Acoustics of Italian Historical Opera Houses

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ABSTRACT

Opera houses represent a large group of performance spaces characterized by great complexity and, at the same time, versatility with respect to different usage (from opera to symphonic music and ballet). This kind of building originated in Italy during the 17th century and later spread across the country and then Europe and the rest of the world, slowly evolving into modern theatre shapes. As a consequence of the changes undergone by the interior space, the original acoustic features, which likely influenced many composers, experienced important variations. Thanks to acoustic measurement campaigns inside Italian Historical Opera Houses, promoted by National and Regional Projects, the distinctive features of these spaces were investigated in comparison to modern spaces. In this work the newly acquired data are merged with data in the literature in order to present and discuss some of the distinctive acoustic features of historical spaces as regards their original function. Moreover specific issues such as listening in stalls and boxes and the criteria governing the preference judgment of listeners are considered. The concept and the crucial role of the balance between stage and pit sources is also discussed by means of previous literature studies.

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I. INTRODUCTION

Opera Houses appeared in Italy in the XVII century, their earliest public example being the theatre of San Cassiano in Venice built in 1637, and soon became the most widespread and established theatre venues. Their design concepts were kept, with relatively minor modifications, for 250 years contributing to the creation of a set of buildings now commonly identified as Italian-style Historical Opera Houses. The audience side of these opera houses can be divided into stalls, boxes and gallery. The first is a flat surface with mild slope and with dense seating arrangement. Its plan shape was gradually shifted from the former U-shape to bell shape, semi-elliptic and finally to horseshoe shape. The boxes are sub-volumes partially opened to the main hall volume, they are arranged in tiers and are stacked up along the stalls perimeter so that they enclose the main hall volume. Boxes are usually surmounted by an open gallery which is in close proximity to the hall ceiling. The performer side consists basically of a wide stage where the vocal sources and scenery are usually located, and of an orchestra pit, which is a narrow area between the stalls and the stage, with the latter often covering part of the pit by means of an overhang. Stalls and pit are separated by a blind wooden balustrade, but an open transparent rail can also be found. Figure 1 shows a view from the pit in a typical historical opera house.

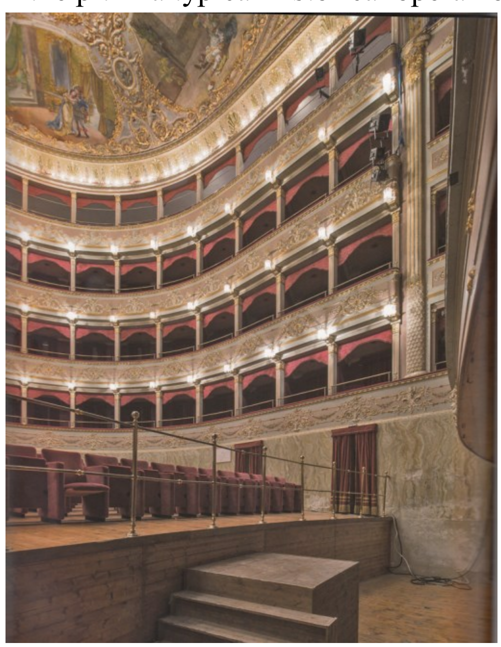

Figure 1 – (Color online) View of a typical historical opera house from the pit (transparent rail). The various parts can be discerned ("Filippo Marchetti" Theatre in Camerino, PU), [picture courtesy of Minerva Soluzioni Editoriali, Bologna].

While also being exported to many European cities, the Italian-style theatre became the reference for many national performance spaces, both large and small. For the whole of Italy, one can estimate that there are more than 800 theatres still actively in use, with auditorium volumes between 1000 m^3 and 10000 m^3. During the 1990s two main events, the fires of Teatro “Petruzzelli” (Bari) in 1991 and of Teatro “La Fenice” (Venezia) in 1996, raised the question of safeguarding the acoustic heritage of historical opera houses. Committed actions were promoted and especially two International Conferences (“Acoustics as a Cultural Heritage” at Teatro Regio in Turin on October 16th 1996 and “Acoustics of Historical Opera Houses: a cultural heritage” at Teatro Comunale in Ferrara on November 8th 1998) focused on the topic and provided the background for several investigations and safeguarding activities. In particular guidelines to standardize acoustic measurements inside historical opera houses were developed with the aid of a panel of experts[1,2]. In the following years, a measurement campaign was promoted in the frame of the National Interest Research Project (PRIN)[3]. More recently, the above data were disseminated both with reference to single venues and to the whole set of data[4]. Measurement data collected during the PRIN project was later merged with a consistent data set collected in 23 Apulian theatres (with about half of them belonging to the historical opera house group)[5] and lastly with data from various literature, which is mainly in Italian language[6-21]. The data gathered so far comes from 50 historical opera houses and the possible general information to be extracted from them is one of the concerns of the present work. In fact, while a global view on the acoustics of International opera houses both modern and traditional was elaborated in the past[22], a specific similar work for Italian historical opera theatres is still lacking.

During the past years, two review works, respectively published in 2002[23] and in 1998[24], started to report on the acoustics of these spaces. The former discussed some of the prominent acoustic features (such as listening conditions in the boxes, focusing effects in the back of the stalls, coupling with the stage-tower) but lacked a comprehensive set of data to outline the typical trends of objective parameters. The latter work was a unique historical review of the design concepts implemented over the centuries.

After these contributions new research work was performed since the year 2000 and some open issues were addressed. In particular new information was achieved on the characteristic of listening conditions at different places (stalls, boxes, and gallery)[25-27], on the interplay of stage and pit sources[28-31] and on the relationship of stage-house, stage set and main hall[32-34].

The present work is arranged as follows. Firstly the available data is combined and analyzed to extract some reference figures suitable for describing the acoustics of historical opera houses (Sec. II). These results are then compared with equivalent values in modern opera houses (Sec. III). Secondly the findings on specific issues are reviewed and discussed, that is how listening can be described in the different seating areas (Sec. IV), the assessment of subjective preference of listeners (Sec. V) and finally the problem of balance between pit and stage and the implications it has in view of qualification and design (Sec. VI) .

II. COLLECTING AND REVISING PRIMARY DATA

Collecting data from different sources is not always easy, because, despite the existence of international standards[35] and specific guidelines[2], having comparable results depends on many factors such as source and receiver placement, or state of the stage-house.

All the data reported here was measured in unoccupied spaces with an omni-directional source placed on the forestage. In most cases the source was located according to Ref. 2, 2 m behind the line of the fire-curtain and 1 m off the symmetry axis, but small variations were observed in a limited number of cases.

One of the features that is very difficult to control but that is likely to affect results is the condition of the stage-house. The stage-house has a volume comparable to the main hall and thus may easily change the response of the system due to acoustic coupling. In fact, even though a standardized preparation was suggested in Ref. 2, it may happen that access to the theatre is granted during the regular season, when proper scenery is on the stage. Conversely, it may also happen that the stage-house is free of any curtains and draperies during the measurements. Similar variations were observed also during the more structured PRIN campaign, in which nine different teams were involved. In addition, the literature is not always clear about the stage-house condition at the time of the measurements. After the collection of supplementary information from the authors, whenever possible, and after investigating on the available visual and numerical evidences, the 50 theatres were grouped into two sub-sets. Group A (Table I, including theatres ID for quicker reference), included 14 theatres with empty stage (or only partial draperies), or unusually large stage-house compared to main hall (PA, and PG), or, finally, large hard reflecting surfaces (FI, CS, VR, SS, LU, and ND). These three characteristics of Group A theatres were all expected to produce an increase of reverberation time, so that Group A could be regarded as the group setting the upper reverberation limit. On the other hand Group B (Table II) included "regular" theatres having the stage-house set with a typical area of draperies or with a sound absorbing opera scenery. Unfortunately, such subdivision could not rely on an exact quantitative description, but at least was able to explain specific trends, as described below. Two theatres (FE and RO) were measured with both empty and full stage set, so they appear in both Groups. A simple comparison between the reverberation time T30 and the early decay time EDT values can immediately show the influence of the stage-house on the final results.

Table I: Primary data for the theatres in Group A. *) theatres belonging to PRIN dataset; †) theatres belonging to Apulian dataset. Subscripts "M" and "3" mean that average is calculated, respectively, over 500 and 1000 Hz, and over 500, 1000, and 2000 Hz octave bands. Subscript "E" refers to 0-80 ms interval. V is the hall volume (without stage-house), and N is the seating capacity.

ID	*Name, Location*	$T30_M$ [s]	EDT_M [s]	*BR*	$C80_3$ [dB]	G_M [dB]	$IACC_{E3}$	*ITDG* [ms]	*V* [m³]	*N*	*V/N* [m³]
PA	Massimo, Palermo	1.65	1.52	-	1.6	-	-	-	12000	2228	5.4
FI	Verdi, Florence	1.57	1.42	-	1.9	-	0.33	13	10950	1538	7.1
RM	Opera, Rome*	1.63	1.56	1.35	1.4	1.0	-	-	10000	1500	6.7
CT	Massimo Bellini, Catania	1.54	1.28	-	1.7	-	-	-	10000	1359	7.4
SS	Verdi, San Severo†	1.96	1.79	1.46	2.2	9.9	0.35	23	6900	590	11.7
VE	La Fenice, Venice*	1.60	1.45	1.18	0.8	-	0.52	-	6800	1000	6.8
VR	Filarmonico, Verona	1.70	1.50	-	-	-	-	-	6500	1200	5.4
RE	R.Valli, Reggio Emilia*	1.52	1.36	1.26	4	-	0.61	-	6200	1136	5.5
PI	Verdi, Pisa	1.92	1.70	1.23	-	-	-	-	6000	888	6.8
BO	Comunale, Bologna*	1.63	1.61	1.18	0.4	-0.1	0.18	14	5500	1006	5.5
CS	Regina Margherita, Caltanissetta	1.43	1.44	-	1.1	-	-	-	4962	340	14.6
FEa	C. Abbado, Ferrara*	1.40	1.20	1.20	1.7	-	-	-	4500	990	4.5
MO	L. Pavarotti, Modena*	1.55	1.35	1.23	1.7	6.4	0.30	-	4500	900	5.0
FC	A. Bonci, Cesena*	1.48	1.20	1.38	5.5	3.0	-	-	3422	798	4.3
PG	F. Morlacchi, Perugia	1.65	1.63	1.32	1.4	2.5	0.68	-	3112	785	4.0
SP	Nuovo, Spoleto	1.55	1.42	1.22	1.9	3.8	0.71	-	3000	800	3.8
ROa	R. Zandonai, Rovereto	1.65	1.49	1.00	-	-	-	-	2970	550	5.4
NA2	Mercadante, Napoli*	1.40	1.02	1.25	5.5	-	-	-	2900	553	5.2
BC	Goldoni, Bagnacavallo	1.49	1.20	1.56	1.0	-	-	-	1600	390	4.1
ND	Comunale, Nardò†	1.60	1.17	1.42	5.1	8.1	0.32	10	1505	200	7.5
LU	Garibaldi, Lucera†	1.30	1.07	1.27	4.6	10.3	0.32	13	1320	264	5.0
BU	Francesco di Bartolo, Buti	1.36	1.10	1.15	-	-	-	-	900	236	3.8

The main acoustic data given in Tables I and II (for Groups A and B respectively) are multi-octave averages (where subscripts "M" and "3" refer to average values calculated, respectively, over 500 and 1000 Hz, and over 500, 1000, and 2000 Hz octave bands), further averaged across receiver combinations. Apart from reverberation times, the other acoustic quantities are not always available. This implied that only the most populated data sets could be used for a significant statistical analysis in order to have sufficient number of variables in the observations. Consequently, the initial time delay gap ITDG, that is the time interval (in milliseconds) between the arrival of the direct sound and that of the first reflection, and the interaural cross-correlation $IACC_{E3}$ could not be considered, whilst the sound strength G_M was used only for Group B.

Table II: Primary data for the theatres in Group B. *) theatres belonging to PRIN dataset; †) theatres belonging to Apulian dataset. Subscripts "M" and "3" mean that average is calculated, respectively, over 500 and 1000 Hz, and over 500, 1000, and 2000 Hz octave bands. Subscript "E" refers to 0-80 ms interval. V is the hall volume (without stage-house), and N is the seating capacity.

ID	*Name, Location*	$T30_M$ [s]	EDT_M [s]	*BR*	$C80_3$ [dB]	G_M [dB]	$IACC_{E3}$	*ITDG* [ms]	*V* [m^3]	*N*	*V/N* [m^3]
N1	San Carlo, Naples*	1.15	1.08	1.81	2.4	0.5	-	-	13700	1414	9.7
MI	La Scala, Milan*	1.25	1.20	1.17	1.6	-2.0	0.22	21	11200	2015	5.6
FI2	"La Pergola", Florence	1.25	1.26	-	0.8	-	0.17	16	7500	950	7.9
TS	Verdi, Trieste*	1.07	0.99	1.14	3.3	-	0.36	-	7200	1300	5.5
BS	Grande, Brescia*	1.05	0.95	1.05	4.1	1.3	-	-	6500	900	7.2
PD	Verdi, Padova	0.91	1.01	-	3.1	-	-	-	5500	700	7.9
BA	Piccinni, Bari*,†	1.11	1.09	1.30	3.3	2.2	0.45	10	5400	700	7.7
CO	Sociale, Como*	1.04	0.92	1.15	5.3	4.7	0.43	-	5000	900	5.6
PR	Regio, Parma*	1.08	1.07	1.22	2.5	3.0	0.67	-	5000	1200	4.2
PV	Fraschini, Pavia*	1.30	1.16	1.15	6.0	1.4	0.42	-	4980	780	6.4
BN	Comunale, Benevento	1.10	0.83	-	6.5	-	-	-	4907	400	12.3
PG2	del Pavone, Perugia	1.11	1.01	1.52	4.9	7.4	0.54	-	4725	530	8.9
TV	Comunale, Treviso	1.05	1.05	1.27	2.8	-	0.44	-	4660	810	5.8
SA	Verdi, Salerno*	1.07	0.96	1.20	5.2	4.1	-	-	4500	610	7.4
FEb	C. Abbado, Ferrara*	1.02	0.93	1.35	3.0	5.0	-	-	4500	990	4.5
TN	Sociale, Trento	1.20	1.26	-	2.9	-	-	-	4500	642	7.0
RC	Siracusa, Reggio Calabria	1.18	1.32	1.41	2.4	-	-	-	4441	400	11.1
PS	G. Rossini, Pesaro	1.03	0.96	1.39	5.5	-	-	-	4000	872	4.6
AT	Alfieri, Asti*	1.00	0.90	1.13	5.3	3.4	-	-	4000	750	5.3
CV	Accademia, Castelf. Veneto	1.17	1.01	-	4.2	-	-	-	4000	900	4.4
BR	Curci, Barletta†	1.11	1.03	1.09	5.1	4.5	0.38	15	3900	495	7.9
ROb	R. Zandonai, Rovereto	1.22	1.15	1.06	2.5	6.5	0.85	14	2970	550	6.4
SC	Civico, Schio	1.30	1.08	1.08	0.9	-	-	-	3400	563	6.0
RV	Sociale, Rovigo	1.18	1.06	1.38	4.3	-	0.46	-	3351	886	3.8
BI	Traetta, Bitonto†	1.15	0.95	1.57	6.0	12.7	0.37	17	1925	246	7.8
LE	Paisiello, Lecce*,†	0.92	0.85	1.26	5.6	8.8	0.30	20	1680	304	5.5
NV	Comunale, Novoli†	1.20	1.20	1.19	3.1	10.7	0.35	13	1485	186	8.0
GA	Garibaldi, Gallipoli†	1.19	1.07	1.18	4.2	10.9	0.32	14	1020	175	5.8
VI	Sociale, Villastrada	1.05	0.96	1.30	4.5	8.5	-	5	900	264	3.4
MB	Van Vesterhout, Mola di Bari†	0.77	0.78	1.51	7.0	13.4	0.35	20	810	186	4.4

Figure 2 shows that a linear regression between volume and number of seats fits the data quite well (R^2 = 0.74, highly significant). Three intervals are identified with reference to opera house volume: smaller than 3000 m^3, between 3000 and 8000 m^3, and equal to or bigger than 10000 m^3. Most auditoriums fall in the intermediate range, with the highest concentration for those halls accommodating 800 to 1000 people. The average volume per person is 6.0 m^3 with a standard deviation of 1.6 m^3. A few outliers appear in the plot, corresponding to theatres with a strangely lower seating capacity compared to volume (e.g. SS, NA1), usually resulting from application of fire protection regulations which require the number of seats be proportionate to openings for exit and that the seating blocks be at an appropriate distance from walls to allow for sufficiently wide aisles.

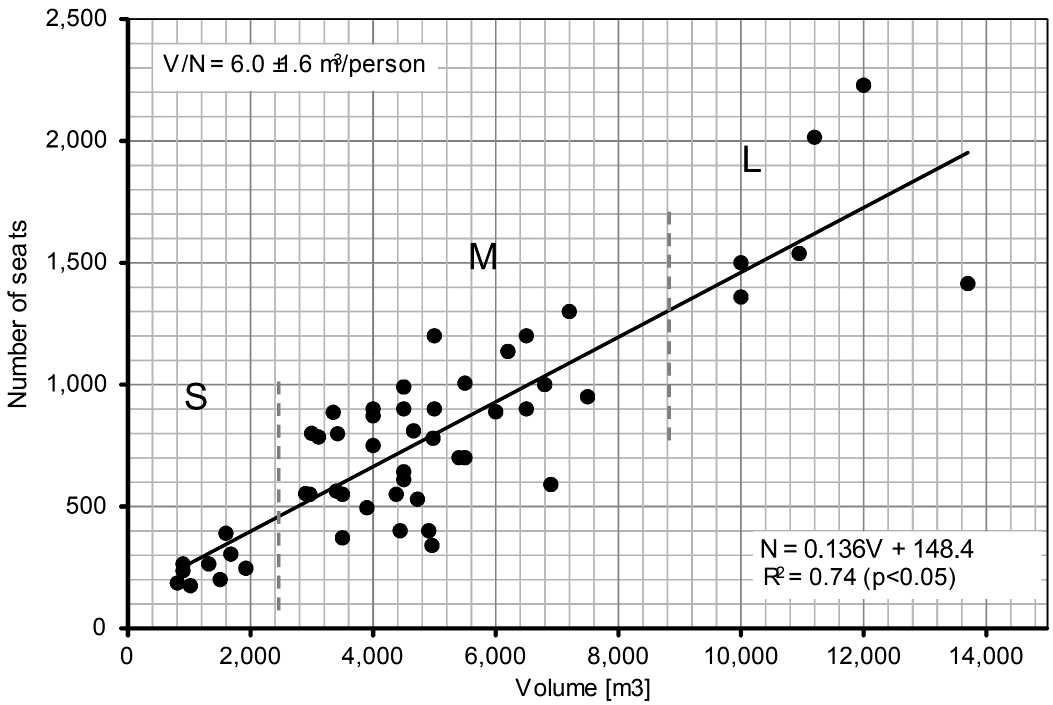

Figure 2 – (Color online) Plot of seating capacity as function of volume in the historical opera house (whole sample) with a subdivision into small (V < 3000 m^3), medium (3000 m^3 < V < 8000 m^3) and large halls (V > 8000 m^3).

III. OUTLINE OF ACOUSTIC PARAMETERS

A. Reverberation time

Figure 3 shows the reverberation time $T30_M$ (that is the average of 500 and 1000Hz values) as a function of volume for the two subsets (Groups A and B). Each group can be separately described with a proper regression, and both of them, despite a modest R^2, are significant from the statistical point of view (as shown by *p*-values reported in the caption).

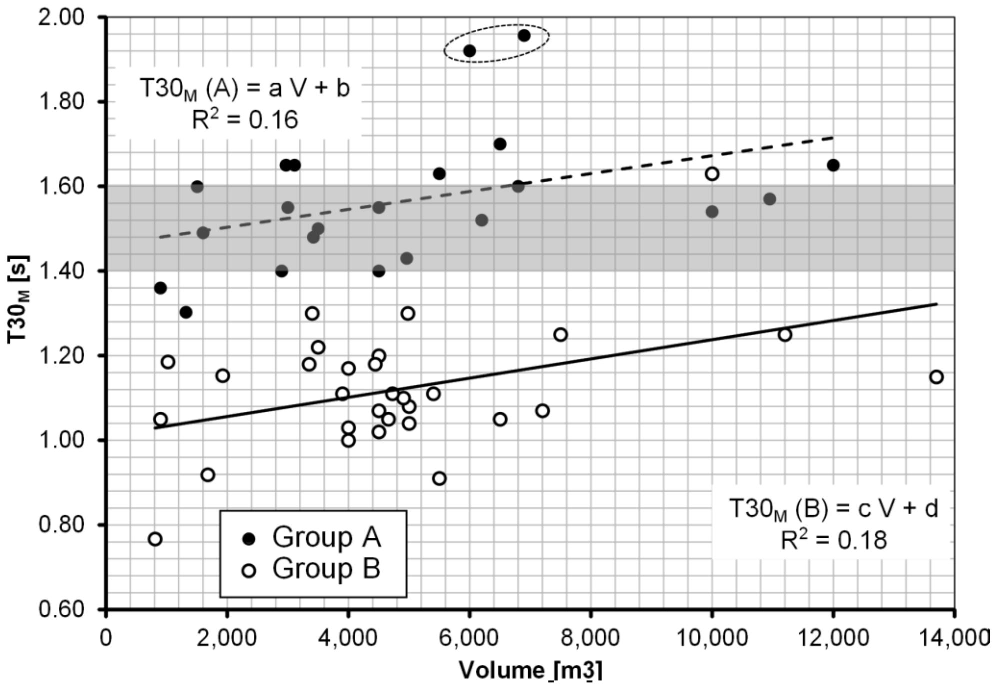

Figure 3 – Plot of reverberation time (T30$_M$) at mid frequencies (500Hz and 1000 Hz) for the two groups. The values of the regression coefficients are a=2.01×10^{-5} (p=0.049) and b=1.46 ($p<10^{-5}$) for group A and c=2.26×10^{-5} (p=0.018) and d=1.01 ($p<10^{-5}$) for group B. The shaded area corresponds to the preferred range according to Hidaka and Beranek[22].

As expected, considering how the groups were composed, theatres in Group A are more reverberant, but the slopes of the regressions are very similar, suggesting a comparable relationship with the room volume. Two outliers appear at the top, representing SS and PI. For the first one, large concrete surfaces finished in plaster (the theatre was completed in 1937), combined with a significant reduction of seating capacity may explain the odd behavior. Figure 3 also shows the "suggested" range of mid frequency reverberation times indicated in the Hidaka and Beranek survey[22] (full absorbing scenery). One can see that theatres in Group B only rarely fit into the suggested range, while quite a few theatres in Group A with empty or lightly furnished stage houses do have the suggested reverberation times

Thus, "regular" historical opera houses appear "dry" compared to more modern opera houses on which Hidaka and Beranek interval is based.

In terms of spectral variation of reverberation time, analyzed theatres showed a clear increase in the low frequency range (in 125 and 250 Hz octave bands), which is one of the key features of traditional theatres. Such behavior is usually the result of extensive mid- and high frequency absorbing finishes and on the layout and impact of the boxes (see Sec. IV). Taking into account bass ratio (BR), meant as the ratio of the reverberation times at low frequencies (125 and 250 Hz octave bands) to those at mid-frequencies (500 and 1000 Hz octave bands), no statistically significant correlation with other acoustic parameters was found. However, the grand average value of BR was found close to 1.3 (in unoccupied conditions), with values ranging from 1.0 to 1.8. The bass ratios given in Ref. 22 are in the range from 1.07 to 1.32 and their grand average is 1.21. Even though they refer to occupied conditions, as well as the recommended values (BR > 1.05), the presence of an audience is unlikely to change the ratio in a significant way, so it can be concluded that traditional theatres tend to be acoustically "warmer" than modern ones.

B. Early decay time

When mean mid-frequency early decay times (EDT_M) are compared with reverberation times measured in the same space ($T30_M$), an average reduction of 13% (Group A) and 6% (Group B) is observed. Such decreases are not unusual in performance spaces and are likely to be due to the high absorption located in the audience area and also to the coupling phenomena of main hall and fly-tower. It is to be remarked that in historical opera houses the stage-house very rarely has fixed sound absorbing treatment, which is more common in modern opera theatres.

Since Hidaka and Beranek[22] give unoccupied EDT values for 23 houses, most of them built according to modern criteria (e.g. with balconies in place of boxes, larger seat spacing), it is interesting to compare their acoustics with that of historical ones. In order to increase the significance of the comparisons, theatres belonging to the Hidaka and Beranek sample having typical traditional features were removed from that data-set, while data from modern Italian theatres were included. Theaters removed were Milan La Scala (already included in Table II), Budapest Staatsoper, Paris Opera Garnier, and Vienna Staatsoper, while theaters added are listed in Table III.

Taking advantage of the new data, EDT_M values were plotted as a function of room volume (Fig. 4). Results show that modern theatres stand clearly apart from both sets related to historical opera houses. In particular, modern theatres have larger volumes and higher seating capacity, showing a steeper EDT_M variation as a function of volume, also resulting from the larger range of EDT_M values observed (from 0.6 to 2.5 s). Conversely, traditional theatres show a much milder slope (particularly those belonging to Group B), resulting from a significant increase in absorption when volume grows. Such behavior may likely be explained by the presence of boxes that increase the exposed absorbing area without affecting the volume, thus contributing to lower the mean-free-path and changing its distribution[36]. In addition, use of velvet curtains, tapestries, and carvings is also likely to increase the absorption coefficients of surfaces compared to modern theatres.

Table III: Primary data for Italian modern theatres. †) theatres belonging to Apulian dataset. Subscripts "M" and "3" mean that average is calculated, respectively, over 500 and 1000 Hz, and over 500, 1000, and 2000 Hz octave bands. Subscript "E" refers to 0 - 80 ms interval. V is the hall volume (without stage-house), and N is the seating capacity.

ID	*Name, Location*	EDT_M [s]	$C80_3$ [dB]	G_M [dB]	$IACC_{E3}$	*ITDG* [ms]	*V* [m^3]	*N*	*V/N* [m^3]	*Stage Set*
CA	Cagliari,Opera	1.50	3.0	2.2	-	-	14500	1635	8.9	-
BR	Verdi, Brindisi†	1.41	3.1	5.0	0.45	28	11000	1172	9.4	y
CO	Comunale, Corato†	1.43	1.9	5.4	0.31	28	4500	560	8.0	y
BC	Garibaldi, Bisceglie†	1.03	3.3	10.6	0.36	13	3360	404	8.3	y
CR	Mercadante, Cerignola†	0.63	8.3	2.7	0.38	15	2900	432	6.7	-
GI	Comunale, Gradisca d'Isonzo	1.40	2.4	-	-	-	3500	371	9.4	-
AR	Arcimboldi, Milano	1.75	0.0	2.0	0.30	20	19500	2385	8.2	-
GE	Carlo Felice, Genova	1.80	1.5	-	-	-	11200	2000	5.6	-
GA	Condominio, Gallarate	1.16	4.1	4.2	-	-	4000	616	6.5	y

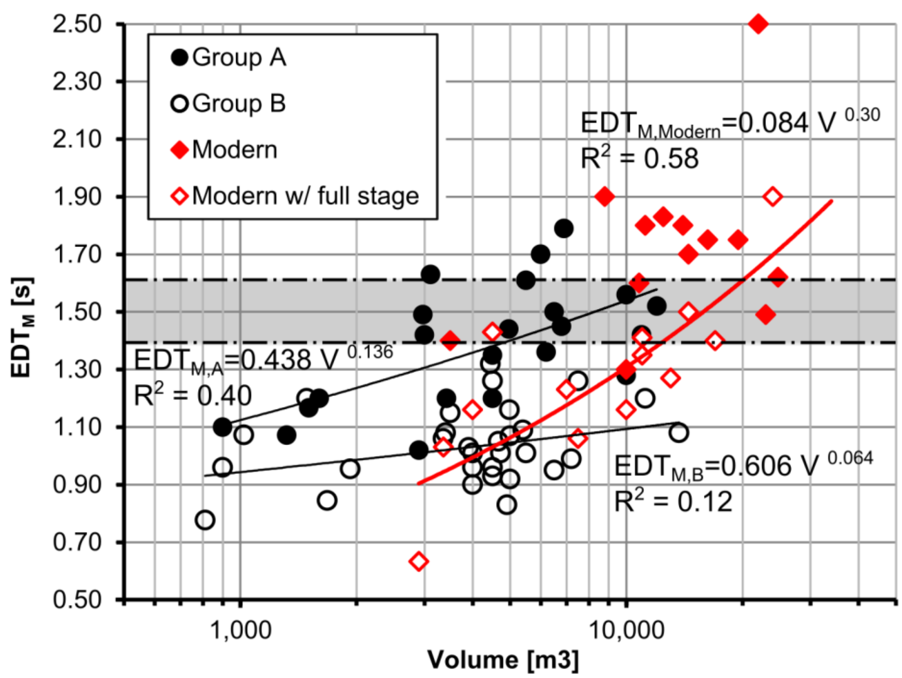

Figure 4 – (Color online) Plot of early decay time (EDT_M) at mid frequencies (500 and 1000 Hz) for the two groups and for the "modern" set of theatres. The shaded area corresponds to the preferred range according to Hidaka and Beranek[22].

C. Clarity

Clarity for music (C80) is one of the most frequently used acoustic parameters in historical opera houses and is calculated for positions in the stalls and in the boxes, with the latter locations best chosen at the box front opening. Despite it being often criticized for the rather arbitrary nature of the time interval, for its sometimes too sudden variations, and its possible correlation with reverberation time on space average basis, C80 can provide interesting information on the effectiveness of reflections in the early part of the impulse response and this is valuable both on a space average basis and when single positions are examined (See also Sec. IV). Considering now the spatial average of the parameter $C80_3$ (mean over the 500-2000 Hz octave bands) in Fig. 5, it is shown that, as expected, the indicator is well correlated with EDT_M, with clarity being higher in rooms with shorter reverberation times. A comparison with the range of suitable values derived in Ref. 22 for modern theatres shows that traditional ones tend to have a much clearer sound, as shown by the grouping of the points in the upper left area of the plot. This is likely to happen mostly in the medium- and smaller-volume halls belonging to Group B, whereas the bigger ones (and particularly those belonging to Group A), show a better agreement with the suggested range.

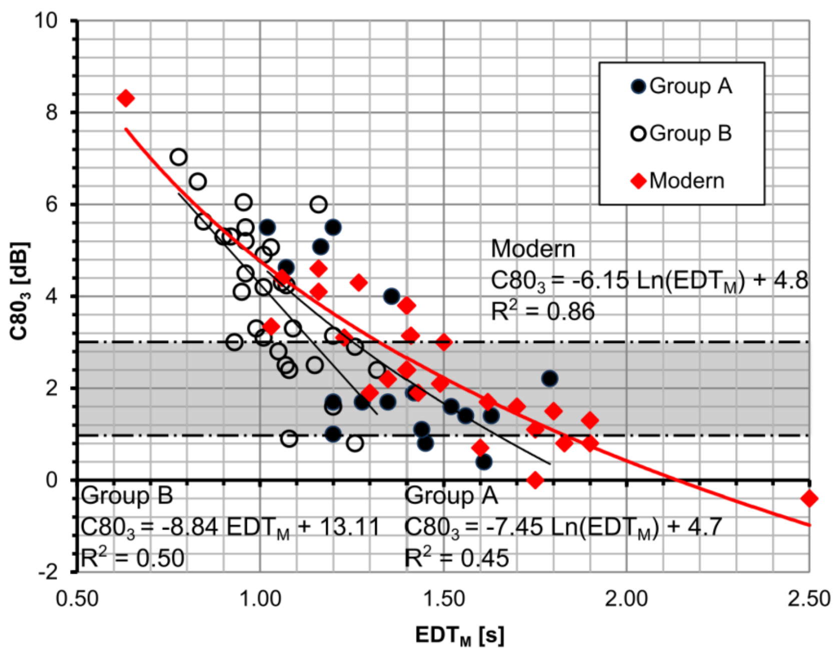

Figure 5 – (Color online) Plot of Clarity ($C80_3$) vs. EDT_M, respectively averaged over the 500, 1000, and 2000 Hz bands and 500 and 1000 Hz bands. The shaded area corresponds to the preferred range according to Hidaka and Beranek[22].

Even though average values can hardly describe the effect that source position as well as receiver location may have on the perceived sound, the comparison with modern opera houses shows an interesting difference. In fact, given a certain value for clarity, modern houses usually show a longer reverberation time than traditional ones (particularly those belonging to Group B). This could suggest that while in modern houses clarity is obtained through proper design of early reflections (thus affecting EDT less), in historical opera houses clarity is more strictly related to reverberation. This can be traced back to the specific geometry of such spaces, where the only significant reflecting surface is the proscenium arch, while ceiling and box front reflections are not entirely effective for improving the clarity at all seats.

D. Sound strength

In order to complete the analysis of the objective descriptors, the spatial averaged sound strength (G_M, mean over 500 and 1000 Hz octave bands) was finally considered. As the available data for Group A was not large enough to ensure statistical significance of the regressions, only Group B was considered. Figure 6 plots the spatial averaged G_M against the spatial averaged $(EDT_M/V)\cdot 10^6$, EDT was used in place of T30 to allow a straightforward comparisons with results given in Ref. 22. The data cover a much broader interval than considered by Hidaka and Beranek, due to the noticeably smaller room volume of most of the historical opera houses taken into account. However, despite this difference, the regression line for traditional theatres ($R^2 = 0.77$) is quite close, just 1 dB below, Line B found in Ref. 22 (corresponding to theatres with absorbing stage-house). Line A was typical of concert halls or theatres with closed stage-house and consequently is 3-4 dB higher. Such a difference is not surprising, as the large volume of the stage-house is, in many cases, equal or even greater than hall's volume, thus halving the acoustic energy density and finally reducing G_M by 3 dB. Similarly, the difference found between traditional and modern theatres (Line B) is consistent with the gap of reverberation time discussed earlier since it can be estimated that the expected G_M gap of the reflected sound would be around 1.3 - 1.4 dB for a volume $V = 5000$ m^3 and a reverberation time gap of 0.4 s. Line A is closer to the diffuse field theoretical value that G_M should assume as a function of room volume and reverberation time, thus suggesting that the difference between Line A and Line B simply stems from the bigger volume in which sound propagates in theatres (hall + fly tower).

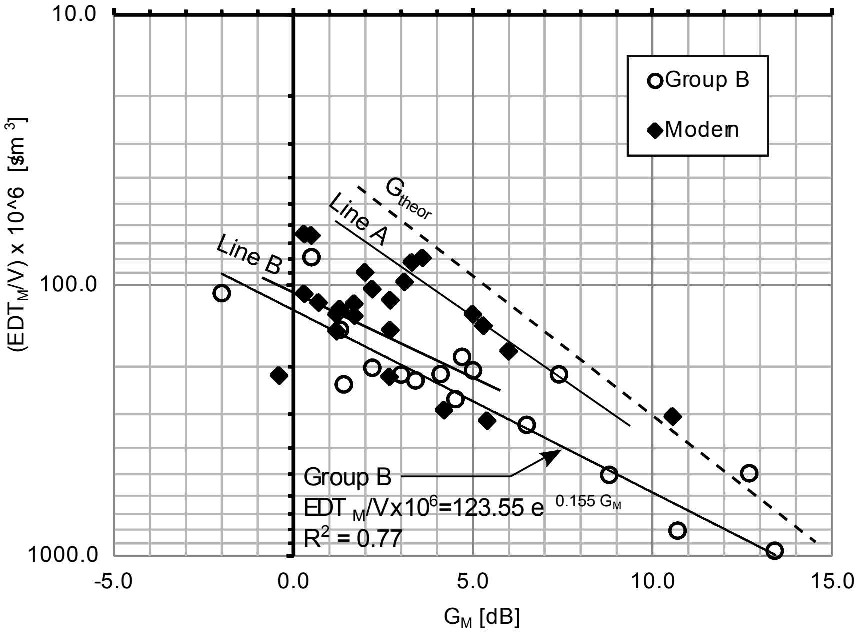

Figure 6 – Regression of space averaged G_M and EDT_M/V and comparison with regression lines shown in Ref. 22, where Line A was referred to opera houses with enclosed stage house or with orchestra shell, and Line B was referred to houses with highly absorbing stage house. G_{theor} represents theoretical values of G_M calculated as a function of EDT_M and V according to diffuse field theory.

IV. ACOUSTIC DIFFERENCES BETWEEN THE STALLS, BOXES, AND GALLERY

In order to better compare the variations of objective parameters between different parts of a theatre, results from individual opera houses were considered. In fact, when trends of acoustic parameters at specific locations are considered, significant differences can be found within the same venue. To start with, the trend of sound level can be described. Referring to the “Luciano Pavarotti” Theatre in Modena (MO in Group A), in Fig. 7 (data taken from Ref. 25) one finds side by side the listening levels that stage and pit sources are able to produce in the stalls (Figs. 7a and 7b), in a sidebox, close to the stage, in the third tier called Box A (Figs. 7c and 7d) and in a box opposite the stage in the third tier called Box B (Figs. 7e and 7f). A series of measurements in boxes at different locations in this medium-sized opera house were made. For each box, four positions were measured (described in Fig. 8), firstly position 1 at the box opening and positions 2-4 at 0.8, 1.6 and 2.4 m points behind the box front. Position 4 in the second box row had listeners in front. The same variations, with minor modifications, were applied to stalls measures too.

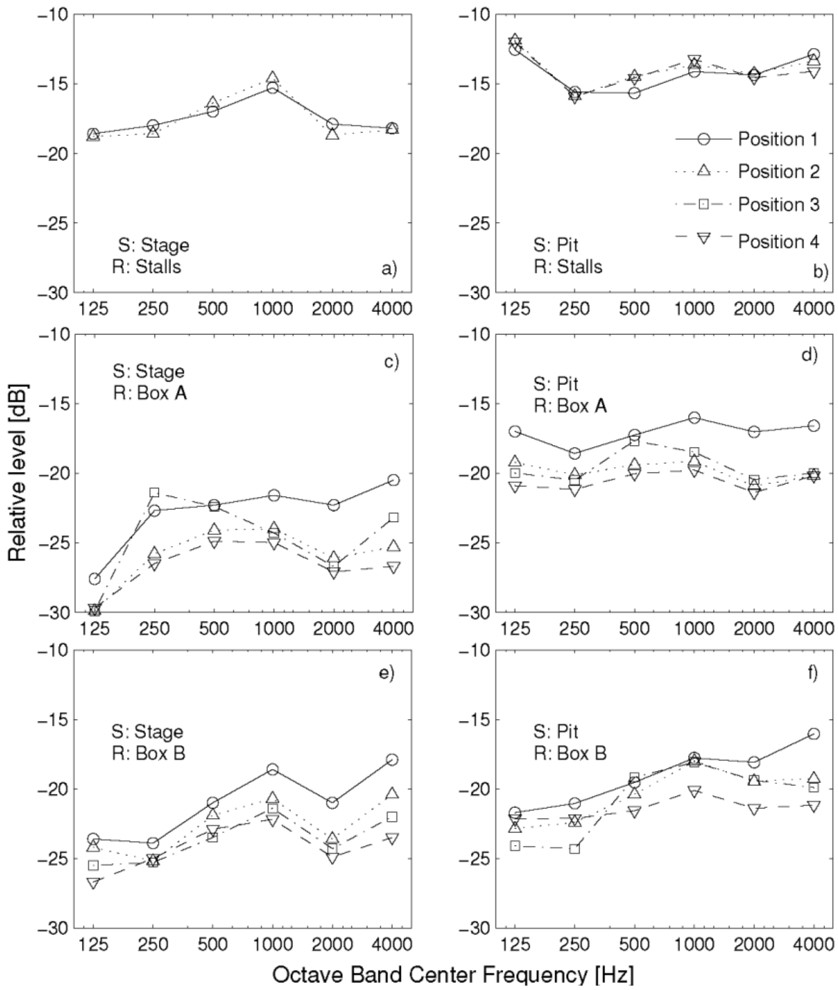

Figure 7 – Values of listening level at different places inside boxes and in the stalls (from Ref. 25). The listening levels (LL) are octave band sound level values relative to a reference position placed 1 m from the omnidirectional source emitting a white noise excitation. a,b) receiver in the stalls. In a) only positions 1 and 2 (one row behind) were measured; c,d) receiver in a sidebox, close to the stage, in the third tier; e,f) receiver in a box opposite the stage in the third tier;

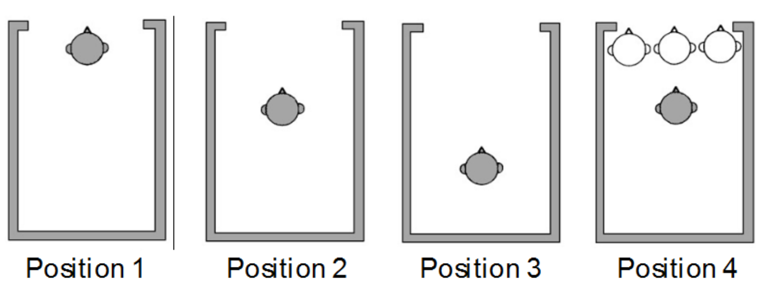

Figure 8 – The placement of the listener (hatched head) according to four positions in the boxes. The same patterns were followed in the stalls by spacing position 2 and 3 one and two rows, that is respectively 0.85 m and 1.7 m behind position 1.

By inspecting the Figures 7a – 7f one can describe and compare the peculiarities of the sound field at the selected locations. Sound in the stalls is louder than at other receiver locations, as well as often having more clarity, despite some frequency variations appeared between stage source (higher frequency decrease) and pit source (low frequency boost). Sound level is also much louder when the source is in the pit source than when it is on the stage. In the boxes only the listening position at the box opening is recommended since sitting in the second row involves a decrease of about 5 dB in level. It is interesting to note that the best tone balance and similarity of level between stage and pit is found in box B. That is to say that shading the orchestra by means of the rail can be a benefit for some areas of the audience. In fact, although box B is not as loud as the stalls, in this place sound seems more "natural" compared to the other locations due to the limited timbre coloration.
Motivations for listening in boxes compared to the stalls have also been discussed[26,37]. In particular the box volume, especially when provided with velvet drapes and sound absorbing finishes, acts as a resonator for the lower frequency range whereas it behaves as a full absorber at higher frequencies. This explanation is corroborated by a direct comparison of the EDT measured in the stalls and in the boxes. In Fig. 9 the data for the same theatre as above (MO) are reported for a sound source on the forestage. The EDT results in the stalls indicate the influence of the seat-dip effect at 125 Hz, whereas in the boxes absorption of early sound depresses the EDT at mid-frequencies. Sound in the boxes is not affected by the seat-dip effect. Similar behavior is not observed in the RT values. A similar trend is found in many historical opera houses although the details may vary much according to the specific geometry.

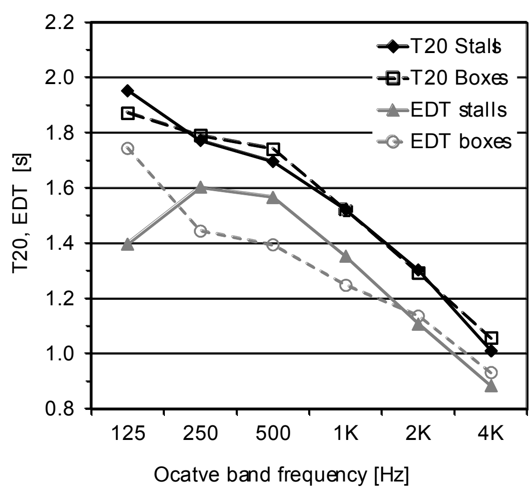

Figure 9 – Spatial average values of reverberation times EDT and T20 in the stalls and in the boxes of MO. Local trends can be identified by EDT whereas differences are not significant if T20 is considered.

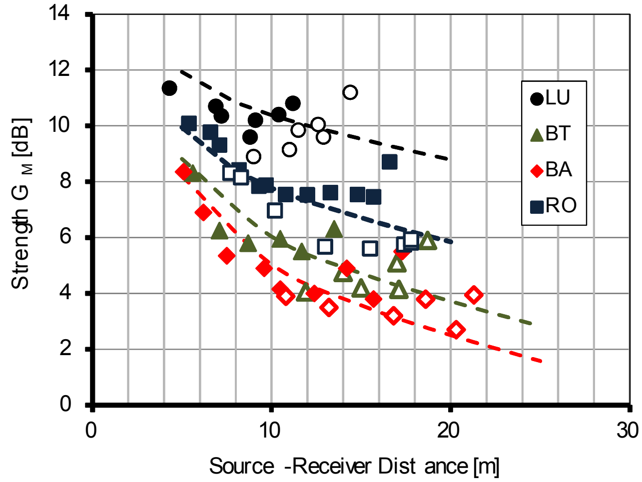

Figure 10 – (Color online) Plot of strength (G_M) as a function of source-receiver distance in four selected theatres (BA, BT, RO, and LU). Empty symbols correspond to values measured in boxes, while full symbols correspond to receivers in stalls. Dashed lines were calculated according to Barron's theory[38] starting from measured T30 and calculated volume of whole space (hall + stage house).

Another effect related to the specific behavior in the stalls and boxes was observed in other theatres, as it can be observed by plotting strength values as a function of distance (Fig. 10). In proportionate spaces, such plot is expected to show a mild decreasing trend in agreement with Barron's theory[38]. However, in traditional theatres two major effects may be identified. First of all, values measured in boxes, although showing a fairly good agreement with theory, usually have lower values (about 2 dB less) than receivers in the stalls at the same distance. This behavior is likely explained by consideration of materials and finishes in the boxes that tend to affect side boxes where direct sound and early reflections arrive from grazing angles. However, the difference is somewhat emphasized by another characteristic behavior that appears at the farthest receivers in the stalls, where the effect of strong (and sometimes focused) reflections from the curved back wall tend to significantly boost G compared to theoretical value (and hence to the boxes).

Finally, two theatres from the Apulian dataset (namely BA and LU), served as examples to show further influences on clarity values (C80) as a function of box position (Fig. 11). The boxes were distributed on two different levels (usually second and fourth tiers) and horizontally located opposite the stage center, and on the side (with critical sight conditions). Results show that, apart from absolute values, clearly depending on the theatre considered, boxes on the side and higher levels experienced the less clear sound, with significant drops particularly in the high frequency range. Conversely, for both the center positions the clarity was very high over the whole spectrum, with absolute values higher than those observed at the center rows in the stalls.

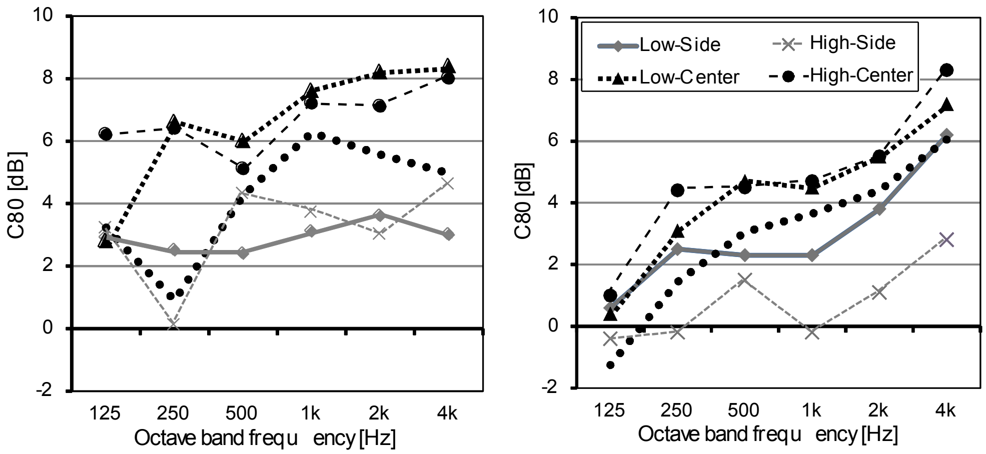

Figure 11 – Clarity (C80) as a function of frequency in six selected boxes in BA (left), and LU (right). Thick dotted line corresponds to average values for seats located at an intermediate position in the stalls.

It is also of interest to display examples of a 3D mapping technique[39] to show that some of the hypotheses made to explain acoustic effects in the previous paragraphs, are consistent with actual behavior observed in the surveyed historical opera houses. A selection of impulse responses measured using Ambisonic microphones during the Apulian survey were used as input. Figure 12a shows what happens in a side box at the second tier in BA, the microphone being placed at the center of the front row. A long time window (1 s) was chosen here to include in the map also the contribution from late reflections, while direct sound was excluded. The level distribution clearly shows that most of the loudest reflections only came from the front direction, within an angular span of ±45°, while reflections from the back (from the interior of the box) are much weaker. Reflections from below or from the soffit are almost irrelevant.

Figure 12b shows the directional intensity map in a specific seat in the stalls of SS where higher sound pressure levels were observed and a significant image shift (phantom source) is often apparent to listeners. The plot this time included direct sound and early reflections (0 to 50 ms) and clearly shows that a reflection with the same intensity as the direct sound (actually, slightly louder) arrives from an azimuthal angle of 110° in the horizontal plane. Analysis of the impulse response (not shown here for brevity) confirms that such reflection (or, better, cluster of reflections), arrives about 12 ms after direct sound. The origin of this focused reflection was the curved wall behind the stalls that, in this theatre, was made of plaster on a rigid wall with a smooth finish and no decorations.

Finally, Figure 12c shows the map measured in the gallery in SS, at the receiver position far from the balcony rail. In this house there is a shallow dome finished in plaster, though the soffit above the gallery is flat. The time window used for this map was again 1 s, excluding direct sound, so that late diffuse reflections could be mapped. The highest levels appear from the front direction (corresponding to early reflections), but here diffuse reflections arrive from nearly all directions above the horizontal plane, while the presence of the rail and of the seats considerably reduces reflections from below. So, the lack of separations between one box and the other, as well as the (slightly) higher ceiling (compared to the typical box height), contributed to make the sound field in a gallery different from that in a box.

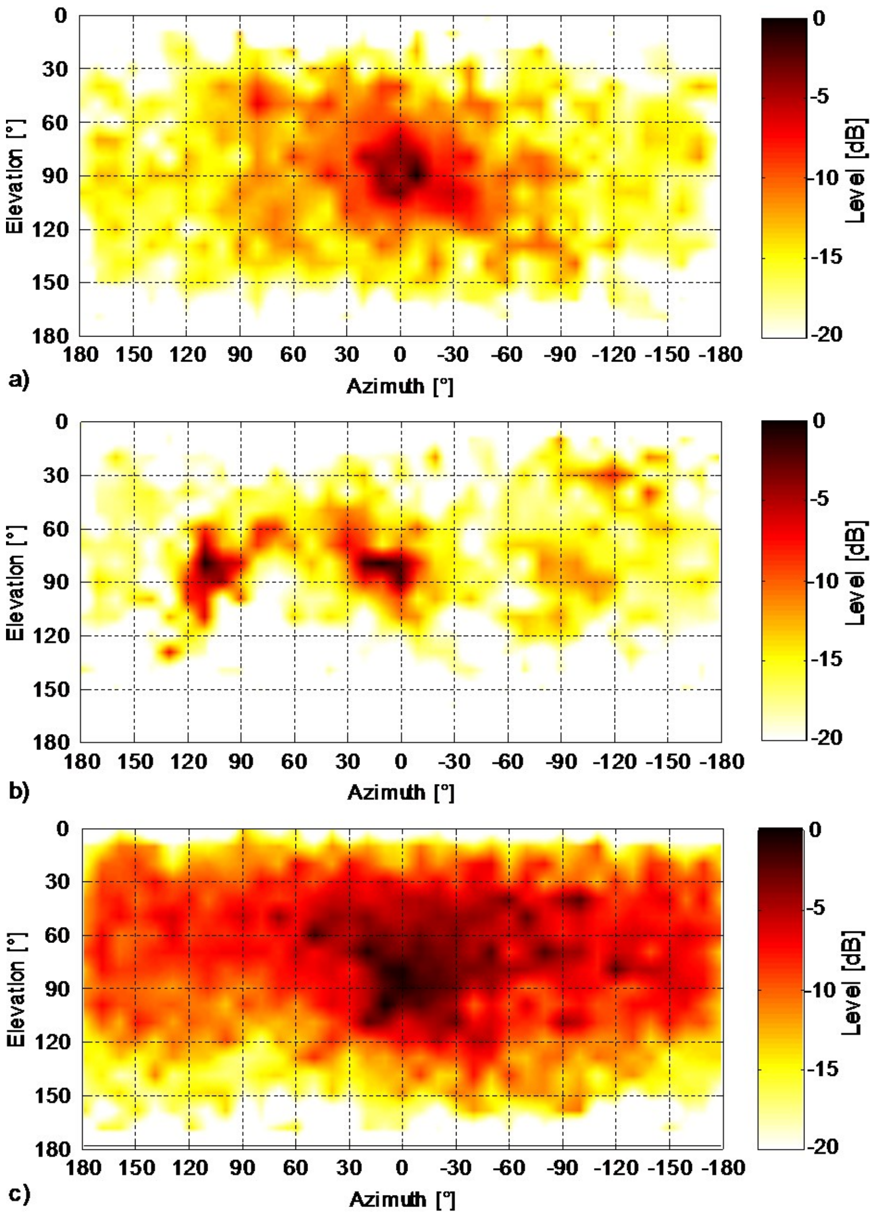

Figure 12 – (Color online) Directional intensity maps calculated for source on stage and receiver located in: a) Side box on 2nd tier in BA, 1 s time window starting from 0.005 s; b) Rear position in stalls in SS, 0.05 s time window starting from 0 s; c) Gallery in SS, 1 s time window starting from 0.005 s. Microphone is always aimed at the sound source located at (Az: 0°, El: 90°).

V. SUBJECTIVE PREFERENCE

The objective criteria emerging from the acoustic parameters (primarily those derived from the standard[35]) suggested that the perceived sound field in the historical opera house shall encompass a fairly large set of subjective impressions. The question is thus how the available acoustic information can be used to interpret (and possibly predict) listeners' subjective preference for one position or another. In addition, providing a satisfactory answer to the previous question would also contribute to explain which are the most important acoustic parameters, and what optimal values correspond to the best listening conditions.

To deal with this problem in opera houses becomes inherently more complex because different types of natural sources (voice and musical instruments), occupying different positions (the stage and the pit), must find a delicate, and often difficult, balance.

So, for example, Hidaka and Beranek provide a set of "ideal" ranges for the different acoustic parameters, based on the values pertaining to the best halls[22]. However, the same authors investigated regressions between subjective and objective ratings, which produced the result that IACC and ITDG are "important objective parameters for approximating the quality of opera houses, provided that RT_M is 1.3 s or greater, etc…". Thus, proper reverberation and a suitable strength are prerequisites for any further contribution from other parameters.

Moreover, with subjective responses also the issue of repeatability shall be considered, since listeners are accustomed to attend performances in specific halls and may have developed their own "regional" bias[40,41]. As an example, as a follow up of the Apulian measurement campaign, two listening tests were carried out. In both cases selected binaural impulse responses measured in different theatres (the same position, at the center of the stall area, was considered for each venue) were convolved with anechoic material (a singer with piano accompaniment, respectively convolved with stage and pit source) and played back through headphones. Sound pressure levels were carefully adjusted in order to match measured G values and preserve the difference in level between the source on the stage and that in the pit (later on called *balance*). In the first test[40] six different theatres were considered, with $T30_M$ spanning from 0.74 to 2.0 s, BR from 1.09 to 1.57, G_M from 4.5 to 13 dB, and the other parameters showing relatively smaller differences (so that listeners could focus on the most simple acoustic attributes). Results from 31 listeners showed that, interestingly, the two best rated historical opera houses had a $T30_M$ of about 1.15 s (and the most preferred was the one with G_M = 4.5 dB and BR = 1.09), while the worst rated was the most reverberant. Unfortunately, apart from a quadratic regression between subjective ratings and $T30_M$, no other correlation was found, but the fact that theatres closer to the "average" traditional theatre were preferred is, by itself, a remarkable result. The second

test[41] included just four theatres (including the best and worst rated of the first round), with $T30_M$ values of 0.9, 1.15, 1.6, and 2.0 s. Impulse responses were now carefully chosen so that larger variations among the other acoustic parameters could be perceived. Results from 16 listeners showed that both the theatres with intermediate $T30_M$ values were preferred (with the one with 1.6 s reverberation receiving slightly higher ratings), but the most interesting aspect was that statistically significant correlations appeared between subjective ratings and stage-pit balance (with a preference for a slightly louder stage), and bass ratio (with a preference for a flat response). However, considering the rather limited number of responses on which the regression was based, results were hard to generalize.
Such complex aspects were better investigated in a multimodal experiment involving sound and visual stimuli[27]. Ten seating positions inside the Ferrara theatre, five in the stalls, four in the boxes and one in the gallery were visually and aurally reproduced. In Fig. 13 one can see the wide angle views from two of the selected positions towards the stage, with a singer in the foreground. The lighting was similar to performance conditions and the stage set was rendered too.

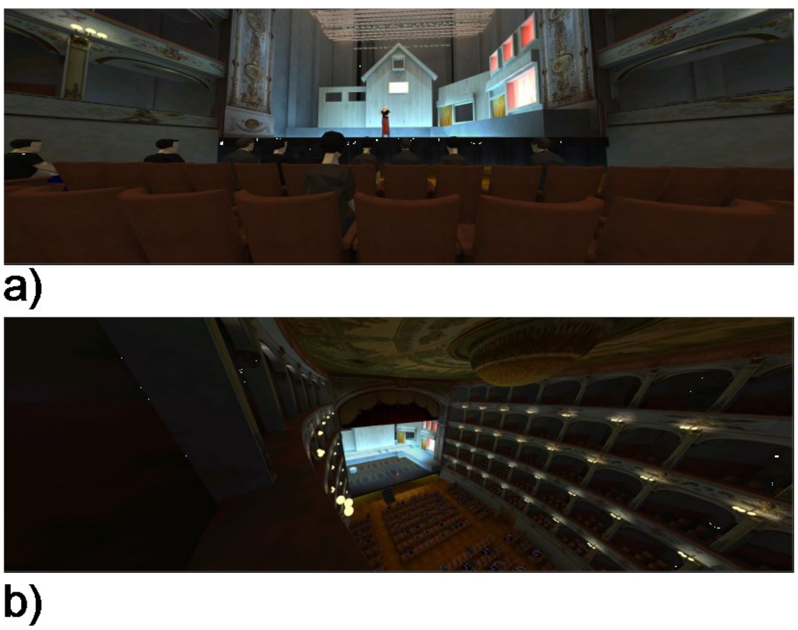

Figure 13 – (Color online) Wide angle views from a stalls position (a) and from a box position (b) in the “Claudio Abbado” theatre in Ferrara. The images were prepared to be projected on a large (6.9 x 2.9 m) curved screen (From Ref. 27).

The sound was obtained by convolving measured pit and stage impulse responses with keyboard and soprano tracks respectively, and by mixing them according to the measured level difference. Also geometrical variables were considered in the analysis, namely distance (D), azimuth (ϑ) and elevation (ϕ) with respect to the sound sources and listening position. Two complementary paired-comparison test experiments were done with different panels of listeners. Moreover, in Experiment 1 the image was optimized (widescreen) and sound was given via headphones, whereas in Experiment 2 the audio was optimized (multichannel trans-aural), and image delivered by means of 42” screen. The results of the two experiments expressed in terms of scale value (*sv*) of preference for balance are detailed in Ref. 27. They are consistent between the experiments and, by means of multiple-regression analysis, the most important factors to describe the scale value of subjective preference were assessed.

A set of quantitative objective indicators gave statistically significant correlations with *sv*, with the only exception of EDT probably due to the limited variation across the listening positions. In particular, the attention focused on the highest and significant correlations obtained with $L_{eq,A}$ or L_{Max} of total, of soprano alone and on the difference between soprano and keyboard (*balance, B*). Correlations were also made with C80 (stage - pit) calculated by algebraic subtraction of the pit source value from the stage source one, IACC (stage/pit) which is obtained by taking the ratio between soprano and keyboard value and ϕ which all have significant correlations with subjective preference. Within this set of quantities the best regression equation was obtained as:

$$sv \approx a_1 L_{eq,A}(total) + a_2 B \tag{1}$$

where the range of the total $L_{eq,A}$ span from 68.9 to 75.1 dB and the balance *B* from 0.2 to 7.8 dB. This is to say that the relative preference among seat positions was governed by a total sound level and by stage-pit level difference. The specific coefficients a_1 and a_2 depend on the experiment and on the audio-video combinations. For Experiment 1 they were a_1 = 0.18 [$p< 0.05$] and a_2 = 0.34 [$p< 0.01$] with R^2 = 0.89 [$p<0.01$], while for Experiment 2 they were a_1 = 0.25 [$p < 0.01$] and a_2 = 0.31 [$p < 0.01$] with R^2 = 0.91 [$p<0.01$]. It is remarkable that, adding C80 (stage), IACC (stage), D or ϑ as variables did not improve the regression in a statistically significant manner.

VI. BALANCING SINGERS AND ORCHESTRA

From the above findings it is immediately evident that the appraisal for a given location within a theatre depends on the way the historical opera house is able to convey in the right way the two competing sound sources, singer on the stage and orchestra in the pit. The struggle between the two can be explained in terms of sound power values. In fact, singers would be difficult to hear since singers’ “Forte” can get as close to 102 dB sound power level, whereas an orchestra can reach 114 dB[42]. But singers can compete with the orchestra thanks to the mechanism of formant frequencies[43].

While investigating for an appropriate B range, according to Eq. (1), it appears that the role of the overall sound level cannot be neglected. In the past, a preferred range was found in the interval -2.0 to 2.3 dB[29] by means of listening tests having either A-weighted overall level between 77.0 and 83.4 dB or a fixed one at 80 dB. In previous[28] and later studies[27], which were developed at an overall A-weighted level 5-7 dB lower, such an optimal B interval was not confirmed. In both cases higher B values, up to 7 dB, were found to increase the subjective preference and one can infer that the resulting gap was required to set the overall level closer to a preferred range.

Other acoustic properties may affect the B evaluation, such as EDT, C80 and IACC: Their impact was also investigated[30] thanks to data with a wider range of parameters' values obtained from theatres with shorter and longer reverberation times. As finally discussed in Ref. 44 a preferred B condition can be obtained when the stage source, which is preferably a directional one as detailed below, has values in the frequency range (500-4000 Hz) of EDT ≈ 1.2 s, a clarity C80 ≈ 9 dB and a higher IACC. This latter fact denotes the peculiarity of listening to two simultaneous and competing sound sources. In the present case a higher IACC results in a better focused sound image of the singer, and this result is in conflict with the usual preference for lower values of IACC for a single sound source. This parameter may complement objective clarity or even be a substitute for it; when there is insufficient temporal resolution, spatial resolution may dominate in terms of importance[30].

Furthermore, other issues related to balance have to be considered in order to optimize this indicator in the real cases. For instance a reliable measurement of B strictly depends on the sound source used to mimic a singer. An earlier proposal to address this problem consisted in the adoption of a dodecahedron with 11 loudspeakers sealed[45]. In a later experimental work[46] several types of loudspeakers were tested and in particular the similarity of an anthropometric sound source with directional sources was assessed. It was found that two-driver monitor loudspeakers were not a reliable choice due to their great variability among different models. If a directivity more similar to the singing voice (but nonetheless different) has to be used, then a full range one-way loudspeaker was the best choice[47].

Finally, from the point of view of acoustic design, B is largely affected by pit geometry and its materials, together with the proscenium arch design. The complicated interplay of the many factors regulating the projection of singer and orchestra can be hardly investigated analytically, but some trends can be outlined by numerical simulations[47,48]. The first study[47] showed that controlling B by pit design is more effective inside smaller opera houses rather than in bigger halls, and that pit floor and the height of pit rail could affect balance in the stalls, but only the pit back wall has an impact on the whole auditorium.

VII. CONCLUSIONS

Despite some limitations outlined above, the merging of data sets from literature and more recent measurement campaigns allowed to depict a clearer picture of historical opera house acoustics outlining how they differed from modern houses. In all of the cases, but particularly in the less reverberant traditional theatres, the stage-house volume and its different set up significantly affected the reverberation time in the hall, so that data had to be divided into two groups, isolating "unusually reverberant" and "regular" historical theatres. Correlations between room averaged acoustic parameters and geometric features were first investigated. The most important findings were listed below:

- A correlation between T30 and V appeared, with regular theatres being less reverberant than the others. However, the slope of the $T30_M/V$ curves was independent of the grouping, thus suggesting that differences in T30 were likely to depend on the amount of sound absorption rather than on room geometry, consequently affecting late reverberation rather than early sound.
- The study of EDT as a function of V showed that traditional theatres are much drier than modern ones, and remain dry even when volume grows. Conversely, modern opera houses tend to become very reverberant when volume grows, as demonstrated by the steeper EDT_M/V slope of the regression line that crosses those pertaining to the two groups in which historical opera houses were divided.
- An explanation for this behavior might stem from the characteristic geometry of traditional theatres that consequently might affect the distribution of the free paths[36]. Similar differences were also found when taking into account C80 and G.

Data from the more detailed measurement exercises were used to show and explain some typical local behavior, and particularly to illustrate how the listening conditions vary from stalls to boxes. Several factors come into play such as pit rail shading and sound absorption in the stalls. A better tonal balance and higher clarity is usually achieved in central boxes generally at second or third tier, but only the frontal positions exposed to the main hall volume can be attractive for listening. On the other hand, in the stalls the sound level is usually higher but noticeable variations may appear depending on source position and focused reflections. Hotspots may sometimes be found where source shifting takes place.

Studies on listeners' preference showed that criteria defined for modern theatres or for concert halls can hardly be applied in historical opera houses. In fact, total sound pressure level together with the stage-pit balance were the acoustic parameters that mostly affected the final subjective rating. Consistent with these findings the assessment of any preferred balance range needs the overall listening level to be specified, as different results were found depending on the fixed playback level. However, further investigations proved that other acoustic factors may influence the perception of balance. In particular, when a directional sound source was used to simulate the singer, IACC, C80 and EDT proved to influence the perception of balance, also showing trade-off effects between different parameters.

In conclusion, the analysis of the acoustic features of Italian traditional theatres outlined their distinctive features often in contrast with modern theatres. This should be kept in mind during any restoration work that could, more or less willingly, affect the acoustics. In fact, adaptation to modern criteria is often pursued rather than pure conservation, with significant loss of the original character. Further research is, however, needed in this field, as many aspects, such as the role of the stage-house and its relation with the main hall, just to mention one, are far from being clearly understood.

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