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The Acoustics of Renaissance Theatres in Italy

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Summary

The Teatro Olimpico in Vicenza, which opened in 1585, is the oldest, fully preserved, modern theatre in Europe. It served as a model for later theatre buildings of the Renaissance period, such as the theatres in Sabbioneta (1590) and Parma (1618), all of them integrating elements of Roman theatre design into a large and reverberant enclosed space. Room acoustical measurements according to ISO 3382 were conducted in all theatres, along with simulations of the occupied condition and a partial reconstruction of the historical state, based on computer models of the rooms. With reverberation times of more than two seconds, mean values for the definition of $D_{50\mathrm{m}} < 0.5$ and speech transmission indices of STI < 0.6, modern standards of theatre acoustics with their predominant focus on speech intelligibility are not met, even in the occupied condition. However, in the light of their consistently positive contemporary reception as documented by historical sources, their acoustical properties have to be considered as appropriate for theatrical performances of the 16th and early 17th century with their important musical parts, anticipating elements of the new genre of the opera emerging at the same time historically.

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1. Introduction

The Teatro Olimpico in Vicenza, which opened in 1585, is the oldest, fully preserved, modern theatre in Europe. Together with the theatres in Sabbioneta (1590) and Parma (1618), it is one of only three surviving examples of Renaissance theatre design. These theatres have consistently puzzled visitors as well as historians, due to their impressive architecture, which adopts many elements of Roman theatre design (Figure 1), along with an apparently deficient functionality, partly attributed to the reverberant acoustics with an unsatisfactory speech intelligibility according to modern standards. The acoustical properties, as they are presented in the following, however, have to be considered in the context of their cultural history and the repertoire performed in these venues, in order to arrive at a historically informed interpretation of the data.

The earliest evidence of theatre buildings in early modern Europe comes from the late 15th century, when temporary stages were built in several cultural centres of Italy. In the course of the 16th century a development towards permanent, roofed buildings can be observed, yielding a new building type and a new challenge for architects. However, most theatres of this period have been destroyed, such as in Ferrara or in Piacenza, where only the outer wall of an early stone theatre building from ca. 1560 has survived [1]. The driving forces behind those theatrical enterprises were of different origin. The Teatro Olimpico in Vicenza was commissioned by an academy – a regularly convening circle of artists and intellectuals formed according to the classical archetype of the Platonic *akademeia*. Many of these humanistic societies were founded throughout Italy in the 15th century. Thus, the *Accademia Olimpica*, established in 1555 in Vicenza with the main purpose of promoting scientific and theatrical activities, was already a late example. Having organized several theatrical representations already in the 1550s and 1560s, the academy in 1580 commissioned one of its founding members, the architect Andrea Palladio (1508–1580), with the design of a permanent theatre, to be integrated into an already existing mediaeval complex of buildings.

In his design for the Teatro Olimpico, Palladio drew upon his thorough investigation of the remains of Roman theatres in Italy and of their building techniques, which he examined during a series of journeys throughout the Italian peninsula and Istria beginning in 1541. When in 1556 the Paduan amateur architect and professor of philosophy Daniele Barbaro (1514–1570) edited and annotated the Italian edition of Vitruvius' *Ten Books on Architecture*, the only architectural source of classical antiquity on theatres, the illustrations were provided by Palladio, including the ground and elevation plan of an ideal Roman theatre as an interpretation of Vitruvius' textual description [2]. After Palladio's death in August 1580, the architect Vincenzo Scamozzi (1548–1616) was commissioned to supervise the project during the last months of construction. The theatre was finally opened in 1585 with a perfor-

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Table I. Volume, basic dimensions and estimated capacity for the three theatres in comparison. The length, width and height describe the greatest distance. The capacity was estimated by assuming two persons per meter along the tiers. Additional space for standing audience, sometimes with restricted visibility, was ignored. The volume is given for the auditorium alone and for auditorium plus stagehouse (in parenthesis). The figures for Parma and Sabbioneta correspond to the room with reconstructed original ceiling height (see 3.2).

Name	Volume [m^3]	Length [m]	Width [m]	Height [m]	Capacity
Teatro Olimpico, Vicenza	7700 (11000)	40.0	35.0	14.3	700
Teatro Olimpico, Sabbioneta	3200	28.0	11.4	11.4	100
Teatro Farnese, Parma	35000 (47000)	87.0	32.0	31.0	1000

mance of the Greek tragedy *Oedipus Rex* by Sophocles in a new Italian translation (*Edipo tiranno*).

The same Vincenzo Scamozzi was commissioned for the design of the Teatro all'Antica by Duke Vespasiano I Gonzaga (1531–1591), a member of the Gonzaga family, which ruled over Mantua, as part of his effort to construct a new, idealized classical city between Mantua and Parma. Built between 1588 and 1590, the theatre in Sabbioneta is the first free standing modern theatre building. Although there are obvious references to the Teatro Olimpico, the elliptic form of the audience area, which was made necessary by the already existing outer structure in Vicenza, was transformed into a horseshoe in Sabbioneta (Figure 3), and the classically inspired scaenae frons was replaced by a perspectival scenery. The stage hosted regular performances by an existing theatre ensemble which was raised to a court ensemble by Vespasiano.

The Teatro Farnese was built by Giovanni Battista Aleotti (1546–1636), who transformed a large armoury hall on the first floor of the palace of Duke Ranuccio I Farnese in Parma into a representative theatre for grandiose spectacles, of which only nine have been reliably documented during its lifetime. The theatre was completed in 1618 but opened only 10 years later with the opera *Mercury and Mars* and music by Claudio Monteverdi. It included the staging of an equestrian ballet and a naval battle, with water injected into the area in front of the elevated stage. With a rectangular floor plan of huge dimensions (Table I, Figure 3), the theatre stands at the transition from Renaissance to Baroque theatre design, introducing new elements such as the large proscenium arch separating the stage and the audience area, and a tower with sliding wings instead of a fixed stage scenery. After the last spectacle in 1732, the theatre began to decay, until it was almost completely destroyed by an air raid in 1944 and partially rebuilt in the 1950s and 1960s according to the original drawings.

Whereas the room acoustical conditions of open and roofed ancient theatres [3, 4] as well as of baroque theatres and opera houses [5, 6, 7] are quite well documented, theatres of the early modern period have so far attracted little attention regarding their room acoustics in spite of their significance for European cultural history. Prodi and Pompoli [8] have conducted measurements for the venues investigated here in their present, unoccupied condition. The current study complements a new series of measurements with a partial reconstruction of the historical state of the buildings along with acoustical simulations for the occupied condition based on computer models of the rooms. By considering the room acoustical conditions in the light of their contemporary reception and the theatrical performance practice of their time we try to investigate the extent to which later standards for acoustical design are applicable to theatres of the Renaissance period.

2. Descriptions of the theatres

2.1. Teatro Olimpico, Vicenza

In its present form, the proscenium area is 25 m wide and 6.7 m deep. The scaenae frons, which is 25 m wide and 15 m high, with statues framed by columns (aediculae) and structured into three storeys of decreasing height, has one grand central archway and two lateral openings towards the backstage scenery (Figure 1). The latter consists of seven aisles providing the illusion of long street views on the classical city of Thebes, while the actual backstage area is only 25 m wide and 8 m deep, increasing to 13 m in the central hallway (Figure 2, Figure 3). The half-elliptical orchestra pit, today 0.95 m below stage level, has been raised by ca. 0.2 m relative to its original level, as revealed by the preserved structure. 2.35 m above orchestra level, there are 12 rising tiers, each ca. 0.38 m in height and 0.5 m in depth, yielding a seating rake of 37°. The semi-oval cavea, which is 34 m in width and 15 m in length (from stage front), is framed by a portico with 30 columns at its rear end, with standing room for additional audience members behind.

There was some doubt about the authenticity of the current design of the ceiling. In the years after the opening in 1585, the ceiling was obviously not completely finished as the “stucco and painting” [10] had not yet (in 1591) been added. However, an engraving dated 1620 [11] already shows a wooden coffered ceiling covering the stage – the same as can be found today as a result of restoration works – which was already documented in the acts of the *Accademia Olimpica* in 1648. After this date, most of the original construction substance can be assumed to have been preserved. A view of the interior dated 1830 shows the ceiling as a cloth, and reproduces deplorable conditions [12], certainly due to damage later than 1620; thus, this cannot be considered as an evidence for the existence of a cloth (with significant acoustical effect) in the original

Figure 1. Teatro Olimpico. View on stage, orchestra, and part of the cavea.

hall. The existence of a ceiling is suggested both by various designs by Andrea Palladio, from which we deduce that wood was the material he planned to use, and by the preserved structure of the auditorium, which still includes the old, mostly original, wooden beams, as confirmed by the local conservators. The room volume (Table I) could be extracted from a very detailed CAD model, which was also the basis for the room acoustical simulation (see 3.2).

2.2. Teatro all'Antica, Sabbioneta

Both the stage and the audience area are inscribed in a square of equal size and ca. 11 m side length, with a rectangular orchestra space of 11 m width and 6 m depth in between. The cavea (today) consists of 5 rising semi-circular tiers with a seating rake of 45°. It is framed by a colonnade of 12 columns, separating the audience area from the prince's gallery, with the duke's seat in the centre below an architrave supporting statues of Olympian gods. Whereas the primary structure is largely original, many elements of the interior design have subsequently been replaced, such as the original scenery on stage, which was removed already in the 17th century and rebuilt in the 20th century according to the original plans. Also the tiers with their opening towards the modern entrance opposite the stage are not original [13].

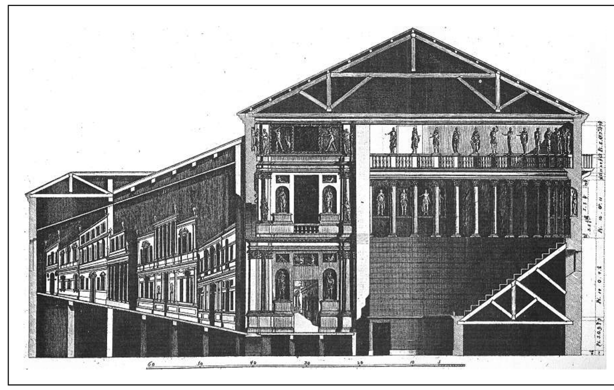

Figure 2. Longitudinal section of the theatre showing the proportions of the backstage scenery (left), scaenae frons and auditorium (right) [9].

2.3. Teatro Farnese, Parma

The theatre consists of a wooden structure installed in a huge rectangular hall of 87 m length, 32 m width and 22 m height. Since the original ceiling is not preserved, today's view reaches the top of the roof framework 31 m above the floor. About half of the volume is filled by the audience area with elongated, U-shaped rising tiers and a steep seating rake of 45° around an orchestra area with high lateral boundaries. The interior decoration of the hall is mainly made of wood, painted straw and plaster simulating the appearance of marble and precious stones. Separated by a large proscenium arch of 12 m width and height is a stage area of 40 m depth in three sections, originally hosting a mobile scenery of sliding wings. Today it is open towards the adjacent part of the building hosting an exhibition on its history. Due to the extensive destruction in 1944, most of the construction had to be rebuilt. Many elements of the interior design such as the original frescoes and paintings and the original ceiling yielding the illusion of an open sky, were not restored, however, though the major part of these were still in situ.

3. Acoustical Investigation

3.1. Measurements

Impulse response measurements were performed in all rooms using an FFT-based measurement system with swept sine excitation (Monkey Forest), with a 3-way dodecahedron speaker as sound source [14], a diffuse field calibrated measurement microphone, a Neumann KU81i dummy head for BRIR acquisition, and a Fostex 6301B speaker with 4" broadband driver simulating speaker directivity, as suggested by IEC 60268:16 for STI measurements. The dodecahedron speaker was used as an omnidirectional source and equalized to a white power spectrum between 60 Hz and 14 kHz in order to obtain impulse responses approporiate for auralization. The source and receiver positions for the measurements are shown in Figure 3.

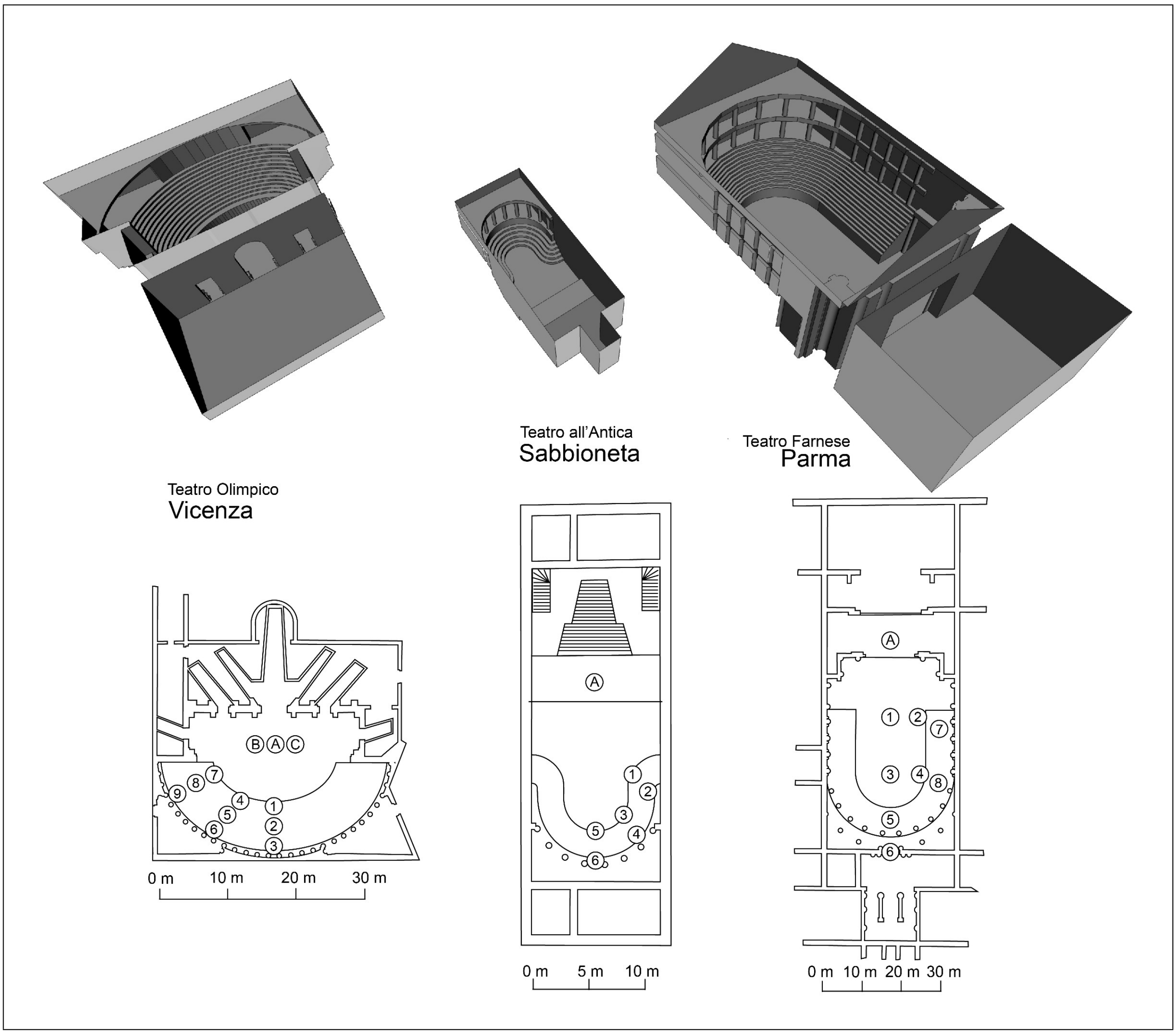

Figure 3. 3-D views of the room acoustical models (true to scale) and plans including source (A, B, C) and receiver positions (1–9) used for measurements and simulation.

3.2. Simulation

For the simulation of the occupied state, computer models were created for all three theatres. In the case of the Teatro Olimpico in Vicenza, a computer model commissioned by the city of Vicenza was provided to the authors[1]. Originally consisting of 4801 layers the model was reduced to a resolution of ca. 1200 faces by manually eliminating the representation of small surface structures (< 0.5 m) [15, p. 176]. For the other two theatres, 3D CAD models were created based on measurements in the actual theatres as well as architectural drawings and pictures, as available, for example in [16].

For Vicenza, a model corresponding to the current state of the building was used, because the room is almost perfectly preserved. For Sabbioneta and Parma, a model corresponding to the current state of the hall was only used for the adjustment of absorption values to the measurement results, while a second model was built with the original ceiling as reconstructed by Guaita for Sabbioneta [13, p. 117ff. and Fig. 51] and as assumed for Parma (see 2.3), which results in a considerable difference in the primary structure, reducing the room size by about 60 m^3 for Sabbioneta and 6650 m^3 for Parma. This model was used for simulating the historical conditions (with and without audience). Moreover, the back wall of the stage house in Parma today leads to another large room from which little energy is assumed to be reflected back into the room. Therefore, the model has been closed with $\alpha = 0.9$ at this point.

All geometrical models, with a resolution of ca. 500 (Sabbioneta) and 1200 faces (Parma) were transferred to a commercial software for acoustical simulation[2]. Figure 3

[1] Alberto Torsello, SAT SURVEY S.p.A.- Geo Sigma. The model was commissioned by the city of Vicenza and generated with AutoCad Civil 3D 2009.

[2] Odeon 11.23 Combined

Table II. Absorption coefficients for the room acoustical simulation. Different materials were used for the tiers in the unoccupied case (4), for the audience area (5), and for the stage floor in Vicenza (6).

	Material	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
1	Residual absorption, Vicenza	0.20	0.15	0.12	0.12	0.12	0.13	0.15
2	Residual absorption, Sabbioneta	0.16	0.15	0.14	0.14	0.14	0.14	0.12
3	Residual absorption, Parma	0.26	0.24	0.22	0.24	0.26	0.28	0.29
4	Wood, 1” with airspace behind[3]	0.19	0.14	0.09	0.06	0.06	0.05	0.05
5	Audience on wooden chairs[4]	0.20	0.35	0.72	0.80	0.94	0.84	0.59
6	Parquet floor[5]	0.15	0.11	0.10	0.07	0.06	0.07	0.07

shows the models of the three theatres. An omnidirectional source was placed on stage at a height of 1.7 m, and listener positions were inserted corresponding to the microphone positions of the actual measurements in the theatres at a height of 1.2 m. The absorption coefficients used for the simulation were defined according to observations in the actual theatres. Different absorption coefficients were assigned to the stage and backstage floor, the unoccupied tiers, and the audience, while all other surfaces were treated with a residual absorption coefficient. The latter was fitted so that the simulated reverberation times T_{20} in the unoccupied theatres would match the measured values within 0.1 s resolution. All materials used and their corresponding absorption coefficients are shown in Table II. The simulations were conducted using a hybrid mirror image/ray tracing algorithm with 500,000 rays [17].

3.3. Post-Processing

Both from the measured and simulated room impulse responses, a selection of room acoustical parameters according to ISO 3382-1:2009 [18] was calculated, including:

- The sound strength G (dB) as a predictor for perceived loudness.
- The reverberation time T_{20} (s) as a measure for the duration of reverberation.
- The early decay time EDT (s) as a predictor for perceived reverberance.
- The definition D_{50} (early to total sound energy ratio) as a predictor for speech clarity.
- The clarity C_{80} (dB) as a predictor for perceived transparency with music.
- The early lateral energy fraction J_{LF} as a predictor for apparent source width (ASW).
- The late lateral sound level L_{J} (dB) as a predictor for listener envelopment (LEV).

G, J_{LF} and L_{J} were determined only in the simulation. In addition to these parameters, the speech transmission index (STI) was calculated according to IEC 60268-16:2011 [19]. $T_{20\mathrm{m}}$, G_{m}, $\mathrm{EDT}_{\mathrm{m}}$, $C_{80\mathrm{m}}$ were calculated as average values of the 500–1000 Hz range, J_{LF}, L_{Jm} as average values of the 125–1000 Hz range. For all parameters (except STI), impulse responses generated with a 3-way dodecahedron loudspeaker (in the measurement) and a perfectly omnidirectional loudspeaker (in the simulation) were used to derive the acoustical parameters. For STI determination, impulse responses generated with a 4" broadband driver were used (in the measurement), whereas a loudspeaker with speaker directivity was used in the simulation. The background noise level was set to 20 dB for each octave band.

4. Results

4.1. Temporal structure of the sound field

Figure 4 shows the early part of an impulse response in the Teatro Olimpico (Vicenza) for a central source and receiver position, as well as the degree to which it could be reproduced in the simulation. After the direct sound, arriving at 24 ms corresponding to 8 m path length, we can identify four important room reflections: A first order reflection from the orchestra floor (1), almost identical to those observed in open ancient theatres both in level and delay [3], and a first order reflection from the ceiling (3). Moreover, a second order reflection over ceiling and back wall of the auditorium (4), and a cluster of simultaneously arriving reflections from the rising tiers behind the receiver (2). The latter could – unlike the other reflections – not be correctly reproduced in the simulation, due to the limited modelling accuracy of scattering and diffraction from this complexly structured surface. The high intensity of the second order reflection over ceiling and back wall (4) is due to the focusing effect of the concave back wall, that is, it corresponds, like reflection 2, to a cluster of reflections arriving simultaneously from different directions. This type of reflection was observed in all three theatres for central listening positions (cf. Figure 5, where it does not appear for a lateral position).

Figure 5 shows the impulse response for a lateral listening position. After the direct sound, arriving at 39 ms corresponding to 13 m path length, we can identify three important room reflections. Similar to the central position (Figure 4), we find a first order reflection from the orchestra floor (1) and a first order reflection from the ceiling (3). Unlike for the central position (with the open stage portal behind the source), there is an additional strong reflection from the back wall of the stage (scaenae frons, 2).

[3] L.L. Beranek: Concert and Opera Halls. How They Sound. Woodbury 1996, Appendix 5, 626, Table A5.7

[4] W. Fasold, H. Winkler: Bauphysikalische Entwurfslehre, Bd. 5: Raumakustik. Berlin 1976, Grafik 94, Kurve 1, 55

[5] M.D. Egan: Architectural Acoustics. J. Ross Publ. 2007, 52

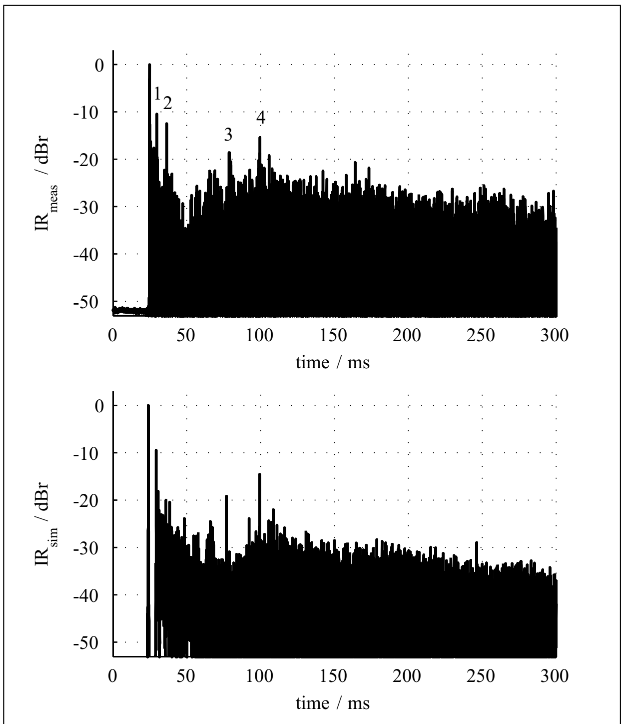

Figure 4. Measured (top) and simulated (below) normalized room impulse response for the Teatro Olimpico (unoccupied), for a central listening position (source position A, receiver position 1, cf. Figure 3). Numbers 1–4 mark important room reflections from the orchestra floor (1), from the rising tiers behind the receiver (2), from the ceiling (3) and a second order reflection over the ceiling and the back wall of the auditorium (4). In the simulation, three of these early reflections could be reproduced with good accuracy.

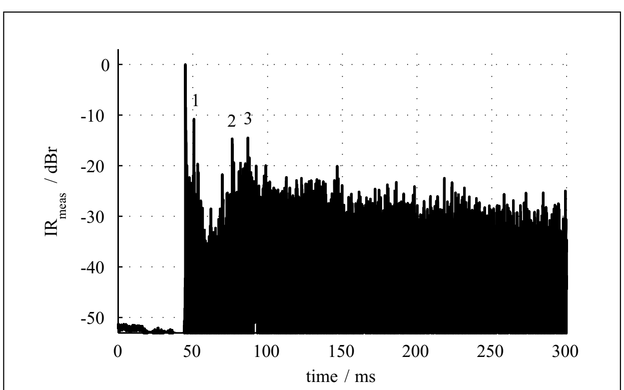

Figure 5. Measured room impulse response (normalized) for the Teatro Olimpico (unoccupied) for a lateral listening position (source position A, receiver position 5, cf. Figure 3). Numbers 1–3 mark important early reflections from the orchestra floor (1), from the back wall of the stage (2), and from the ceiling (3).

4.2. Reverberation times

Figure 6 shows the frequency-dependent values of T_{20} for the three theatres as an average value of all listener positions. Figures for the unoccupied case are derived from the measurement, while figures for the occupied case are derived from the simulation. For the Teatro Farnese (Parma),

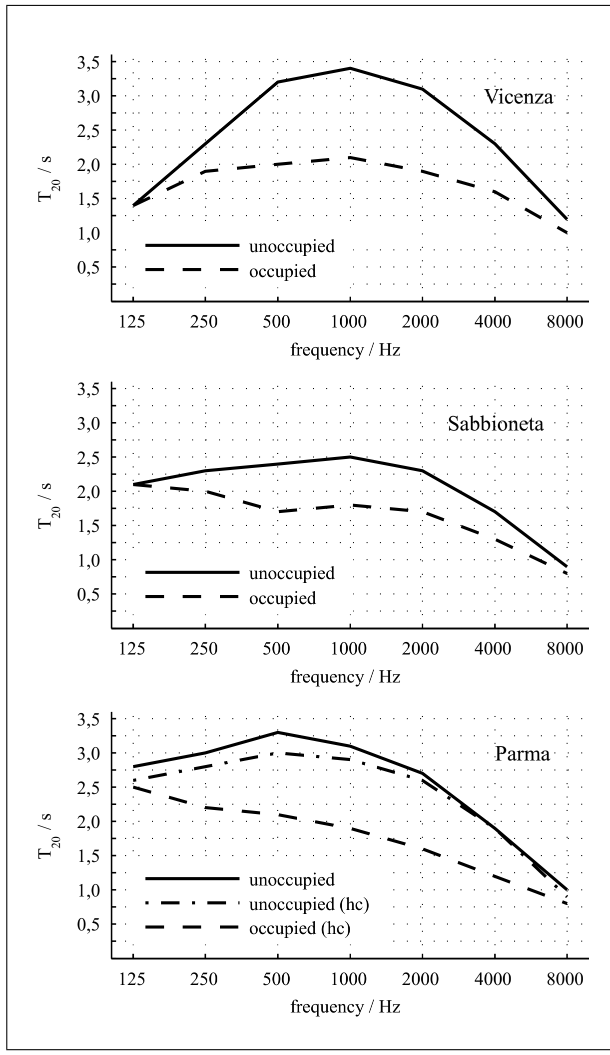

Figure 6. Reverberation times T_{20} for the Renaissance theatres in Vicenza, Sabbioneta, and Parma. Values are given for the unoccupied case, derived from measurements, and for the occupied case, derived from the simulation. For the theatre in Parma, additional values are given for the simulated, unoccupied condition, including the reconstructed, historical flat ceiling (marked ‘hc’). For the theatre in Sabbioneta, modelled values for the current structure and the reconstructed historical ceiling are identical.

additional values are given for the simulated, unoccupied condition, including the reconstructed, historical flat ceiling.

With reverberation times T_{20m} of 3.3 s (Vicenza), 2.4 s (Sabbioneta) and 2.9 s (Parma) for the unoccupied room, the theatres of the Renaissance period are considerably more reverberant than typical baroque opera houses such as those in Naples (opened 1737, T_{30} = 1.1 s) [5], in Bayreuth (opened 1748, T_{30} = 1.4 s) and Drottningholm (opened 1766, T_{30} = 1.2 s), or the neo-classical opera houses in Versailles (opened 1770, T_{30} = 1.6 s) [7], and in Milan (La Scala, opened 1778, T_{30} = 1.35 s) [20]. In the occupied condition, reverberation times are still relatively long and remarkably similar, with values of 2.0 s (Vicenza), 1.7 s (Sabbioneta), and 2.0 s (Parma).

Table III. Room acoustical parameters according to ISO 3382-1:2009 [18] for the Renaissance theatres in Vicenza, Sabbioneta, and Parma for the unoccupied (U) and the occupied (O) case derived from the simulation. Parameters derived from measured impulse responses are printed in bold. Parameters of the Teatro Farnese in Parma and the Teatro all'Antica in Sabbioneta are derived from simulations with the reconstructed original ceilings. The individual receiver positions (R1–R9) are shown in Figure 3.

	G_m (dB)		EDT_m (s)		C_{80m} (dB)		D_{50m}		J_{LF}		L_{Jm} (dB)		STI	
	U	O	U	O	U	O	U	O	U	O	U	O	U	O
Teatro Olimpico, Vicenza														
R1	10.8	6.9	**3.3**	2.1	**-2.1**	0.7	**0.23**	0.45	0.03	0.02	-0.3	-0.8	**0.56**	0.58
R2	9.6	5.7	**3.4**	2.1	**-6.2**	-0.1	**0.21**	0.40	0.07	0.03	0.0	-0.6	0.45	0.50
R3	9.4	5.2	**3.5**	2.1	**-3.1**	-1.0	**0.18**	0.39	0.11	0.05	0.0	-0.4	**0.49**	0.47
R4	10.4	6.5	**3.5**	2.1	**-3.5**	1.1	**0.19**	0.44	0.08	0.07	-0.3	-0.7	0.53	0.56
R5	9.3	5.2	**3.3**	2.2	**-3.9**	0.2	**0.20**	0.40	0.11	0.06	-0.1	-0.6	**0.44**	0.50
R6	8.8	4.4	**3.2**	2.2	**-3.6**	-0.7	**0.21**	0.38	0.14	0.08	0.0	-0.5	0.39	0.46
R7	10.3	6.2	**3.4**	2.0	**-2.6**	0.1	**0.28**	0.31	0.11	0.11	-0.2	-0.6	0.51	0.50
R8	9.5	5.4	**3.3**	1.9	**-4.1**	0.4	**0.20**	0.31	0.16	0.10	-0.2	-0.8	0.40	0.45
R9	9.2	4.9	**3.3**	1.9	**-7.3**	0.8	**0.20**	0.41	0.19	0.15	-0.2	-0.8	0.38	0.43
Mean	9.7	5.6	**3.4**	2.1	**-4.0**	0.2	**0.21**	0.39	0.11	0.07	-0.1	-0.6	0.46	0.49
Teatro all'Antica, Sabbioneta														
R1	13.7	11.8	2.6	2.0	-2.0	0.2	0.30	0.42	0.32	0.31	-0.3	-0.4	0.50	0.57
R2	13.7	12.3	2.5	1.9	-1.9	-0.2	0.28	0.37	0.23	0.23	-0.3	-0.4	0.49	0.54
R3	13.0	10.5	2.5	1.9	-3.0	-1.0	0.24	0.33	0.28	0.25	-0.2	-0.4	0.48	0.54
R4	13.1	11.3	2.5	1.8	-2.8	-1.0	0.24	0.31	0.24	0.24	-0.2	-0.3	0.47	0.52
R5	13.1	9.2	2.4	1.8	-2.5	-1.7	0.29	0.32	0.30	0.22	-0.2	-0.5	0.53	0.54
R6	13.0	11.2	2.3	1.7	-1.8	0.2	0.31	0.39	0.28	0.28	-0.3	-0.4	0.53	0.59
Mean	13.3	11.1	2.5	1.9	-2.3	-0.6	0.28	0.36	0.28	0.26	-0.3	-0.4	0.50	0.55
Teatro Farnese, Parma														
R1	3.3	2.5	3.0	1.4	1.1	3.1	0.51	0.60	0.09	0.09	-0.6	-0.8	0.57	0.62
R2	2.7	0.3	3.1	2.0	0.6	3.6	0.48	0.61	0.01	0.01	-0.5	-0.9	0.57	0.64
R3	1.2	-1.0	3.2	1.8	-3.3	0.0	0.19	0.31	0.09	0.07	-0.1	-0.5	0.46	0.52
R4	2.0	-1.1	2.5	1.6	-1.4	2.5	0.26	0.40	0.08	0.08	-0.2	-0.7	0.49	0.55
R5	1.4	-3.4	2.4	1.5	1.0	2.3	0.38	0.44	0.31	0.16	-0.6	-0.9	0.53	0.56
R6	-0,3	-3.7	2.4	1.6	-1.9	0.9	0.24	0.37	0.22	0.17	-0.3	-0.6	0.45	0.52
R7	1.5	-3.2	2.6	1.4	-4.9	2.6	0.16	0.50	0.13	0.07	-0.1	-0.4	0.41	0.54
R8	1.2	-2.2	3.1	2.0	-1.1	2.7	0.33	0.56	0.03	0.03	-0.3	-0.7	0.49	0.58
Mean	1.6	-1.5	2.8	1.7	-1.2	2.2	0.32	0.47	0.12	0.09	-0.3	-0.7	0.50	0.57

4.3. Room acoustic parameters

Table III shows the room acoustical parameters of the three theatres calculated for the occupied (O) and the unoccupied (U) condition. Most of the data for the unoccupied condition was derived from measured impulse responses (indicated in bold), while parameters for the occupied condition were derived from the simulation. For the Teatro Farnese (Parma) and the Teatro all'Antica (Sabbioneta), simulated impulse responses for a model with the reconstructed historical ceiling were used. Measured values in the current hall are given in Table IV.

From the parameters it becomes obvious, that the acoustical conditions of all three theatres do not meet modern standards for speech intelligibility and theatre design. Evidence for this are D_{50m} values < 0.5 even in the occupied halls, except for the two most forward positions in the Teatro Farnese, as well as STI values < 0.6, again except for the two most forward positions in Parma. These values are generally considered unsatisfactory for speech intelligibility in modern theatres [19, 21].

The room acoustical conditions do, however, seem favourable for music, according to modern standards. This is indicated by EDT_m values in a range of 1.9–2.2 s for the Teatro Olimpico (Vicenza), 1.7–2.0 s for the Teatro all'Antica (Sabbioneta), and 1.4–2.0 s for the Teatro Farnese (Parma) in the occupied condition, and C_{80m} values in a range of -1.0–1.1 dB for the Teatro Olimpico (Vicenza), -1.7–0.2 dB for the Teatro all'Antica (Sabbioneta) and 0.0–3.6 dB for the Teatro Farnese (Parma), again for the occupied condition. All of these values would be considered optimal for modern concert halls [20].

Due to the substantial difference in size, the sound strength G_m varies from -3.7–2.5 dB (Parma) via 4.4–6.9 dB (Vicenza) to 9.2–12.3 dB (Sabbioneta), indicating little acoustical support in the huge Teatro Farnese (Parma), but considerable support for sound sources in the Teatro Olimpico (Vicenza) and even more in the rather small Teatro all'Antica (Sabbioneta). The extent to which these conditions were regarded as appropriate, consider-

Table IV. Room acoustical parameters according to ISO 3382-1:2009 [18] of the Teatro Farnese in Parma and the Teatro all'Antica in Sabbioneta for the unoccupied (U) and the occupied (O) case, as derived from measurements in the room and a simulation of the current state, with destroyed ceiling. Parameters derived from measured impulse responses are printed in bold. The individual receiver positions (R1–R9) are shown in Figure 3.

	G_{m} (dB)		$\mathrm{EDT}_{\mathrm{m}}$ (s)		$C_{80\mathrm{m}}$ (dB)		$D_{50\mathrm{m}}$		J_{LF}		L_{Jm} (dB)		STI	
	U	O	U	O	U	O	U	O	U	O	U	O	U	O
Teatro all'Antica, Sabbioneta														
R1	14.1	12.1	**2.4**	2.0	**-2.5**	0.1	**0.24**	0.41	0.32	0.30	-0.3	-0.4	**0.53**	0.55
R2	13.8	12.3	**2.4**	1.9	**-3.0**	-0.2	**0.23**	0.38	0.22	0.20	-0.3	-0.5	0.48	0.52
R3	13.2	10.7	**2.4**	1.9	**-2.5**	-1.1	**0.22**	0.33	0.28	0.20	-0.2	-0.4	**0.45**	0.51
R4	13.1	11.2	**2.4**	1.9	**-2.1**	-1.1	**0.26**	0.32	0.27	0.20	-0.2	-0.3	0.45	0.50
R5	13.0	9.3	**2.5**	1.9	**-2.0**	-1.6	**0.25**	0.32	0.27	0.20	-0.2	-0.5	**0.49**	0.50
R6	13.0	11.1	**2.6**	1.8	**-3.4**	0.1	**0.35**	0.41	0.31	0.30	-0.3	-0.5	**0.51**	0.56
Mean	13.4	11.1	**2.5**	1.9	**-2.6**	-0.6	**0.26**	0.36	0.28	0.23	-0.2	-0.4	0.49	0.52
Teatro Farnese, Parma														
R1	3.3	2.4	**3.1**	1.8	**-0.9**	2.9	**0.39**	0.6	0.01	0.09	-0.4	-0.7	**0.62**	0.61
R2	2.5	0.2	**3.3**	2.5	**0.2**	2.4	**0.47**	0.6	0.01	0.01	-0.5	-0.8	0.58	0.63
R3	0.3	-1.3	**3.3**	2.1	**-4.5**	-1.7	**0.19**	0.3	0.10	0.07	0.0	-0.3	**0.55**	0.51
R4	1.5	-1.3	**3.2**	2.2	**-3.7**	1.1	**0.23**	0.4	0.12	0.10	-0.2	-0.6	0.49	0.54
R5	2.2	-2.8	**2.8**	1.6	**-0.5**	0.2	**0.38**	0.3	0.29	0.19	-0.5	-0.8	**0.59**	0.54
R6	-0.3	-3.0	**3.1**	1.7	**-1.7**	-0.9	**0.29**	0.3	0.19	0.17	-0.3	-0.4	**0.53**	0.36
R7	0.5	-3.1	**3.2**	1.6	**-2.8**	1.2	**0.27**	0.5	0.16	0.10	-0.2	-0.6	0.42	0.52
R8	1.1	-2.2	**3.1**	2.3	**-1.5**	0.0	**0.36**	0.5	0.01	0.01	-0.1	-0.4	0.48	0.56
Mean	1.4	-1.4	**3.1**	2.0	**-1.9**	0.7	**0.32**	0.4	0.11	0.09	-0.3	-0.6	0.53	0.53

ing the performed repertoire and the expectations of the audience, will be discussed below.

4.4. Original Data

The measured and simulated impulse responses for all listener positions (Figure 3), along with the 3D models used for simulation (in DXF and SKP format) are available as an electronic publication [22]. This also contains an anechoic recording of the prologue of *Edipo tiranno* [23] and convolutions with stereo impulse responses recorded in the three theatres with AB stereo miking (1 m microphone basis), suitable for loudspeaker reproduction.

5. Discussion

With the theatres in Vicenza (1585), Sabbioneta (1590) and Parma (1618), the only survivors of Renaissance theatre design have been investigated with respect to their room acoustical conditions, with measurements in the empty rooms and simulations of the occupied condition, including a partial reconstruction of the historical state. At first sight and by modern standards, all venues from this period would seem acoustically largely inappropriate for theatrical performances. With reverberation times of $T_{20\mathrm{m}}$ = 2.4–3.3 s for the unoccupied room and still 1.7–2.0 s with audience, they are far from modern recommendations for speech venues of 1.0 seconds or less [21]. The same conclusion is suggested by values for the definition and the speech transmission index, with $D_{50\mathrm{m}} < 0.5$ and STI < 0.6. Hence, one could be tempted to consider the buildings as acoustical failures, potentially due to a lack of experience in theatre design or a lack of room acoustical knowledge in general.

This conclusion would, however, not take account of the cultural context. First, the architects' experience with theatre design should be considered. In the case of Andrea Palladio, this was not only derived from his comprehensive analysis of classical Roman theatres, in which case it could be argued that he underestimated the effect of the roof and the enclosed space, but also from his own earlier theatrical buildings. These include stages built for the Palazzo della Ragione (today called Basilica Palladiana), the seat of the government in Vicenza, which was used for theatrical performances in 1561 and 1562. With a wooden stage inserted into a large hall of 50 m length, 20 m width and 24 m height with stone walls (Salone Principale, renovation completed in 2011), an even longer reverberation time can be assumed than in the Teatro Olimpico. In 1565 Palladio was again commissioned with the design of a stage in the Convento della Carità in Venice, also featuring a medium size wooden theatre "in the shape of a colosseum", that is, with a half elliptical auditorium of rising tiers [11]. Thus, the acoustics of the Teatro Olimpico could not have been a surprise, neither to the architect nor to the Accademia Olimpica as his client.

Moreover, none of the numerous preserved reactions to the opening performance of *Edipo tiranno* in the Teatro Olimpico indicate that the contracting institution was unsatisfied with the building or with the production itself. On the contrary, all sources underline the positive overall impression of the performance as a result of the selected play, its staging and the performance space with its visual and acoustical properties. They also bear witness to the importance of the musical part of the theatrical performance. For a setting of the choral parts of the tragedy, Andrea Gabrieli (1532–1585), composer and organist at San Marco in Venice, was commissioned. The score of his six-part work has been preserved and is available in modern notation [24], while additional composed or improvised instrumental parts have been lost. According to members of the academy, the musical composition was appropriate to the subject and composed in a way that even with all voices convening almost every word could be clearly understood [25]. With respect to the instrumental parts, Angelo Ingegneri (1550 after 1613), the stage director of the opening performance, reports that "after the curtain had fallen in front of the stage, an instrumental and vocal music, the sweetest one may imagine, and at the same time equally soft, would begin to resonate from behind the stage. It appeared as if it would resonate from far away and be the conclusion of a long harmony which would have been performed until just before the curtain would open and any further singing performance would begin" [26].

Whereas the choir, consisting of 15 singers, performed on stage, the musical instruments thus were not, as one might suppose, located in the "orchestra" space in front of the stage, but within the backstage scenery, which gave them a soft and gentle sound, a music that appeared to come "from far away". According to Ingegneri, this was where the musicians usually played in theatre performances during that period [27]. For the choral parts of the play, a duration of at least 30–40 minutes can be estimated from the score. The duration of the purely instrumental parts is unknown, since no score has been preserved. The fact that many comments refer to this partly instrumental music, however, indicates that it was an important part of the play.

Hence, the staging of *Edipo tiranno* has to be considered a musical as much as a spoken theatre. It stands for the idea of an ancient theatre to be resurrected during the Renaissance period. Consequently, the theatrical space has to be judged at least as much with regard to its effect on music as on speech. For the words to be properly intelligible, as it is repeatedly emphasized in reports about the performance, both the musical composition, with a strictly homophonic, note-against-note musical counterpoint [24], and the staging practice, with the musical instruments placed within the backstage scenery, made an important contribution. The architectural design had an additional part in this, with an excellent sightline design, strong early reflections by the orchestra floor and the ceiling, and a close arrangement of stage and audience. At the same time, the rather reverberant space allowed for spatial effects, for music to be perceived "from far away", supporting the illusion of scenic depth, which was also visually converyed by the backstage perspectival views (cf. Figure 1 and Figure 2).

The Teatro Olimpico in Vicenza and its successors in Sabbioneta and Parma stand for the idea of a sacred theatre of antiquity to be reborn in buildings based on antiquity. The musical composition, with its predominant focus on text intelligibility and a subordination of instrumental parts, anticipates elements of the opera, which would emerge as a new theatrical genre only a few years after the opening of the Olimpico, with works such as *La Dafne* (1597), *L'Euridice* (1602) and *L'Orfeo* (1607). That the Teatro Olimpico with its almost church-like acoustical conditions provided an appropriate environment for this new theatrical genre seems strongly confirmed by a variety of contemporary reports.

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