 for the low–mid frequencies and 0.5 at 4 kHz. This increase in value could be attributed to the design of the arches of the boxes, where the geometry configuration in Mantua allows the sound to surround the listeners. All the trendlines were found to be outside of the JND values for this acoustic parameter, especially at 500 Hz.

In terms of IACC, the values at mid–high frequencies were similar, except for the stalls of the Communal Theatre, which showed a spike close to 0.5 at 1 kHz and were consequently outside of the JND range. At low frequencies, all the values were around 0.6–0.7; this means that the sound was arriving more homogeneously to the listener due to the pronounced diffusiveness of the sound energy at low frequencies.

Figure 8c indicates that the G values inside the Scientific Theatre of Mantua were higher than those inside the Communal Theatre of Bologna, considering the same distance of the receiver from the source, specifically 7 m, 10 m, and 20 m. The only peaks indicated in Bologna at 11 m and 19 m were when the listener was close to the side wall of the main hall. This variation could be attributed to the different volumes of the fly tower, which has been enlarged in Bologna to meet the needs of theatrical services but remained as originally built in Mantua. This hypothesis should be confirmed with acoustic simulations that will be conducted in further research studies, using a scientific method to assess and discuss the influence of the fly tower on the acoustic response of the hall.

7. Additional Discussions

This study focused on the acoustics assessment of the Communal Theatre of Bologna and the Scientific Theatre of Mantua, both designed by the architect A. Galli Bibiena. The results of the analysis of the architectural decorations and geometry of the main halls are of primary importance to understand the measured acoustic results. Both the monoaural and binaural values indicated optimal acoustics for their relative room functions.

The relationship of the room volume with the seat capacity should be considered in order to objectively evaluate the results of the reverberation time, as deeply analysed in a previous study [36]. The range of the optimal target is between 6 and 10 m^3/people. Based on the data related to the geometry of the two theatres, the volume-to-seat ratio of the theatres designed by A. Galli Bibiena are summarised as follows:

- Bologna: 4.4 m^3/person;
- Mantua: 5.7 m^3/person.

The results related to the volume-to-seat ratio in both theatres are below the lower range limit set for many opera houses, meaning that the actual capacity is higher.

Furthermore, Equation (1) can be used to find a projection of the reverberation time at 100% occupancy [37] inside the two selected theatres. This calculation can give a quick idea as an alternative to proper acoustic simulations that deliver a more exhaustive result.

$$RT = \frac{0.1 \cdot V}{seat} + 0.7(\mathrm{s}) \tag{1}$$

where V is the volume dedicated to the auditory area. Based on the data related to the two theatres designed by A. Galli Bibiena, the reverberation time at full occupancy was calculated for the 1 kHz octave band:

- Bologna: RT = 1.14 s;
- Mantua: RT = 1.27 s.

By comparing the two values just calculated, the results shown in Figure 9 indicate that both Bologna and Mantua are very close to the trendline set for the correlation between the reverberation time in occupied conditions and the volume-to-seat ratio.

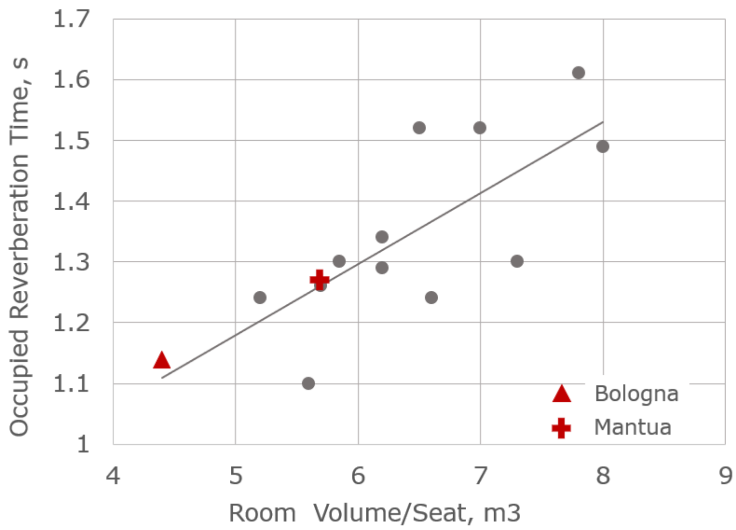


Figure 9. Relationship between occupied reverberation time and volume per seat for the Communal Theatre of Bologna (Δ) and the Scientific Theatre of Mantua (+).

8. Conclusions

The theatres designed by Galli Bibiena are fascinating from an acoustic perspective for their volume shape other than the material selection, dictated by the needs of the time other than the commissioner's choices. Further studies need to be undertaken to determine the acoustic functionalities of the different stage sets. In addition, it would be worth considering the evaluation of the musicians and conductors that spend many hours in the theatres and can technically assess the acoustic response, possibly in relation to different styled musical compositions. In this way, the evaluation can be used so that both conductors and performers can make a particular piece shine in a specific environment. The outcomes of this future study can be compared with those theoretically performed by A. Galli Bibiena during the 17th century and with the acoustic measurements scientifically recorded with the latest technology.

Author Contributions: Conceptualisation, A.B. and L.T.; methodology, A.B.; software, L.T.; validation, A.B. and L.T.; formal analysis, A.B.; investigation, L.T.; resources, L.T.; data curation, A.B.; writing—original draft preparation, A.B. and L.T.; writing—review and editing, A.B. and L.T; visualisation, A.B.; supervision, L.T.; project administration, L.T.; funding acquisition, L.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Myers, M.L. *Architectural and Ornament Drawings: Juvarra, Vanvitelli, the Bibiena Family & Other Italian Draughtsmen*; The Metropolitan Museum of Art, The Leether Press: New York, NY, USA, 1975.
2. Hyatt Mayor, A. The Bibiena Family. *Metrop. Mus. Art Bull. New Ser.* **1945**, *4*, 29–37. (In Italian)
3. Spiriti, A.; Zanlonghi, G. *Comunicazioni Sociali. Rivista di Media, Spettacolo e Studi Culturali*; Publ. Universita Cattolica del Sacro Cuore: Rome, Italy, 2006. (In Italian)
4. Lenzi, D. La tradizione emiliana e bibienesca nell'architettura dei teatri. In *Architettura, Scenografia, Pittura di Paesaggio*; Alfa: Florence, Italy, 1980; pp. 93–102. (In Italian)
5. Lenzi, D.; Bentini, J.; Bibiena, I. *Una Famiglia Europea*; Marsilio: Padua, Italy, 2000; pp. 19–35, 127. (In Italian)
6. Mioli, P. *Teatro Comunale di Bologna*; Scripta Maneant: Bologna, Italy, 2019.
7. Torelli, S. Le caratteristiche acustiche del teatro Scientifico di Antonio Galli Bibiena in Mantova. In *Civiltà Mantovana, III s., XXXVI*; Biblioteca Teresiana: Mantua, Italy, 2001; Volume 112, pp. 114–131. (In Italian)
8. Archivio Accademia Nazionale Virgiliana. Teatro Scientifico. In *Il teatro Scientifico di Mantova. Capitoli co' Quali, l'Accademia de Timidi di Mantova Accetta il Progetto Presentato dal Signor Cavaliere Antonio Bibiena Regio Architetto*; Accademia Nazionale Virgiliana: Mantua, Italy, 1767; pp. 51–52. (In Italian)
9. Tronchin, L.; Shimokura, R.; Tarabusi, V. Spatial sound characteristics in the Theatre Comunale in Bologna, Italy. In Proceedings of the 9th Western Pacific Acoustics Conference (WESPAC), Seoul, Republic of Korea, 26–28 June 2006.
10. Tronchin, L.; Tarabusi, V. Caratterizzazione acustica del Teatro Comunale di Bologna e del Teatro Bonci di Cesena. In Proceedings of the Associazione Italiana di Acustica (AIA), Venice, Italy, 23 November 2011. (In Italian).
11. Amoruso, G. The Teatro of Bologna as a Transformable Space: Drawing, Geometry and Invention in the Study of the Wooden Model of the Theater by Antonio Galli Bibiena. In *Digital Wood Design. Lecture Notes in Civil Engineering*; Bianconi, F., Filippucci, M., Eds.; Springer: Cham, Switzerland, 2019; Volume 24.
12. Rimondini, G.; Samoglia, G. *Archbishop Archive of Bologna*; Archidiocesi di Bologna: Bologna, Italy, 1979; Volume 14, pp. 151–152.
13. Bibiena, F. *L'architettura Civile Preparata su la Geometria, e Ridotta alle Prospettive*; Paolo Monti: Parma, Italy, 1711. (In Italian)
14. Serlio, S. *Sette Libri Dell'architettura di Sebastiano Serlio Bolognese (Seven Books of Architecture)*; Francesco de'Franceschi Senese: Paris, France, 1545. (In Italian)
15. Giordano, L. *Il Teatro dei Quattro Cavalieri e la Presenza di Antonio Galli Bibiena a Pavia (The "Teatro dei Quattro Cavalieri" and the work of A. Galli Bibiena in Pavia)*; Bollettino D'arte: Roma, Italy, 1975; Volume 60, pp. 88–102. (In Italian)
16. Algarotti, F. *Saggio Sopra L'opera in Musica (Essay on Opera)*, 2nd ed.; Library of Congress: Washington, DC, USA, 1764. (In Italian)
17. Patte, P. *Essai sur L'architecture Théatrale, ou, De L'ordonnance la Plus Avantageuse à Une Salle de Spectacles, Relativement aux Principes de L'optique et de L'acoustique: Avec un Examen des Principaux Téatres de L'europe, et une Analyse des Écrits les plus Importans sur Cette Matiere (Essay on Theatre Architecture, or on the Most Advantageous Design of a Performance Hall, and an Analysis of the Most Important Writings on This Topic)*; Moutard: Paris, France, 1782. (In French)
18. Milizia, F. *Trattato Completo, Formale e Materiale del Teatro (About the Theatre)*; Pasquali: Venezia, Italy, 1794. (In Italian)
19. Tronchin, L. Francesco Milizia (1725–1798) and the Acoustics of his Teatro Ideale. *Acta Acust. United Acust.* **2013**, *99*, 91–97. [CrossRef]
20. *ISO 3382:2009*; Acoustics—Measurement of Room Acoustic Parameters—Part 1: Performance Spaces. International Organization for Standardization: Geneva, Switzerland, 2009.
21. Farina, A. Simultaneous measurement of impulse response and distortion with a swept-sine technique. *J. Audio Eng. Soc. (JAES)* **2000**, *48*, 18–22.
22. Farina, A.; Tronchin, L. Measurements and reproduction of spatial sound characteristics of auditoria. *Acoust. Sci. Technol.* **2005**, *26*, 193–199. [CrossRef]
23. Pompoli, R.; Prodi, N. Guidelines for acoustical measurements inside historical opera houses: Procedures and validation. *J. Sound Vib.* **2000**, *232*, 281–301. [CrossRef]
24. Tronchin, L.; Farina, A. Acoustics of the Former Teatro "La Fenice" in Venice. *J. Audio Eng. Soc. (JAES)* **1997**, *45*, 12.
25. Beranek, L. *Concert Halls and Opera Houses*; Springer: New York, NY, USA, 1996.
26. Kürer, R.; Kurze, U. Integration method for the evaluation of reverberation measurements. *Acta Acust. United Acust.* **1967**, *19*, 313–322.
27. Beranek, L. *Music, Acoustics and Architecture*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 1962.
28. Reichardt, W.; Abel Alim, O.; Schmidt, W. Definition und Messgrundlage einnes objectiven Masses zur Ermittlung der Grenze zwischen brauchbarer und unbrauchbarer Durchsichtigkeit bei Musikdarbeitung. *Acta Acust.* **1975**, *3*, 126–137.
29. Thiele, R. Richtungsverteilungs und Zeitfolge der Schallruckewürfe in Räumen. *Acta Acust.* **1953**, *3*, 291–302.
30. Tronchin, L.; Merli, F.; Nastasi, B. The sound diffusion in Italian Opera Houses: Some examples. *Build. Acoust.* **2020**, *27*, 333–355. [CrossRef]
31. Tronchin, L.; Merli, F.; Manfren, M. On the acoustics of the Teatro 1763 in Bologna. *Appl. Acoust.* **2021**, *172*, 107598. [CrossRef]
32. Wang, P.; Lin, Z.; Qiu, X. Influence of interaural cross-correlation coefficient and loudness level on auditory source width at different frequency. *Appl. Acoust.* **2020**, *162*, 107198. [CrossRef]
33. Prodi, N.; Martellotta, F.; Pompoli, R.; Sato, S. Acoustics of Italian Historical Opera Houses. *J. Acoust. Soc. Am.* **2015**, *138*, 769–781. [CrossRef] [PubMed]

34. Manfren, M.; Nastasi, B.; Merli, F.; Vodola, V. Acoustics and spatial sound distribution in the theatre comunale in Bologna, Italy. In Proceedings of the 4th IBPSA Conference on Building Simulation Applications, Bozen, Italy, 19–21 June 2020.
35. Mazzarella, L.; Cairoli, M. Petrarca Theatre: A case study to identify the acoustic parameters trends and their sensitivity in a horseshoe shape opera house. *Appl. Acoust.* **2018**, *136*, 61–75. [CrossRef]
36. Hidaka, T.; Beranek, L.L. Objective and subjective evaluations of twenty-three opera houses in Europe, Japan, and the Americas. *J. Acoust. Soc. Am.* **2000**, *107*, 368–383. [CrossRef] [PubMed]
37. Barron, M. *Auditorium Acoustics and Architectural Design*; Spon Press: New York, NY, USA, 2009.