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Abstract

Italian Historical Opera Houses (IHOH) are private or public spaces built around a cavea, with tiers of boxes on the surrounding walls. At the early age – from 16th to 18th Century – boxes were private properties of the richest class, typically the financial responsible of the whole building. The stalls hosted the middle class, that gradually increased its social position and for this reason the wooden seats were progressively replaced by chairs. The gallery was reserved to lower classes. Does this social division correspond to a different acoustic comfort? The present work tries to answer this question using subjective preference models provided by scholars. With this aim, the room criteria defined by different authors and in distinct times are lined up with the ISO 3382 standards and analysed depending on the acoustic peculiarities of an IHOH selected as case study. Calibrated impulse responses were handled through the numerical simulations of a whole orchestra of virtual sound sources in the pit.

Keywords

Opera house, GA simulation, Calibrated impulse responses, Subjective preference

Introduction

The first attempts to define a subjective evaluation of performance spaces date back to the early era of room acoustics [1, 2]. These works provided several results of optimal reverberation time values, depending on the hall's volume. During the 1950s Beranek extended the theory, correlating the results of questionnaires to objective measurements. Intimacy, which seemed to be the main subjective

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factor influencing the listener perception, was correlated to the objective criterion of Initial Time Delay Gap (ITDG) [3]. The limits of this approach were in the monaural model, as it was confirmed a few years later by Barron [4]. Therefore, in the 1970s the first studies on *Subjective preference* included binaural measurements and needed binaural listening procedures. The work on European Concert Halls by Schroeder et al. [5] employed a listening room with a cross-talk cancellation provided by analog inverse filtering. This approach was improved by Ando, who proposed metrics of preference based on orthogonal factors [6]. In 2003 Beranek [7] proposed further metrics of preference including more criteria: some objective ones, e.g. the Bass Ratio in occupied conditions, and some subjective ones, as the Surface Diffusivity Index. Using a factor analysis approach, a series of works [8, 9, 10] identified orthogonal factors, taking into account the sound strength at low frequencies. Later, Cerda et al. correlated their approach to the Ando–Beranek model [11]. This kind of study is involved in the field of elicitation properties, i.e. the minimum number of regression parameters needed to compute the subjective preference [12]. However, the discussion on elicitation attributes is still open [13, 14, 15, 16].

Cirillo et al. [17] adapted the Ando–Beranek approach to Italian Historical Opera Houses (IHOHs), taking into account the balance between soloists and orchestra and the intelligibility of singer/actor's voice. They proposed also different weighting coefficients and optimal values, given the peculiarity of the small and mid sized opera houses under study. Furthermore, several studies [18, 19, 20, 21] analysed the range of values considering the simultaneous presence of a singer on the stage and an orchestra in the pit: these proposals highlighted the complexity of the opera house as an acoustical system. More recently, Ando himself adapted his model to IHOHs [22]. A summary of subjective preference models is shown in table 1.

In IHOHs, the balance soloist–orchestra and the simultaneous needing to have suitable acoustic conditions for voice and music has always been so critical to influence the historical development of the opera house. For instance, in the early age of the opera [23] the orchestra was initially placed in front of the stalls, in the reverberant volume of the cavea. The increased number of instruments in the evolution of the drama led to the Wagnerian idea of orchestra pit, the so–called "mystic gulf", conceived for the Bayreuth Festspielhaus (1872) [24] and then used also for Italian theatres from the early 1900s [25].

IHOHs have been measured by several works [26, 27, 28] but it is quite difficult to collect a complete set of measured room criteria. Numerical simulations, instead, may be useful during the study of the acoustics of an opera house. For instance, simulating the presence of the audience allows to extract room criteria values defined in occupied conditions [29]. Furthermore, the possibility to simulate different configurations of the drapes and the scenes on the stage could lead to a deeper analysis of the consequent variation of room criteria.

For all these reasons, the present paper proposes a methodology for qualifying an opera house through acoustic simulation, in order to collect all the acoustic

Table 1. Summary of subjective preference models.

	Ando [22]	Beranek [7]	Cirillo et al. [17]
Sound Strength	LL	G_M	G_M
	≈ 79 dBA	> 1 dB	$1-8$ dB
Intimacy	ITDG	ITDG	ITDG
	$20(1+C_7/20)$ ms	< 20 ms	< 20 ms
Reverberance	$T_{15}^{(a)}$	EDT	EDT
	$0.46\,\text{s}^{(b)}$	2.5 s	$1.4-1.6$ s
Spatial impression	IACC	BQI	BQI
	< 0.3	0.7	> 0.7
Warmth	–	$BR^{(a)}$	$BR^{(a)}$
	–	$1.1-1.2$	$1.05-1.25$
Diffusivity	–	SDI	SDI
	–	1	1
Perceived clarity	–	–	C_{50}
	–	–	$1-5$ dB
Balance	–	–	$G_{M,\text{stage}} - G_{M,\text{pit}}$
	–	–	$(-2)-2$ dB

[a] Even if not explicit in the original studies, the room criteria are referred to occupied conditions.
[b] $\tau_e = 20$ ms is assumed for singer, based on the analysis of anechoic recordings [20]. This value may be increased using other approaches [30, 31], thanks to the availability of more opera recordings [32, 33].

criteria proposed by scholars [34] and then assess the corresponding subjective preferences. An acoustic measurements campaign was performed in a IHOH selected as case study, in order to achieve the objective acoustic criteria according to ISO 3382 [35]. Basing on the measured values, a rigorous calibration of the computer model of the theatre was carried out. Finally, a multi-source approach was used in the simulation [36, 37]. A whole orchestra and a soloist were simulated for different levels of orchestra loudness: "pianissimo" (*pp*), "mezzo-forte" (*mf*) and "fortissimo" (*ff*).

Method

The opera house of the present study is the *Teatro Comunale* in Bologna (TCBO), designed by Antonio Galli da Bibiena and opened on 14 May 1763 at the early period of the Italian Melodrama. At that time, the theatre was innovative in several aspects thanks to the design choices of the architect, like the bell shape of the main hall and the use of construction materials like stone and gypsum instead of wood (see fig. 1). During its history the theatre was restored several times. In 1935, after a fire that destroyed much of the stage, the fly tower was rebuilt, wider than the previous one and with a higher ceiling. The last renovation was in August 2016 when all the seats of the stalls were replaced, while the original materials

Figure 1. *Sala Bibiena* of the *Teatro Comunale* in Bologna (Photo by: Lorenzo Gaudenzi, Own work, CC BY-SA 4.0, Wikipedia)

of the walls, ceilings and floors were not affected. The shape, the materials, the arrangement of the stage and the fly tower/main hall volume ratio provide a quite reverberant performance space, such that at the end of the 19th Century the theatre became one of the preferred places for performing Wagner's operas outside Germany. The theatre hosted the first Italian representation of *Lohengrin* (1871), *Tannhäuser* (1872), *Der fliegende Holländer* (1877), *Tristan und Isolde* (1888), and *Parsifal* (1914). Moreover, in the early 19th Century, the theatre hosted twenty Rossini's performances and seven (out of ten) Bellini's operas. The volumes of the hall and the fly tower are about 5500 m^3 and 21100 m^3 respectively; the occupancy is around 1000 seats, depending on the possible configurations adopted.

ISO 3382 measurements

In August and September 2016 an acoustic measurements campaign was made in the TCBO. The objective acoustic criteria, as defined in ISO 3382 [35], were extracted from the impulse responses (about 2.7 seconds long) acquired using an exponential sine sweep signal [38]. The theatre was in an unoccupied condition during measurements. Four sound source positions were used: two on the stage (fore stage and centre stage) and two in the orchestra pit (covered and uncovered area). All the sound sources were omnidirectional and driven with enough power to give sound pressure levels comparable to those of an orchestra and a singer, in order to properly excite the wooden parts of the theatre [39]. Receivers were organized following a dense mesh of points in one half of the audience (stalls,

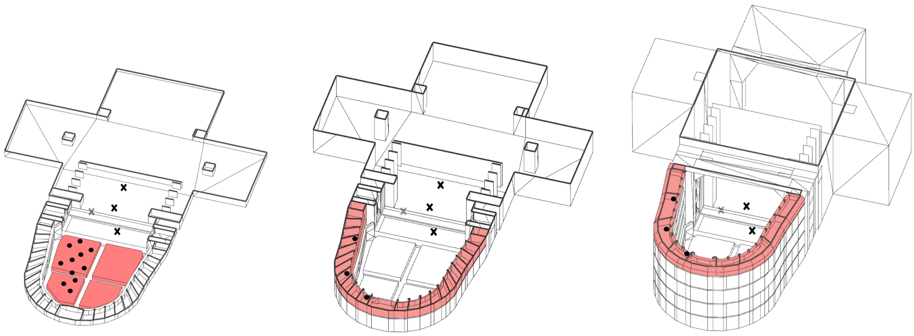


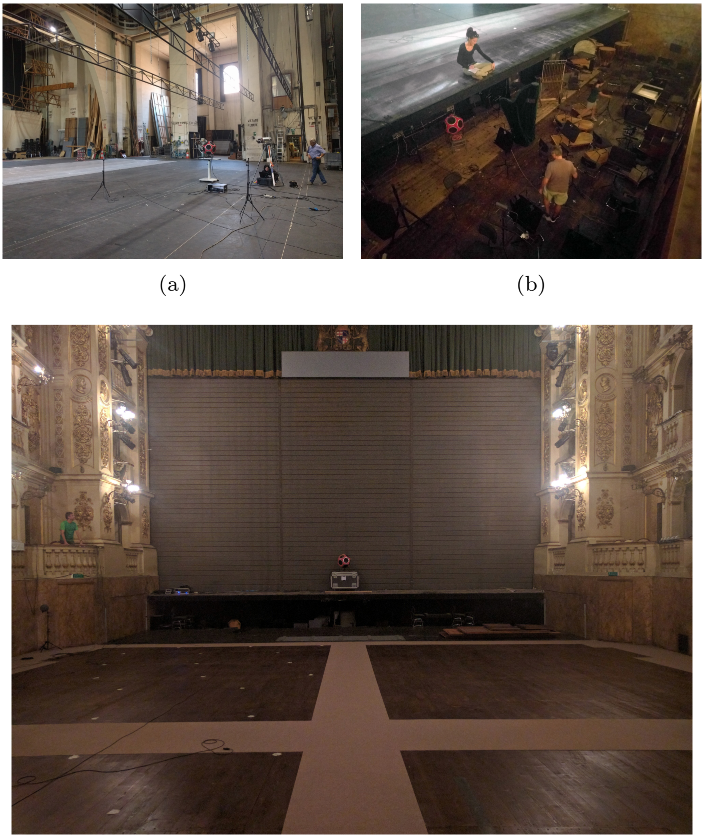
Figure 2. Positions of sound sources (crosses) and receivers (circles) during the acoustic measurements. Gray cross indicates the sound source position in the covered part of the orchestra pit.

boxes and gallery), exploiting the symmetry of the hall [40]. The placement of sound sources and receivers is shown in figure 2.

In order to estimate the influence of sound absorbing materials on the whole sound field behaviour, the acoustic measurements were performed with and without the drapes in the fly tower (fig. 3(a)). Their presence may influence the acoustic coupling between the volume of the fly tower and the main volume of the cavea [25, 41]. Similarly, the acoustic role of the orchestra pit was investigated opening and closing the pit during the measurements (fig. 3(b)). Moreover, exploiting the recent refurbishment of the stalls, it was possible to carry out the acoustic measurements with and without the chairs in the cavea (fig. 3(c)). Results confirm the significant influence of the equivalent absorption area of the chairs on measured room criteria [42]. Finally, measurements were also done with the firedoor closed in order to evaluate the single behaviours of the sound field in the two distinct volumes, placing sound sources and microphone receivers in the fly tower and then in the main hall.

Calibration of the model

A computer model of the theatre was created using SketchUp software and then imported into the geometrical acoustics software Odeon v. 12 [43]. The geometrical model includes 2150 surfaces with a total surface area of about 12500 m^2 and a total volume of about 26000 m^3 (fig. 4). The virtual model was organised in different layers, corresponding to the actual materials of the opera house. The initial values of sound absorption coefficients applied to the surfaces were taken from available databases [44] and previous research [45]. In a second moment, as a common practice, the values were adjusted in an iterative way [46] to achieve the



(a) (b) (c)

Figure 3. Views of the opera house during different measurements configurations: (a) with and without the wings in the fly tower, (b) with the orchestra pit closed and open, (c) with and without the chairs in the stalls (firedoor closed).

calibration. The outcoming values of absorption coefficients are shown in table 2, together with the scattering coefficient applied to each layer.

A sample of the carpet was taken and measured in laboratory (ISO 354) allowing to obtain an accurate absorption value for the corresponding layer. The absorption and scattering coefficients of the plaster in the main hall are higher than "regular" plasters to compensate the lack of details resulting from the modeling approximation. Absorbing characteristics of the whole fly tower, which is a complex system including trusses, service facilities, catwalks and lighting fixtures, were determined through the iterative calibration process. The measurements carried out with and without the drapes on the stage facilitated

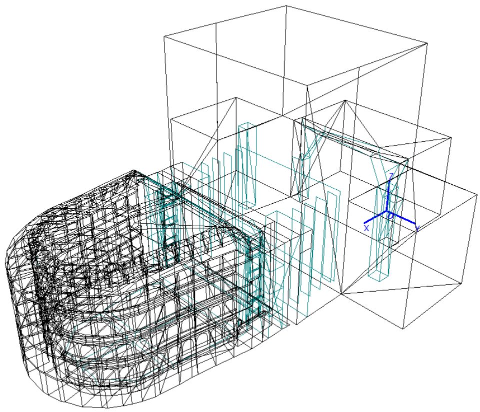


Figure 4. Wireframe view of *Teatro Comunale*'s model as shown in the acoustic simulation software.

Table 2. Absorption (α) and scattering (s) coefficients of the materials used in the simulations. Scattering values are provided at the mid–frequency 707 Hz, according to the software algorithm [43].

	Absorption coefficient						s	Ref.
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz		
Carpet	0.04	0.05	0.06	0.08	0.16	0.20	0.05	Measured
Wood	0.30	0.28	0.20	0.16	0.14	0.08	0.20	[25]
Plaster	0.09	0.09	0.10	0.10	0.10	0.10	0.30	–
Marble	0.02	0.02	0.03	0.04	0.04	0.04	0.05	[44]
Drapes	0.11	0.16	0.50	0.65	0.73	0.73	0.05	[44]
Fly tower	0.25	0.25	0.25	0.25	0.25	0.25	0.50	–
Stage grid	0.35	0.45	0.50	0.65	0.65	0.65	0.50	[45]
Seats	0.35	0.45	0.55	0.60	0.60	0.60	0.70	[42]
Audience	0.72	0.80	0.86	0.89	0.90	0.90	0.70	[42]
Musicians	0.18	0.30	0.45	0.62	0.83	0.90	0.70	[47]

the evaluation of the properties of these absorbing materials. The scattering coefficients were chosen according to the software's manual recommendations, previous research [48, 49] and considering the removal of several small elements during the modeling process.

During the calibration process, acoustic simulations were performed in the octave bands from 125 Hz to 4 kHz, setting the model with an impulse response length of 3.5 s, 100,000 late rays [50]. The transition order between early and late reflections, typically set equal to 2 in ordinary rooms, was set equal to 0, due to the complexity of the geometry and the high number of surfaces, as recommended by guidelines. The acoustic criteria values were simulated for two out of four sound

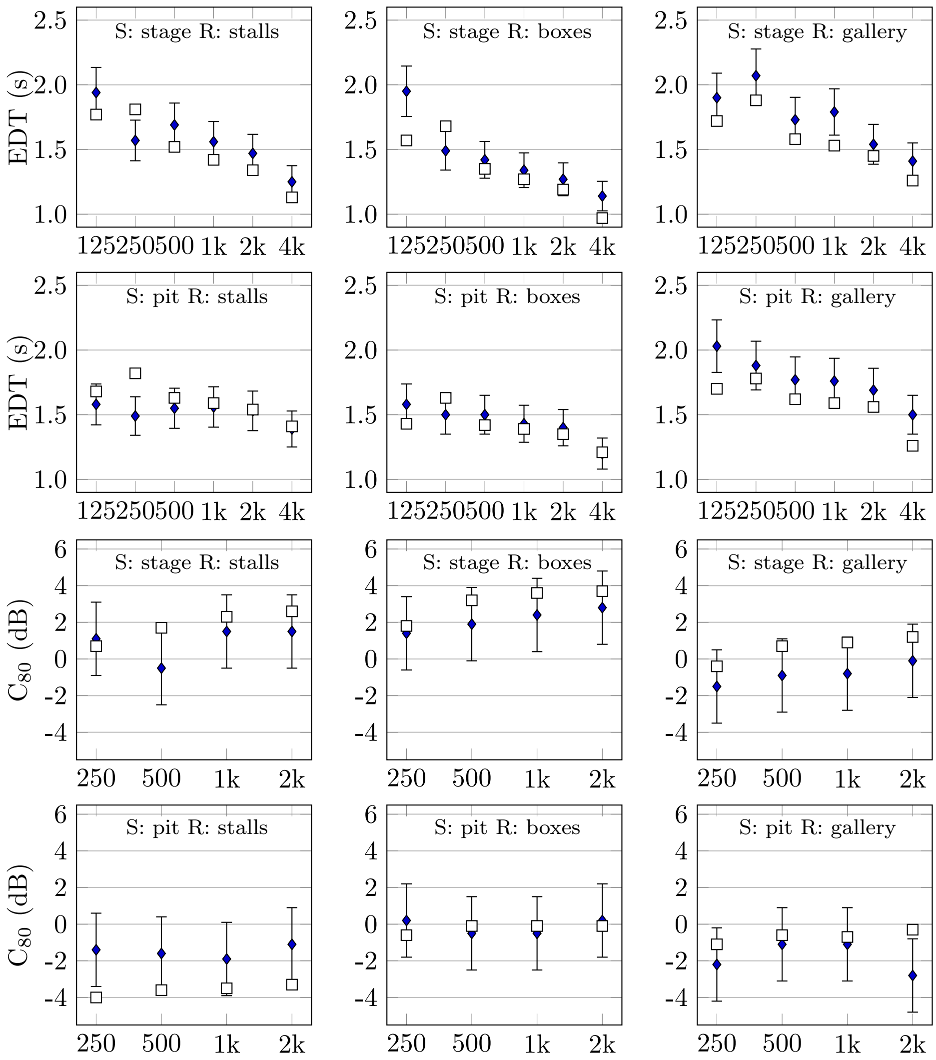


Figure 5. Calibration of TCBO theatre: comparison between the simulated values (white squares) and the measured values (black diamonds) of *EDT* (rows 1 and 2) and C_{80} (rows 3 and 4) for two sound source positions: centre stage and the uncovered part of the orchestra pit. The receivers are subdivided into the three categories (stalls, boxes and gallery) and averaged over the corresponding measurement positions. The error bars correspond to twice the Just Noticeable Difference (JND), i.e. 10% of *EDT* values and 2 dB for C_{80}.

source positions used in the measurements campaign, the first one on the stage (central position) and the second one in the orchestra pit (uncovered area). For calibration purposes, in addition to the reverberation time, the values of early decay time EDT and sound clarity C_{80} were taken into account (see fig. 5). The resulting values are shown averaged over the three receivers areas (stalls, boxes and gallery), as a function of the frequency. The calibration was considered achieved when 90% of differences between measured and simulated values were within twice the Just Noticeable Difference (JND) in each octave band [44].

Simulation

Once the calibration of the virtual model is achieved, any further acoustic condition, different from the measurements situation, could be simulated and then assessed. For instance, the actual sound field in the opera house during a performance is returned simulating the occupancy in the theatre [29]. Findings from previous works provided references to properly simulate the presence of the audience [42] and the musicians in the orchestra pit [47]. The absorption coefficients applied to the seats in the stalls were provided by Beranek's research (see tab. 2) [42]. When applied to the floor of the boxes and the gallery – where no seats were modeled at all – the same absorption coefficients were reduced depending on the density of people on the corresponding surface. Since a virtual orchestra of 42 musicians is simulated on a 87 m^2 pit floor, the absorption coefficients referred to a density of 2 person/m^2 are selected [47]. The reverberation time in occupied conditions is reported as a function of the frequency in figure 6.

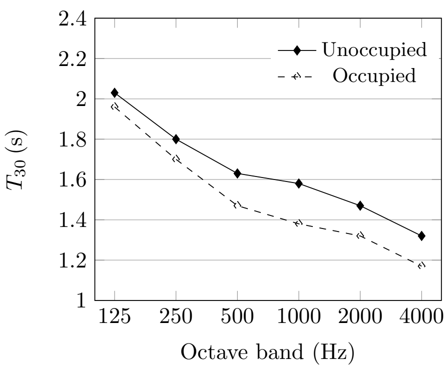


Figure 6. Measured T_{30} values (unoccupied condition) and simulated T_{30} values (occupied condition) in octave bands. Mean values are averaged over all the receivers positions.

MIMO simulation

Being $s(t)$ an anechoic signal emitted at the source position $\mathbf{r}_0$, the signal $p(t, \mathbf{r})$ listened at the receiver position $\mathbf{r}$ is equal to:

$$p(t, \mathbf{r}) = s(t) * h(\mathbf{r}_0, \mathbf{r}, t). \quad (1)$$

In an opera house there are several sound sources, so the signal listened at the position $\mathbf{r}$ is due to N sound sources on the stage (singers and choir), each singer playing his i-th part at position $\mathbf{r_0}_i$, and M sound sources in the pit (orchestra), each musician playing his j-th part at position $\mathbf{r_0}_j$:

$$p(t, \mathbf{r}) = \sum_{i=1}^{N} s_i(t) * h(\mathbf{r}_{0i}, \mathbf{r}, t) + \sum_{j=1}^{M} s_j(t) * h(\mathbf{r}_{0j}, \mathbf{r}, t). \quad (2)$$

In the present case, a Multiple Input Multiple Output (MIMO) simulation was performed putting a soloist on the stage ($N = 1$) and an orchestra of 42 musicians ($M = 42$) in the orchestra pit, considering a reference for 1800s Italian operas until Wagner's revolution. As shown in fig. 7 the virtual sound sources were oriented

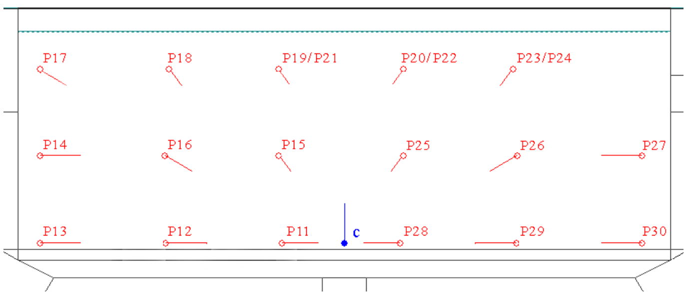


Figure 7. Layout of the virtual sound sources placed in the orchestra pit: a virtual orchestra of 42 musicians pointing towards the conductor (c) was adopted in this study (see tab. 3).

towards the conductor (c). It can be noticed that the seating arrangement used in the present study may differ from others seating arrangement, due to relative low-depth of the pit in mid-sized opera houses [51]. The instruments' directivities have been taken from the Odeon v. 12 directivity files library. Because of variations in sound power level of each instrument, three sets of instruments were taken into account, one for each dynamics of the score, respectively, "pianissimo" (*pp*), "mezzo-forte" (*mf*) and "fortissimo" (*ff*). Details for all the orchestra sound power levels are provided by table 3. For spaciousness criteria, Binaural Room Impulse Respones (BRIRs) were synthesized through Head Related Transfer Functions (HRTFs), setting elevation = 0° and azimuth = 0°.

Results and discussion

The acoustic simulations allow not only to analyse the trend of room criteria in any listener position, but also to obtain the required condition for subjective indicators, such as the occupied status of the opera house. In the present section each simulated room criterion is reported and discussed in view of the corresponding subjective preference described (see tab. 1). A comparison has been

Table 3. Sound power levels of each orchestral instrument playing "pianissimo" (*pp*), "mezzo-forte" (*mf*) and "fortissimo" (*ff*). The number of musicians (N. mus.) for instruments, the number of the virtual sound sources for each instrument and the gain used in the simulation are provided. Since each virtual sound source corresponds to more than one musician, the relative gain is calculated as 10log (n. musicians of *j*-th instrument/n. virtual sound sources of *j*-th instrument). See the position of each instrumental sound source in fig. 7.

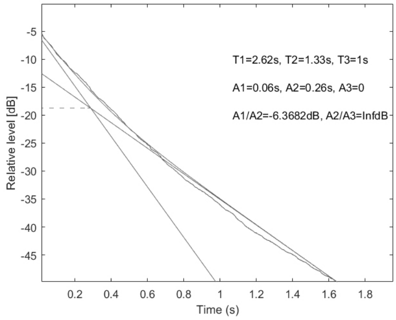
Section	Instrument	L_w (dB)			N. mus.	N. virtual sources	Gain (dB)
		pp	*mf*	*ff*			
Strings	1st violins	58	89	100	8	4 (P11,12,13,14)	+3
	2nd violins	58	89	100	6	3 (P15,16,17)	+3
	Violas	62	87	95	6	3 (P28,29,30)	+3
	Cellos	62	90	98	5	2 (P25,26)	+3.9
	D. Basses	67	92	100	3	1 (P27)	+4.7
Woodw.	Flutes	68	91	101	2	1 (P19)	+3
	Oboes	70	93	103	2	1 (P20)	+3
	Clarinets	58	93	106	2	1 (P21)	+3
	Bassoons	72	93	102	2	1 (P22)	+3
Brasses	French horns	65	102	118	2	1 (P18)	+3
	Trumpets	78	101	111	2	1 (P23)	+3
	Trombones	72	101	113	2	1 (P24)	+3
Total	–	–	–	–	42	20	–

made between the simulations carried out using omnidirectional sound sources and the calculation results obtained with the multiple virtual sound sources described in the previous section. In case of room criteria involving normalised values (G, BAL), different dynamics (*pp*, *mf*, *ff*) are also provided.

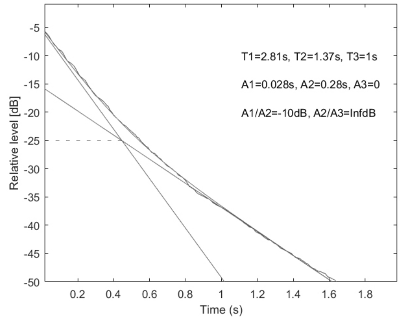
Reverberance and perceived clarity

The Italian theatre is a complex system of reverberating volumes, partially coupled one with the other. If the sound source is on the stage, in the stalls the direct sound is enhanced by early reflections provided by proscenium arch, vault, and side walls. The relative sound energy decay has two contributions corresponding to the sound field of the main hall and the fly tower. Multi-decay analysis [52] of simulated IRs allows to understand these effects, which can vary depending on the listener position in the stalls (see the intersection of the two slopes in figures 8(a) and 8(b)). In the boxes, the first part of the decay curve is affected by the reflections due to the nearest walls while the second part by the diffuse sound field of the cavea (see fig. 8(c)).

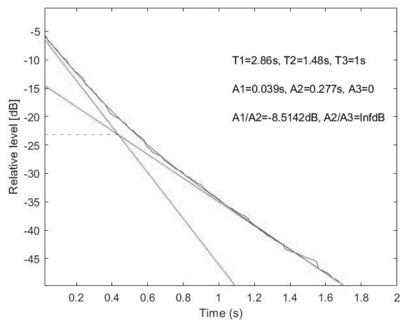
As a consequence, if the omni sound source is on the stage, the stalls show high EDT values and high clarity, the boxes low EDT values and high clarity, the gallery low EDT values but low clarity. It should be noticed that, lower the EDT



(a) R: stalls (center)



(b) R: stalls (rear)



(c) R: boxes

Figure 8. Multi-decay analysis of simulated IRs considering the sound source in the centre of the stage and two receivers in the stalls (figs. (a) and (b)) and a receiver in the second tier of boxes (fig. (c)). According to Xiang et al. [52], $\mathbf{T} = T_1, T_2, T_3$ and $\mathbf{A} = A_1, A_2, A_3$ are the decay parameters which fit the Schroeder curve H_s for a large number of data points K: $H_s(\mathbf{A}, \mathbf{T}, t_k) = A_0(t_K - t_k) + \sum_{S=1}^{3} A_s e^{-13.8 t_k / T_s}$.

values – the optimal value was shown to be about 1.3 s – higher is the preference of reverberations [20, 21]. Instead, when the omni sound source is in the pit, the edges of the pit influence the early reflections in the stalls (low values of clarity) more than the boxes. This behaviour meets the needings of opera summarised in the introduction: the music requires more (perceived) reverberation than the voice. The boxes maximise the preference, due to low EDT and high clarity values for the soloist on the stage, higher EDT and lower clarity values for the orchestra in the pit.

The differences discussed considering the omni sound source (tab. 4) are even more evident when a virtual orchestra and a singer are simulated (tab. 5). Sound clarity in the boxes is about 0 dB when the singer is in the fore stage, and it reaches

Table 4. Average values of EDT, BR_{occ}, and C_{80} simulated with the omnidirectional sound source in three positions: fore stage, centre stage and orchestra pit. Results are provided for each group of receivers: stalls, boxes and gallery. "M" and "3" subscripts identify, respectively, the octave bands 500–1000 Hz and 500–2000 Hz.

Sound source	Position	Receivers	EDT_M (s)	BR_{occ}	$C_{80,3}$ (dB)
Omni	Fore stage	Av. Stalls	1.50	1.3	1.4
		Av. Boxes	1.37	1.3	1.9
		Av. Gallery	1.33	1.3	0.3
	Centre stage	Av. Stalls	1.47	1.3	2.2
		Av. Boxes	1.31	1.3	3.5
		Av. Gallery	1.34	1.2	1.7
	Pit	Av. Stalls	1.64	1.2	-3.5
		Av. Boxes	1.41	1.2	-0.1
		Av. Gallery	1.42	1.2	-0.6

Table 5. Average values of EDT, BR_{occ}, and C_{80} simulated with calibrated sound sources (L_w set at *mezzo-forte* dynamic level): the soloist in two positions (fore stage and centre stage) and the virtual instruments in the orchestra pit. Results are provided for each group of receivers: stalls, boxes and gallery. "M" and "3" subscripts identify, respectively, the octave bands 500–1000 Hz and 500–2000 Hz.

Sound source	Position	Receivers	EDT_M (s)	BR_{occ}	$C_{80,3}$ (dB)
Virtual soprano	Fore stage	Av. Stalls	1.61	1.3	-0.8
		Av. Boxes	1.46	1.3	0.3
		Av. Gallery	1.28	1.2	-0.2
Virtual soprano	Centre stage	Av. Stalls	1.46	1.3	2.6
		Av. Boxes	1.28	1.3	4.0
		Av. Gallery	1.37	1.2	1.9
Virtual orchestra	Pit	Av. Stalls	1.66	1.2	-4.8
		Av. Boxes	1.35	1.2	-0.2
		Av. Gallery	1.42	1.2	-1.0

4 dB value when the singer is on the centre stage. This is in good accordance with the directorial needing of opera: the intelligibility of the singer at the centre stage is higher than the one at the fore stage. Using virtual sound sources, the differences between the three regions (stalls, boxes and gallery) further increase. Also in this case the boxes prove to have the best acoustic condition with the maximum C_{80} value for the singer in the centre stage. Instead, the stalls show some tonal unbalancing returning too low sound clarity values for the orchestra with respect to the intelligibility of the singer. Finally, the gallery seems to be unbalanced in the opposite way with the minimum C_{80} value for the singer.

Warmth

The absorption due to listeners and musicians significantly influences the reverberation time values of the opera house, especially in their trend as a function of frequency [29, 42]. Since the presence of audience and musicians is likely to affect mostly the high frequencies, the trend of reverberation time over the octave bands is usually different in occupied condition. The scholars proposed the *Bass Ratio* criterion BR_{occ} to evaluate the warmth of the space:

$$BR_{occ} = \frac{T_{125\,\mathrm{Hz}} + T_{250\,\mathrm{Hz}}}{T_{500\,\mathrm{Hz}} + T_{1000\,\mathrm{Hz}}} \tag{3}$$

where the subscript "occ" means that the reverberation times assumed in occupied status. As shown in tables 4 and 5, the BR_{occ} values do not depend on the receiver position. The investigated theatre shows to be sensitively "warmer" than other opera houses analysed in the literature, returning values not lower than 1.2 in each receiver position and for every kind of sound source. Past refurbishments indeed increased the absorption at high frequencies using velvet in the boxes, upholstered chairs and heavy fabrics for the wings without compensating the low frequency absorption.

Sound Strength and Balance

In a IHOH, the orchestra pit contributes to decrease the sound strength of the musicians: the deeper the pit, the higher the attenuation. At the same time, the G value of the soloist depends on the geometry and on the reverberation of the room, with lower sound strength values corresponding to larger theatres. Prodi and Velecka [19] proposed an optimal value of balance between -2 dB and +2 dB. Below this range the soloist voice can be masked by the orchestra; above a certain threshold (>4.5 dB) the sound can be "unbalanced" and unpleasant. The simulated values of sound strength at three receivers are shown in table 6. Spanning from 2.5 to 4.3 dB, they satisfy the preferred range proposed in the literature (see tab. 1). When the sound source is placed in the pit, the sound strength values are about 1 dB lower. Therefore, the balance values are in the range between -1 dB and +1 dB.

Which dynamic level corresponds to the preferred value proposed by scholars (about 79 dBA at the receiver)? To answer this question, the table 7 shows the SPL values simulated at three receivers, for each of three dynamics (*pp*, *mf*, *ff*). SPL values are simulated in occupied condition, while G values were simulated in unoccupied condition, according to ISO 3382 requirements.

The results of table 7 point out two important evidences. Firstly, the preferred sound pressure level corresponds to a *mezzo-forte* (*mf*) playing, as one might have predicted in a concert hall. Why, if the G is 3 dB louder in a IHOH, the preferred SPL at the receiver corresponds to a mid-dynamics? This is due to the difference between a early 19$^{\mathrm{th}}$ Century opera orchestra (less than 50 musicians) and a contemporary symphonic orchestra (more than 100 musicians). Secondly,

Table 6. Values of simulated G_M, $G_{125\,\mathrm{Hz}}$ and BAL considering the omnidirectional sound source in three positions: fore stage, centre stage and orchestra pit. Results are provided in unoccupied condition (ISO 3382) and for one receiver of each group: R10 in the middle of the stalls, R17 at the second tier of the boxes and R26 in the gallery. "M" subscript identifies the octave bands 500–1000 Hz.

Sound source	Position	Receiver	G_M (dB)	$G_{125\,\mathrm{Hz}}$ (dB)	BAL (dB)
Omni	Fore stage	R10 (stalls)	4.3	4.7	1.3
		R17 (boxes)	3.0	3.0	-0.6
		R26 (gallery)	3.7	2.9	0.4
	Centre stage	R10 (stalls)	3.4	4.0	0.4
		R17 (boxes)	2.5	3.0	-1.1
		R26 (gallery)	2.6	2.3	0.0
	Orchestra pit	R10 (stalls)	3.0	3.1	–
		R17 (boxes)	3.6	3.3	–
		R26 (gallery)	2.6	1.1	–

Table 7. Values of simulated $L_{p,A}$ and $L_{p,125\,\mathrm{Hz}}$ considering the virtual instruments in the orchestra pit for the three different levels of orchestra dynamics (*pp*, *mf*, *ff*). Results are provided in occupied condition and for one receiver of each group: R10 in the middle of the stalls, R17 at the second tier of the boxes and R26 in the gallery.

Sound source	Position	Dynamics	Receiver	$L_{p,A}$ (dB)	$L_{p,125\,\mathrm{Hz}}$ (dB)
Virt. orchestra	Pit	*pp*	R10 (stalls)	51.6	46.8
			R17 (boxes)	54.8	48.6
			R26 (gallery)	53.2	47.4
		mf	R10 (stalls)	78.0	73.3
			R17 (boxes)	80.7	74.6
			R26 (gallery)	79.3	73.7
		ff	R10 (stalls)	91.6	86.9
			R17 (boxes)	93.8	87.9
			R26 (gallery)	92.7	87.4

in occupied condition the SPL in the boxes is higher than the one in the stalls, even if G values was lower in unoccupied condition. The boxes show lowest EDT values and highest SPL values with respect to other regions of audience (stalls, gallery). It is surprising because in a Sabinian sound field and with equal volume, higher EDT values usually lead to lower G values. The sound field in the boxes, in occupied condition, reach high values of SPL. This may be due to the shape of the hall, the absorption of the audience and the directivity of the multiple sound sources.

Spatial impression

IACC is the most relevant factor in the Ando's subjective preference [22]. Beranek [7] and Cerda et al. [9] proposed the use of the *Binaural Quality Index* as spatial factor in their subjective preference approaches. Other authors used energy parameters, such LFC_{80}, J_{LFC4} [14]. Moreover, the integration limit of 80 ms was set for concert halls, while this threshold should be adapted to 50 ms due the statistical properties of the impulse responses measured [53].

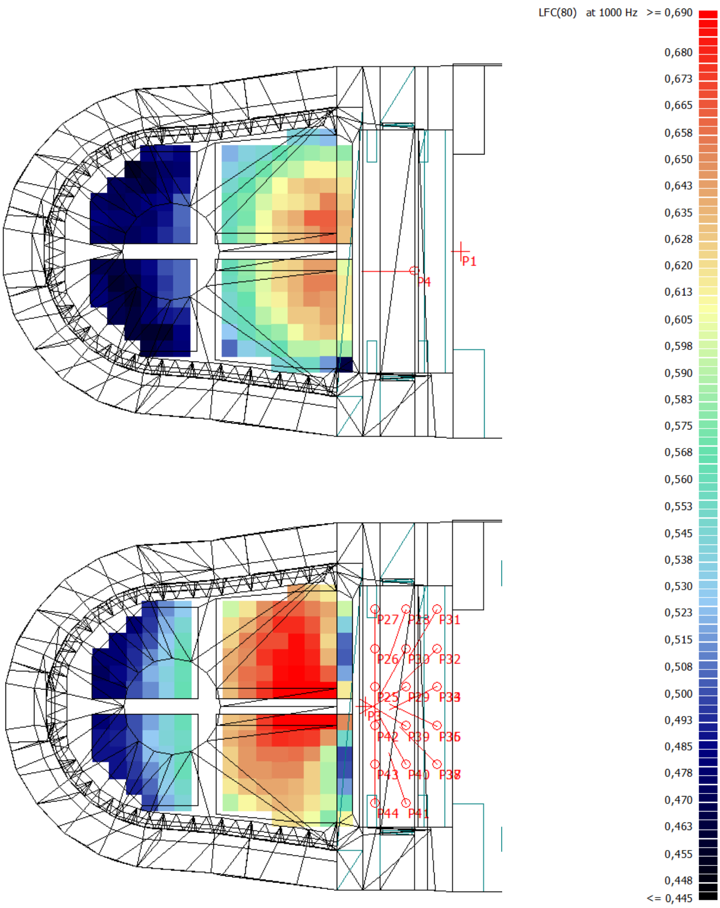


Figure 9. Maps of simulated LFC_{80} values. Comparison between the two kind of simulation: omnidirectional sound source (ISO 3382) in the pit (above) and virtual orchestra in the pit (below).

Beyond the choice of the suitable parameter, the spaciousness depends on the geometry of the hall and the surfaces of walls with respect to the positions of sources and receiver. IHOHs follow well established geometries and dimensional proportions [28]. Although these constant characteristics, architectural features and refurbishment choices may affect the measured values. It is important to spatially locate the singer and the orchestra. The first one does not have significant lateral reflections, also because of the directivity of the voice. Conversely, the orchestra in the pit has strong lateral reflections that allow to locate the orchestra sound. Measured values of spatial criteria from literature are uncompleted and often unclear [27]. Different equipments may return different measurement results. This is more evident for the spatial criteria than the monaural ones. The model of dummy head – or the directivity of the figure-of-eight microphone – may influence the measurement results. These uncertainties may be reduced using numerical simulation, e.g. fixing a common BRIR dataset.

While the singer can be simulated through a single-point sound source with his own directivity [36], the orchestra needs some further considerations. The width of the orchestra is not negligible, because it is comparable (or higher, in part of the stalls) to the source-receiver distance. The effect of the multi-point orchestra is shown in fig. 9. Two maps of simulated values of LFC_{80} were plotted: the first one placing a single-point sound source (omni) in the pit; the second one using a multi-point sound source, each virtual instrument having its own directivity.

LFC_{80} was chosen as spaciousness criterion to compare the spatial impression of a single omnidirectional sound source in the orchestra pit and 42 virtual musicians. Using the omni-sound source instead of the whole orchestra can underestimate the distribution of the room criterion (see fig. 9).

Other factors (Intimacy and Diffusivity)

ITDG was proposed by Beranek to quantify the *Intimacy* and was taken into account in almost all subjective preference models. Since several scholars agree in defining this criterion as historically outdated [3], it was not thoroughly analysed in the present study, even if it can be useful to point out some remarks. TCBO, as other IHOHS, was built in order to provide a private box to several funders. The intimacy of the box is assured by the limited volume (about 8 m^3). The listeners in a box may choose to enjoy the opera seating in the box or leaning toward the main hall. In the first case the first reflection is provided by the walls of the box, in the second case the first reflection is due to the cavea. According to [4] in the first case the reflection produces intimacy, while in the second coloration effects. At the same time, the gallery enabled the lower classes to go to the opera but the listening experience was doomed by the presence of the ceiling near the seats, the lack of visual, and often the absence of the direct sound contirbution. In these conditions ITDG calculation may be meaningless. In the stalls the first reflection comes from the side walls, or to the side of the proscenium arch. In the backward of the cavea the first reflections may be due to the rear surfaces, but in these cases the angle of these reflections is out of the range proposed by Ando [22]. However, taking into account only the mere numerical value, the dimensions of TCBO and the proportion between width and length of the hall assures a first reflection within the first 20 ms [7], so that ITDG may be partially neglected for the purpose of ranking in this work.

Concerning the diffusivity, several features may be assessed: the decorations and bas-reliefs in the main hall, the columns of the boxes, the smoothness of the low side walls and the irregularity of the ceiling. TCBO is characterised by a very absorbing surfaces in the stalls area (seats), a very reflecting surface at the height of the listeners' ears (plaster made of marble powder and slaked lime, called *marmorino*) and by the presence of boxes. Previous studies assign a SDI value of 0.7 to Paisiello Theatre in Lecce and Piccinini Theatre in Bari [17], and thus the same value may be considered for TCBO.

Conclusions

The present work proposes the use of acoustic simulation to evaluate the subjective perception of a listener in an opera house which was carefully calibrated through in-situ measurements. The work introduces the use of an orchestra of virtual sound sources in addition to the omni-directional sound source. Numerical simulations were done applying both the approaches. To answer the initial question, the results confirm the correspondence between social division and different acoustic comfort. The boxes show the best results, in terms of ISO 3382 room criteria considered in subjective preference methods. Moreover, also results with virtual orchestra confirmed and enhanced the difference between the boxes and the other region of audience (stalls, gallery). Due to poor dataset and the difficulty to collect the requested criteria through in-situ measurements (e.g. the occupied condition), the simulation results can contribute to improve this research field of subjective acoustic attributes. For this reason, the virtual model, the measured and simulated IRs are fully available to researchers and technicians in a repository[54].

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References

[1] Knudsen VO. The hearing of speech in auditoriums. *J Acoust Soc Am* 1929; 1(1): 56–82.

[2] MacNair WA. Optimum reverberation time for auditoriums. *J Acoust Soc Am* 1930; 1: 242–248.

[3] Hyde JR. Discussion of the relation between Initial Time Delay Gap (ITDG) and acoustical intimacy: Leo Beranek's final thoughts on the subject, documented. *Acoustics* 2019; 1(3): 561–569.

[4] Barron M. The subjective effects of first reflections in concert halls? The need for lateral reflections. *J Sound Vib* 1971; 15(4): 475–494.

[5] Schroeder MR, Gottlob D and Siebrasse KF. Comparative study of European concert halls: correlation of subjective preference with geometric and acoustic parameters. *J Acoust Soc Am* 1974; 56: 1195–1201.

[6] Ando Y. Calculation of subjective preference at each seat in a concert hall. *J Acoust Soc Am* 1983; 74(3): 873–887.

[7] Beranek LL. Subjective rank-orderings and acoustical measurements for fifty-eight concert halls. *Acta Acust united Ac* 2003; 89: 494–508.

[8] Giménez A and Marín A. Analysis and assessment of concert halls. *Appl Acoust* 1988; 25(4): 235–241.

[9] Cerdá S, Giménez A, Romero J, Cibrián R and Miralles JL. Room acoustical parameters: a factor analysis approach. *Appl Acoust* 2009; 70: 97–109.

[10] Cerdá S, Giménez A, Romero J and Cibrian RM. A factor analysis approach to determining a small number of parameters for characterizing halls. *Acta Acust united Ac* 2011; 97(3): 441–452.

[11] Cerdá S, Giménez A and Cibrián R. An objective scheme for ranking halls and obtaining criteria for improvements and design. *J Audio Eng Soc* 2012; 60: 419–430.

[12] Frongillo R and Kash IA. Elicitation complexity of statistical properties. arXiv preprint arXiv 2015; 1506.07212.

[13] Lokki T, Pätynen J, Kuusinen A, Vertanen H and Tervo S. Concert hall acoustics assessment with individually elicited attributes. *J Acoust Soc Am* 2011; 130(2): 835–849.

[14] Giménez A, Cibrián RM, Cerdá S, Girón S and Zamarreno T. Mismatches between objective parameters and measured perception assessment in room acoustics: A holistic approach. *Build Environ* 2014; 74: 119-131.

[15] Kuusinen A and Lokki T. Wheel of concert hall acoustics. *Acta Acust united Ac* 2017; 103(2): 185–188. DOI: https://doi.org/10.3813/AAA.919046.

[16] Zacharov N. *Sensory Evaluation of Sound*. CRC Press, 2018.

[17] Cirillo E, Dell'Alba M and Martellotta F. Acoustic survey of historical Apulian theatres (in Italian). In: *Proc of 38th Meeting of Italian Acoustic Association*, Rimini, Italy, 8–10 June 2011.

[18] Sakai H, Ando Y, Prodi N and Pompoli R. Temporal and spatial acoustical factors for listeners in the boxes of historical opera theatres. *J Sound Vib* 2002; 258(3): 527–547.

[19] Prodi N and Velecka S. A scale value for the balance inside an historical opera house. *J Acoust Soc Am* 2005; 117(2): 771–779.

[20] Sato S, Prodi N and Pompoli R. Subjective evaluation of the perceived balance between a singer and a piano inside different theatres. *Acta Acust united Ac* 2012; 98: 749–759.

[21] Sato S, Prodi N and Pompoli R. Acoustic parameters affecting the perceived balance between sound sources located on the stage and in the orchestra pit in opera theatres. In: *Proc 22nd ICSV*, Florence, Italy, 12–16 July 2015.

[22] Ando Y. *Opera house acoustics based on subjective preference theory.* Springer, 2015.

[23] D'Orazio D and Nannini S. Towards Italian Opera Houses: a Review of Acoustic Design in Pre-Sabine Scholars. *Acoustics* 2019; 1: 252–280.

[24] D'Orazio D, De Cesaris S, Morandi F and Garai M. The aesthetics of the Bayreuth Festspielhaus explained by means of acoustic measurements and simulations. *J Cult Herit* 2018; 34: 151–158.

[25] D'Orazio D, Rovigatti A and Garai M. The proscenium of opera houses as a disappeared intangible heritage: a virtual reconstruction of the 1840s original design of the Alighieri Theatre in Ravenna. *Acoustics* 2019; 1(3): 694–710.

[26] Farina A. Acoustic quality of theatres: correlations between experimental measures and subjective evaluations. *Appl Acoust* 2001; 62: 899–916.

[27] Prodi N, Pompoli R, Martellotta F and Sato S. Acoustics of Italian Historical Opera Houses. *J Acoust Soc Am* 2015; 138(2): 769–781.

[28] Garai M, Morandi F, D'Orazio D, De Cesaris S and Loreti L. Acoustic measurements in eleven Italian opera houses: correlations between room criteria and considerations on the local evolution of a typology. *Build Environ* 2015; 94: 900-912. DOI: https://doi.org/10.1016/j.buildenv.2015.07.026.

[29] Weinzierl S, Sanvito P, Schultz F and Büttner C. The acoustics of renaissance theatres in Italy. *Acta Acust united Ac* 2015; 101: 632–641. DOI: https://doi.org/10.3813/AAA.918858.

[30] D'Orazio D, De Cesaris S and Garai M. A comparison of methods to compute the "effective duration" of the autocorrelation function and an alternative proposal. *J Acoust Soc Am* 2011; 130(4): 1954–1961.

[31] D'Orazio D and Garai M. The autocorrelation-based analysis as a tool of sound perception in a reverberant field. *Rivista di Estetica* 2017; 66(3): 133–147.

[32] D'Orazio D, De Cesaris S and Garai M. Recordings of Italian opera orchestra and soloists in a silent room. In: *Proc of Meetings on Acoustics*, Buenos Aires, Argentina, 05–09 September 2016, Vol. 28, N. 015014, p. 1. DOI: http://dx.doi.org/10.1121/2.0000425.

[33] D'Orazio, D. Anechoic recordings of Italian opera played by orchestra, choir, and soloists, *J Acoust Soc Am*, 147(2), EL157-EL163.

[34] Jeon JY, Kim YH, Cabrera D and Bassett J. The effect of visual and auditory cues on seat preference in an opera theater. *J Acoust Soc Am* 2008; 123(6): 4272–4282.

[35] ISO 3382-1:2009. Acoustics - Measurement of room acoustic parameters. Part 1: Performance spaces.

[36] Parati L, Prodi N and Pompoli R. Computer model investigations on the balance between stage and pit sources in opera houses. *Appl Acoust* 2007; 68(10): 1156–1176.

[37] Vigeant MC, Wang LM and Rindel JH. Investigations of orchestra auralizations using the multi-channel multisource auralization technique. *Acta Acust united Ac*, 2008; 94: 866–882. DOI: https://doi.org/10.3813/AAA.918105.

[38] Guidorzi P, Barbaresi L, D'Orazio D and Garai M. Impulse responses measured with MLS or Swept–Sine signals applied to architectural acoustics: an in-depth analysis of the two methods and some case studies of measurements inside theaters. *Energy Procedia* 2015; 78: 1611–1616.

[39] D'Orazio D, Cesaris S, Guidorzi P, Barbaresi L, Garai M and Magalotti R. Room acoustic measurements using a high SPL. In: *Proc 140th AES*, Paris, France, 4–7 June 2016.

[40] Pompoli R and Prodi N. Guidelines for acoustical measurements inside historical opera houses: procedures and validation. *J Sound Vib* 2000; 232: 281–301.

[41] Jeon JY, Kim JH and Ryu JK. The effects of stage absorption on reverberation times in opera house seating areas. *J Acoust Soc Am* 2015; 137(3): 1099-1107.

[42] Beranek LL. Analysis of Sabine and Eyring equations and their application to concert hall audience and chair absorption. *J Acoust Soc Am* 2006; 120(3): 1399–1410.

[43] ODEON Room Acoustics Software v.12, Auditorium and Combined edition, 2010. URL: http://www.odeon.dk.

[44] Vorländer M. *Auralization: Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality*. Springer, 2007.

[45] Kim YH, Lee HM, Seo CK and Jeon JY. Investigating the absorption characteristics of open ceilings in multi-purpose halls using a 1:25 scale model. *Appl Acoust* 2010; 71(5): 473-478.

[46] Postma BNJ and Katz BFG. Perceptive and objective evaluation of calibrated room acoustic simulation auralizations. *J Acous Soc Am* 2016; 140. DOI: http://dx.doi.org/10.1121/1.4971422.

[47] Jeon JY, Jang HS and Jo HI. Acoustic evaluation of orchestra occupancies in concert halls: Effect of sound absorption by orchestra members on audience acoustics. *Build Environ* 2018; 143(1): 349–357.

[48] Shtrepi L, Astolfi A, D'Antonio G, Vannelli G, Barbato G, Mauro S and Prato A. Accuracy of the random-incidence scattering coefficient measurement. *Appl Acoust* 2016; 106: 23–35.

[49] Shtrepi L. Investigation on the diffusive surface modeling detail in geometrical acoustics based simulations. *J Acoust Soc Am* 2019; 145(3): EL215–EL221.

[50] Lokki T and Pätynen J. Applying anechoic recordings in auralization. In: *Proc. EAA Symposium on Auralization*, Espoo, Finland, 15–17 June 2009.

[51] Meyer J. *Acoustics and the performance of music - Manual for acousticians, audio engineers, musicians, architects and musical instrument makers*, Springer, 2009.

[52] Xiang N, Goggans P, Jasa T and Robinson P. Bayesian characterization of multiple-slope sound energy decays in coupled-volume systems. *J Acoust Soc Am* 2011; 129(2): 741-752.

[53] De Cesaris S, Morandi F, Loreti L, D'Orazio D and Garai M. Notes about the early to late transition in Italian theatres. In: *Proc* 22^{nd} *ICSV*, Florence, Italy, 12–16 July 2015.

[54] D'Orazio D and Fratoni G. TCBO CAD and measured IRs, Mendeley Data, V1, 2019. DOI: 10.17632/ggty3v22cx