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The Circus-Theater of Albacete: Acoustic characterization and analysis of its double stage configuration

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ABSTRACT

A circus-theater is a particular type of theater space. It is mainly characterized by the possibility of interchanging the typical configuration of theater, where the stage house is settled in quasi-circularly to the audience area, to a circus configuration, in which the stage is totally surrounded by the audience area. Despite the abundant literature that tries to objectively and subjectively assess the acoustic characteristics of several theater spaces, there is scarce information about the acoustics of circus-theaters.

This work is a first approach to the acoustic characterization of such theater spaces. The main goal of this paper is to acoustically evaluate a circus-theater; for that, objective "in situ" measurements have been carried out considering both stage configurations. ISO 3382-1 has been taken as the guidance to select the acoustic parameters to measure, together with some other well-known additional parameters of room acoustics.

Measurements and characterization processes have been applied to the Circus-Theater of Albacete, as this is one of the few Spanish circus-theaters that still offers the possibility of using both stage configurations. Results allow to acoustically characterize a preliminary description of this kind of theater spaces, as well as comparatively study the theater and circus configurations from an acoustic point of view.

1. Introduction and goals

The architecture of the Spanish Circus-Theaters make use of the traditional late 19th Century traditional theater spaces to be adapted to the cultural needs and trends of the civil society of that time through typical design techniques and materials of the second industrial revolution.

In the early 20th Century, many theaters are restructured as multifunctional theater spaces. The aim then is offering a variety of shows: from theater plays to the first movie screenings, together with other performances like circus, equestrian exhibitions, cockfighting, acrobatics, magic shows, dance, etc. During the last decades of the 19th Century and the first decades of the 20th Century, almost 40 Spanish cities had a Circus-Theater [1] (mainly in the regions of Galicia, Cantabria, Levante, Andalucía and Cataluña); more than 60 buildings of that type were built in that time.

The catching design of a Circus-Theater is such that allows to place the stage in a central position, like an arena or circus ring, surrounded by the public all around (with a vision angle of almost 360°). To make this possible, an important reduction of the audience area is required to place the circular stage in the middle of the theater, instead of using the traditional "Italian" style of stage house [2]. The Carré Circus-Theater of Amsterdam and the Circus-Theater of Albacete [3] are two coetaneous examples of this kind of architecture in Europe, being 1852 the foundation year of the most veteran Circus-Theater (Cirque d'Hiver de Paris).

Apart from the historical value of these Circus-Theaters, they also have an important added value from the artistic point of view. It is precisely that capacity of changing the theater space into a multifunctional space what makes so interesting this typology of theaters, as the stage and acoustic characteristics can be adapted to the requirements of each kind of show. Despite the enormous potential of the Circus-Theaters, just one recent published paper has been found dealing with the acoustics of a Circus-Theater [4]; but none has been found that makes a study in depth of the acoustic characteristics of a Circus-Theater in any of its two possible configurations.

Given the scarce literature about the acoustics of Circus-Theaters, the main goals of this paper are on the one hand to provide "in situ" measurements and on the other hand to perform a

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complete acoustic characterization of a Circus-Theater in its double configuration; specifically, it has been done in the Circus-Theater of Albacete. Additionally, a comparison between the results of both configurations is to be carried out. To make possible those goals, selected acoustic parameters included in ISO 3382-1 (Acoustics – Measurement of room acoustic parameters; part 1: performance spaces) [5] have been measured, together with other typical room acoustics parameters.

This paper is organized as follows: after this introduction the second section corresponds to a brief description of the Circus-Theater under study; the third section deals with the methodology and then the fourth section states the results obtained and its discussion. Finally, the fifth section compiles the main conclusions of this study.

2. Brief description of the Circus-Theater of Albacete

The building of the Circus-Theater of Albacete is a historic construction devoted to public performances. Apart from being the only example of such constructions that still remains in Albacete (Castilla-La Mancha), it is declared as an asset of cultural interest in the category of monument and holds the International Circus Festival (13^{th} edition in the year 2020). Its main facade is located in Isaac Peral Str. and its back facade is in Carcelén Str., within Albacete's downtown (official address: Calle Isaac Peral, s/n, 02001-Albacete (Spain)). The Circus-Theater of Albacete [3] is one of the few that still maintains and uses the possibility of setting both configurations. Fig. 1 shows the theater space differences between the theater and circus configurations.

The Circus-Theater of Albacete was built in 1887 and its last restoration was carried out in 2002 by the team of architects composed of C. Campos, J. Caballero and E. Sánchez [6]. It maintains the possibility of setting two well differentiated configurations: the classical theater configuration, where the stage house keeps the typical machinery and stage setting for this kind of performances and the circus configuration, typical of circus performances, where the first section of seats is removed to set a circular stage connected to the stage house. This change essentially affects the audience capacity: from 936 seats in the theater configuration, only 740 are available in the circus configuration.

According to the information obtained from the Computerized Map of Theater Spaces [7], the approximate dimensions of the space are: maximum width 23.5 m, length from the apron 25 m, maximum height 13.5 m; this gives an approximate room volume of 7900 m^3. The main audience area is made up of three stalls (left, central and right), wings, side boxes and two levels of balconies (circles). Seats are made of wood with upholstery in the seat and back areas; if unused, they remain folded and displaying only wood.

The main room is built according to the European style, with columns and structure of iron; it is also combined with Arabic archwork. This premises has now recovered, during the last restoration, the most representative elements of its original morphology, which allows the double configuration of theater and circus; these are: iron smelting pillars, vaulted metallic roof (representative of the construction technology achieved in 1887), neo-Arabic ornamentation (inspired in the Alhambra of Granada and based on horseshoe arches, geometric ornaments, arabesque plasterwork between columns forming a false arch, typical kufic lettering of the Muslim art). The main room vault makes up a huge 5 m diameter curved diffuser made of MDF, which is the same front covering of the circles, and representing the night sky where stars and constellations can be seen [7].

The two level of circles are 3 m of maximum height and 4 m depth; they present no internal partitioning. Ceiling and front of the circles are covered with MDF, whereas the back wall is made of plaster panels. Seats of the circles are identical to those of the stalls.

The stage, in its theater configuration, is 12 m width, 10.2 m depth and 6.5 m height. It is essentially made of plaster panels and cement rendering; the floor is made of wood boards. Finishing touches are of black plastic paint.

A general appearance of the space, its elements, distribution and materials can be seen in Fig. 1 and more details can be found in [3,6,7].

3. Methodology

The study has been carried out in four different phases:

- During the first phase, the acoustic parameters to evaluate have been selected, together with the required instrumentation and the measurement procedures to be applied.
- The field work was done in the second phase, that is, the "in situ" measurements were taken.
- The third phase was devoted to data processing, analysis and study of the measurements in order to make possible the acoustic characterization of the premises in its both configurations.
- The fourth phase, and last, was dedicated to a detailed analysis of the results and to the comparative study of both configurations.

Along the development of this work, new ideas and possibilities have arisen, which will be considered in successive phases and presented in future papers.

3.1. Selection of acoustic parameters

Despite the scarce specific literature about the acoustics of Circus-Theaters, there is plenty of literature about the acoustics

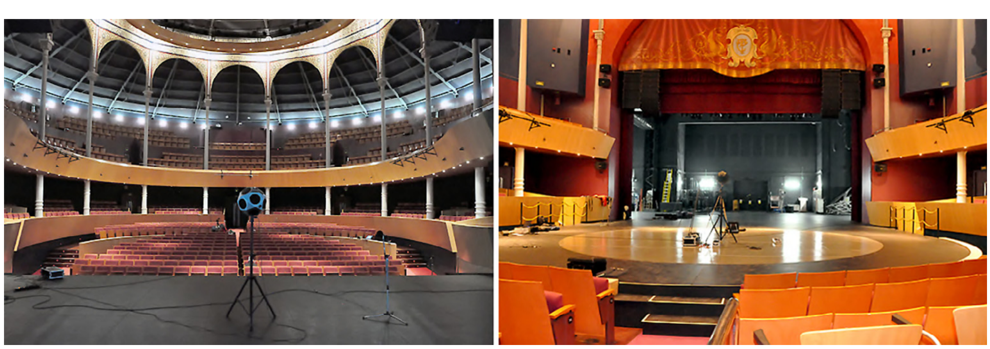

Fig. 1. View of the Circus-Theater of Albacete: theater configuration (left) and circus configuration (right).

of several other typologies of theater spaces, such as concert halls, auditoria and theaters [8–13] or even churches [14,15]. In general, those studies are focused in different aspects, such as the effect of the spatial sampling over the parameters [9,16], the excitation signal [17], clarity and definition of sound, the study of the binaural magnitudes and their relationship with other parameters [18–20], the sensation of the sound envelopment [21,22], the values and interest of JNDs [23–25] or the stage acoustics [26–29].

In order to better identify the acoustic differences between both configurations, the parameters indicated in ISO 3382-1 [5] grouped according to the subjective perception of the listener (in bold in the tables) will be considered. Apart from those parameters, it is proposed to consider some complementary parameters, chosen carefully to provide a more detailed information about the acoustic behavior of the premises in each of its configurations. Besides, considering additional parameters, the single number frequency averaged values of all the selected parameters will be calculated as suggested in Annex A of the standard. This allows comparing the results to the typical values for empty concert halls and multipurpose rooms of up to 25000 m^3.

As previously mentioned, all the selected parameters (ISO 3382-1 and additional ones) have been grouped according to the subjective perception of the listener, resulting in six different groups which are briefly described hereinafter.

- Group 1. Subjective level of sound: apart from the sound strength (G) proposed in ISO 3382-1, the background noise level parameter has been also included. It was calculated as the average of the background noise in all the measurement points. This allows to verify the signal to noise ratio, the presence of tonalities and the possible similarity of the background noise to NC curves.
- Group 2. Perceived reverberance: two perspectives of reverberance parameters have been considered. Those regarding the estimation of the time decay for different dynamic ranges, such as early decay time (EDT – included in ISO 3382-1), diffuse sound decay (T20) and reverberation time (RT); and those regarding the relative variation of the reverberation time among bass, mid and treble frequencies through the calculation of bass ratio (BR) and brightness (Br). The relationship among all this parameters will allow an indirect estimation of the quality of the sound diffusion and the linearity of the reverberation process; given that EDT is associated to the effect of subjective reverberance, a significant quantitative difference with T20 or RT may indicate effects of lack of linearity (double slope) or sound diffusion in the decay process.
- Group 3. Perceived clarity of sound: it includes the classical parameters of clarity (C80) and definition (D50), and also other parameters related to the former, but calculated in different time range. Regarding the clarity, it is also studied the early properties of the sound source (C20) and of the speech (C50). Regarding the definition, it is proposed to additionally study this magnitude in an adequate time frame for the music (D80); from now on, C50 and D80 will be named, respectively, as vocal clarity and music definition. Furthermore, and following ISO 3382-1, the centre time parameter (Ts) is also calculated to consider the gravity centre of the squared impulse response. Even more, information about echo criteria has also been included in this set: speech echo criterion (ECspeech) and music echo criterion (ECmusic) calculated as stated by Dietsch & Kraak [30], provide information about the quantity of reflections perceived as discrete echoes. When analysing the results for Echo criteria, it was decided to use as reference value the most critical one, that is, when 10% of the receiver positions can perceive an echo, whether for speech or for music. As this parameter is calculated for each point considering the whole signal without frequency discrimination, the results will present two values: the maximum and the median. The maximum value corresponds to a high probability of presence of an echo at any of the points, whereas the median value corresponds to the behavior of 50% of the reception points and thus indicates if the echo perception is a common trend for any of the stage configurations or if it is just an isolated phenomenon.
- Group 4. Apparent source width (ASW): just the early lateral energy fraction (JLF) given by ISO 3382-1 is included in this set.
- Group 5. Listener envelopment (LEV): it considers all the binaural magnitudes (interaural cross correlation – IACC) defined in annex B of ISO 3382-1. IACC is calculated for two integration times (50 ms and 80 ms), as well as for two ranges: early reflections (0,t), with an integration interval from the arrival of the direct sound (0) and up to a time (t); and for the reverberant sound (t,+), with an integration interval between the time (t) and another time (+) longer than the corresponding reverberation time. Given that IACC evaluates the sound similarity between both channels of a head and torso simulator (HATS), high values of IACC can indicate a lower envelopment sensation, like that of a monophonic sound.
- Group 6. Perception on stage: early support (STearly) and late support (STlate), as defined in ISO 3382-1, are determined in this set. These parameters describe the capacity of the musicians and artists of listening to themselves and among them on the stage (STearly) and the perceived room reverberance by musicians and artists on the stage (STlate).

Table 1 shows a summary of all the parameters, grouped according to the subjective aspect they are related to (ISO parameters are in bold text).

3.2. Brief description of measurement configuration

All the measurements have been carried out according to the indications of ISO 3382-1, as well as the informative recommendations of its three annexes. This allows the comparison of the results with the references for auditoria (annex A) and the acquisition of binaural magnitudes (annex B) and stage magnitudes (annex C).

As it occurred when making the selection of parameters, there is much literature dealing with the multiple possibilities to plan an "in situ" campaign of measurements. So to decide the source and receivers positions and the type of source and signal to use during the measurement, some of the bibliography that has been checked is [9,16,17,31,32].

All the measurements were performed without public, with a totally empty stage and opened curtain. There was no orchestra pit for the theater configuration. Light conditions were set to the minimum possible to properly work in the Circus-Theater and no HVAC was on. Temperature, relative humidity and barometric pressure were monitored to check that there were no drifts beyond 20% during the measurements.

The measurements were made during two different campaigns, one for each configuration. The selection of the source and receivers positions follow the indications included in ISO 3382-1, as well as those given in similar studies for concert halls and music performances.

The omnidirectional sound source (B&K 4292-L) was placed in the middle of the proscenium arch for the theater configuration (T) and in the center of the stage for the circus configuration (C), see Fig. 2. The sound source was placed 1.5 m above the stage floor in both cases.

The sound source emitted a deterministic exponential sweep signal from 50 Hz to 10 kHz; its duration was chosen to be more than the double of the reverberation time at the minimum

Table 1
Selected acoustic parameters related to subjective aspects.

GROUP	Subjective listener aspect	Acoustic quantity	
1	Background noise	Background level	dB
	Subjective level of sound	**Sound strength**	**G; (dB)**
2	Perceived reverberance	**Early decay time**	**EDT; (s)**
		Diffuse sound decay	T20; (s)
		Reverberation time	RT; (s)
		Bass ratio	BR
		Treble ratio	Br
3	Perceived clarity of sound	Early clarity	C20; (dB)
		Vocal clarity	C50; (dB)
		Clarity	**C80; (dB)**
		Definition	**D50**
		Music definition	D80
		Centre time	**Ts; (ms)**
		Echo Criterion: EC speech	ECspeech
		Echo Criterion: EC cmusic	ECmusic
4	Apparent Source Width-(ASW)	**Early lateral energy fraction**	**JLF**
5	Listener Envelopment -(LEV)	**Binaural coefficients**	**IACC (0,50)**
			IACC (0,80)
			IACC (50,+)
			IACC (80,+)
6	Ensemble conditions	**Early support**	**STearly; (dB)**
	Perceived reverberance	**Late support**	**STlate; (dB)**

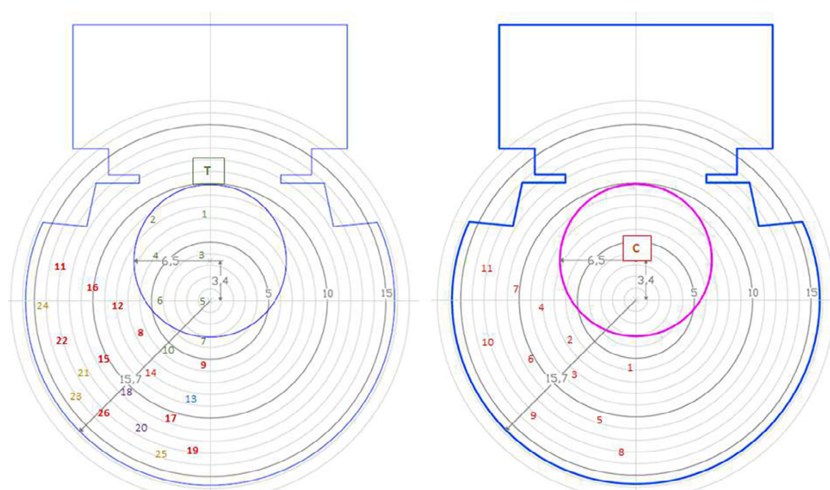

Fig. 2. Distribution of the source and receivers positions. Theater configuration (Theater-26p) (left), and circus configuration (Circus-11p) (right).

required frequency (100 Hz according to the ISO 3382-1) and the number of repetitions was always more than 9, so that the ratio to the integrated impulse response results higher than 35 dB for the frequency range between 100 Hz and 5 kHz. The number of receiver positions has been oversized, at least in a factor of 1.2, regarding the minimum number of positions suggested in ISO 3382–1 depending on the audience. It has been forced that all the audience areas count, at least, one receiver position. The final receivers' distribution has been set depending on the capacity of the premises and proportionally to the number of seats of each audience area.

As there is a longitudinal symmetry axis for both configurations, the receivers have been placed just in the odd section of the audience. The height of the receivers was always 1.25 m above the floor in the position of the seats, except for the stage positions, where a height of 1.5 m was set (equal to the source height).

The number of receiver positions was 26 for the theater configuration, whereas just 11 of those 26 positions have been considered for the circus configuration; this is due to the fact that the first section of stalls is removed in the circus mode. Nevertheless, that subset of 11 positions was proportionally distributed over all the audience areas in the circus configuration. From now on, the dataset corresponding to theater or circus configurations will be referred to as Circus-11p and Theater-26p, respectively.

Table 2 summarizes the number of measurement positions (points) in each area for both configurations. The number of points in all cases is higher than the minimum recommended in ISO 3382-1 (between 6 and 8 positions). The positions have been distributed proportionally to the number of available seats in each area.

Fig. 2 shows the distribution of the measurement positions for each configuration, as well as the relative position of the source for each case (T for theater and C for circus). The positions which are common to both configurations are marked in red. The different colors used in the theater configuration correspond to different sitting areas (amphitheater, box, stalls) whereas all the positions in the circus configuration were set in the stalls area.

Table 2
Distribution of the measurement positions for each configuration.

	Capacity (seats)					Total seats	
	196	140	160	190	250	936	
Theater-Circus Albacete	**Points** 1st. Seating area	**Points** 2nd. Seating area	**Points** Boxes	**Points** 1st. Amphitheater	**Points** 2nd. Amphitheater	**TOTAL Receivers**	**Points** Stage
CIRCUS	*n/a*	*2*	*2*	*3*	*4*	*11*	*3*
THEATHER	6	4	4	4	8	**26**	3
CIRCUS	*n/a*	*18 %*	*18 %*	*27 %*	*36 %*	*100 %*	
THEATHER	23 %	15 %	15 %	15 %	31 %	100 %	

For the calibration of the entire system (hardware and software), the entire protocol established in the Dirac v.6 data analysis and measurement software was exhaustively followed. According to its technical specifications, the software meets the requirements for carrying out measurements under the ISO 3382-1 standard, and with the IEC 6120 standard for filters in 1/1 and 1/3 octave class 0. In addition, it complies with the ISO 18233 (analysis methods) and IEC 60268-16 (speech intelligibility) standards. In this case, both the input/ output levels of the audio card have been verified setting the sampling frequency to 48 kHz. Additionally, a diffuse field system calibration was carried out in the accredited reverberant chamber of the Polytechnic University of Madrid (UPM) of 220 m^3 volume and a SPL calibration was systematically performed for both channels with a SPL calibrator (94 dB/ 1 kHz) before and after each measurement session, checking that the deviations remained in all cases below ± 0.2 dB.

3.3. Measurement set up and calculated acoustic parameters

Four measurement sessions were programmed with differences regarding instrumentation, procedures and aims: in the first three sessions the receiver positions were the same, but the acquisition systems were different, as it will be explained hereinafter; in the fourth session the receivers were placed on the stage.

The first set of measurements had the goal of obtaining the data required to calculate the parameters related to the subjective aspects 1, 2 and 3 (perceived sound level, perceived reverberance, perceived clarity) and to the background noise. For this purpose, two omnidirectional microphones (B&K 4190L) have been used to measaure simultaneously in two different receiver positions. With these data, the following parameters have been calculated for each position: sound strength (G), early decay time (EDT), reverberation times (T20 and RT), bass ratio (BR) and brightness (Br); music clarity (C80), speech definition (D50), centre time (Ts), early clarity (C20), speech clarity (C50), music definition (D80), and the echo criteria for music and speech (ECmusic and ECspeech).

The second set of measurements was planned to determine the fourth subjective aspect (apparent source width – ASW). In this case, a paired configuration of two identical microphones (Audiotechnica AT4050) with different directivity pattern (bidirectional and omnidirectional) has been used. The sensitivity of both microphones was previously adjusted to achieve the same level in conditions of diffuse sound field. The bidirectional microphone is mounted vertically over the omnidirectional microphone, so that the ensemble points from the receiver position (minimum of the bidirectional pattern) towards the sound source position on the stage. The results of these measurements allow to calculate the early lateral energy fraction (JLF).

To characterize the fifth subjective aspect (listener envelopment – LEV), a third set of measurements was carried out. A HATS (B&K4100) was placed at each receiver position, aiming towards the sound source on the stage. With these data, the listener envelopment was determined through the early and reverberant coefficients of the interaural cross correlation (IACC); they describe the dissimilitude between the signals arriving to each of the ears, where the subindex (0,t) indicates early reflections of the IACC and the subindex (t,+) represents the reverberant sound in the IACC.

Finally, the characterization of the stage, sixth subjective aspect, is addressed through the fourth measurement session in order to obtain the early (STearly) and late (STlate) support parameters. The stage was completely empty (without any object on the stage) and the measurement positions were settled on the stage at the same height as the sound source (1.5 m). Three receiver positions were considered over a 1 m radius circle around the sound source and with 90° angle between them (front, back, lateral).

All the measurements were recorded in digital audio format without compression (wav: 48 kHz/24 bits); they were processed with a dedicated software (Dirac v.6) to extract all the results for all the parameters in third-octave frequency bands from 100 Hz to 5000 Hz and in octave bands from 125 Hz to 4000 Hz. Additionally, the HATS was also used to record anechoic signals emitted from the stage; this will allow in the future the evaluation of the subjective perception in all the studied receiver positions.

4. Results and discussion

Hereinafter a summary of the results is presented in different formats: as single value quantities and in octave bands.

Calculating the uncertainty of room acoustics parameters, whether the spectral value or the single value, is still an open field of research. In this paper, and based of previous authors' experience, it is assumed that the uncertainty of all results is below the corresponding JND. According to [33] when measurements are made under similar conditions as the ones presented in this paper (similar equipment, same processing software, exponential sweep signal), the error of all the single value room acoustic parameters included in this paper is much below the corresponding JND. A similar result was found in [34], where a detailed uncertainty budget was calculated for C80 spectral values, finding that the uncertainty budged for a single measurement was on the order of the JND. The fact that in this paper 11 different positions have been used for the CIRCUS configuration and 26 for the THEATER ensures again that the uncertainty of all presented results remain below the corresponding JND. The standard deviation bars included in Figs. 3, 4, 5, 8 and 9 correspond to the average of the 11 or 26 different spatial positions considered in each of the figures.

Table 3, determined as stated in the example A.1 of the annex A of ISO 3382-1, shows the single value results for each configuration (Theater-26p and Circus-11p). Using sigle values format enables comparing the results with those published by other authors and, furthermore, it allows to easily assess which parameters have differences between both configurations equal or greater than the corresponding JND threshold.

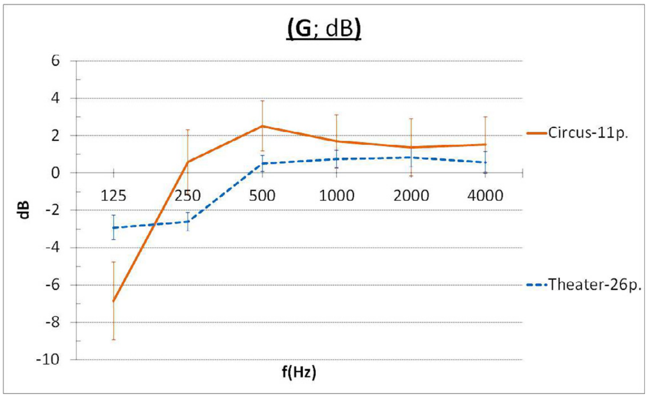

Fig. 3. Sound Strength (G), for both configurations.

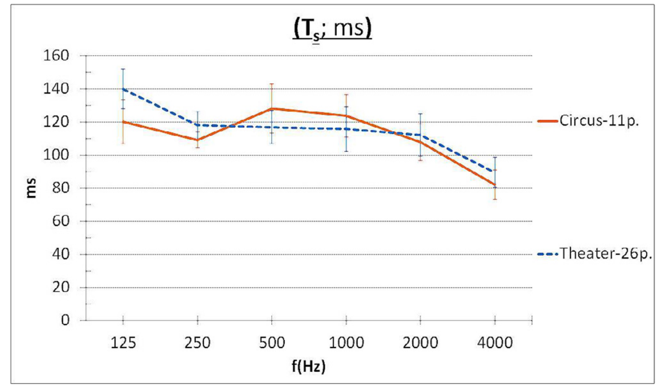

Fig. 5. Centre time (Ts) for both configurations.

Tables 4 and 5 present the results for the theater and circus configurations, respectively, in octave bands from 125 Hz to 4000 Hz, the average value of the selected parameters grouped under the corresponding subjective aspect. Values in bold indicate the frequency bands used to calculate the averaged single number quantities shown in Table 3.

Next, a detailed analysis follows with the results grouped according to the six different subjective aspects described in Section 3.1 and considering the calculated single number values, the JNDs and the spectral values obtained.

The ISO parameters, as Table 3 reveals, are within the typical range stated in ISO 3382-1. This result suggests that, concerning ISO parameters, the "acoustic performance" of the Albacete Circus-Theater, independently of the configuration, is comparable to those recommended for empty concert halls and multifunctional rooms up to 25000m^3.

The right column of Table 3 represents, for those parameters with known JND, how many JNDs are equivalent to the difference in the values obtained for the circus and theater configurations. As it can be seen, the parameters that better distinguish between both configurations are the following: sound strength (G), early decay time (EDT), reverberation times (T20 and RT), centre time (Ts), speech echo criterion (ECspeech), listener envelopment (LEV) relative to the early binaural magnitudes (IACC(0,50) and IACC(0,80)), and the late support magnitude on stage (STlate) (despite no JND threshold exists for the stage support).

Within the Group 1, related to the perceived sound level, the strength (G) allows the differentiation of both configurations. On the one hand, as it can be seen in Table 3, the single value of sound strength is higher for the circus configuration and the difference between the two configurations is also higher than the differential threshold (JND). On the other hand, Fig. 3 shows that the trend of the strength is similar for both configurations, but values are higher for the circus. This behavior may be due to the geometrical distribution and distance between the sound source and the receivers, which are placed almost in a circular sector with narrow distance differences between them (less than 8 m between the farthest and the closest positions). For both configurations, the strenght G shows a dip at 125 Hz, although it is more pronounced

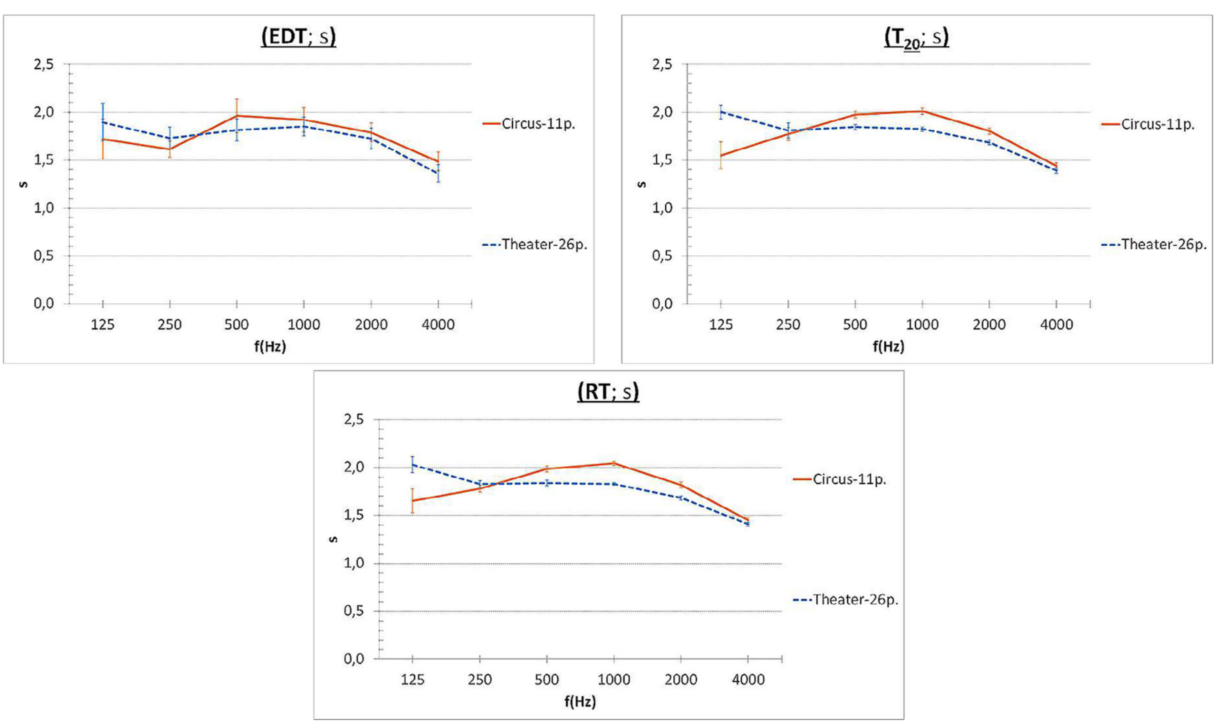

Fig. 4. Comparison among reverberance parameters for both configurations: EDT (left), T20 (right) and RT (down).

Table 3
Summary of the single number frequency averaged values for each configuration (Theater-26p and Circus-11p).

GROUP	Subjective listener aspect	Acoustic quantity		Averaging (Hz)	(JND)	Typical range ISO 3382	*CIRCUS-11p.*	TEATRO-11p.	THEATER-26p.	Relative JND diff
1	Background noise	Background level	dB				*30*	30	30	
	Subjetive level of sound	**Sound strength**	**G; (dB)**	**500–1000**	**1 dB**	**−2 dB; +10 dB**	***2.1***	**0,4**	**0.6**	**1.5**
2	Perceived reverberance	**Early decay time**	**EDT; (s)**	**500–1000**	**Rel. 5%**	**1.0; 3.0**	***1.94***	**1.78**	**1.83**	**1.14**
		Diffuse sound decay	T20; (s)	500–1000			*1.99*	1.83	1.84	
		Reverberation time	RT; (s)	500–1000			*2.01*	1.82	1.83	
		Bass ratio	BR				*0.85*	1.06	1.05	
		Treble ratio	Br				*0.81*	0.84	0.84	
3	Perceived clarity of sound	Early clarity	C20; (dB)	500–1000			*−5.0*	−5.2	−4.4	
		Vocal clarity	C50; (dB)	500–1000			*−1.9*	−1.8	−1.4	
		Clarity	**C80; (dB)**	**500–1000**	**1 dB**	**−5 dB; +5 dB**	***0.5***	**0.1**	**0.2**	**0.32**
		Definition	**D50**	**500–1000**	**0.05**	**0.3; 0.7**	***0.40***	**0.40**	**0.42**	**0.48**
		Music definition	D80	500–1000			*0.53*	0.51	0.51	
		Centre time	**Ts; (ms)**	**500–1000**	**10 ms**	**60 ms; 260 ms**	***126***	**118**	**116**	**1.0**
		Echo Criterion: ECspeech	EC speech med.	Median	EC 10%	0.9	*0.76*	0.73	0.75	
			EC speech max.	Maximum	EC 10%	0.9	*1.23*	0.84	0.95	
		Echo Criterion: Ecmusic	EC music med.	Median	EC 10%	1.5	*0.73*	0.67	0.65	
			EC music max.	Maximum	EC 10%	1.5	*1.11*	0.87	0.87	
4	Apparent Source Width-(ASW)	Early lateral energy fraction	**JLF**	**125–1000**	**0.05**	**0.05; 0.35**	***0.10***	**0.13**	**0.12**	**0.49**
5	Listener Envelopment -(LEV)	**Binaural coefficients**	**IACC (0,50)**	**500–2000**	**0.075**		***0.70***	**0.50**	**0.50**	**2.62**
			IACC (0,80)	**500–2000**	**0.075**		***0.57***	**0.42**	**0.44**	**1.78**
			IACC (50,+)	**500–2000**	**0.075**		***0.18***	**0.14**	**0.15**	
			IACC (80,+)	**500–2000**	**0.075**		***0.17***	**0.14**	**0.14**	
6	Ensemble conditions	Early support	**STearly; (dB)**	**250–2000**	**unknown**	**−24 dB; −8 dB**	***−9.2***	**−9.8**	**−9.8**	
	Perceived reverberance	Late support	**STlate; (dB)**	**250–2000**	**unknown**	**−24 dB; −10 dB**	***−7.9***	**−11.2**	**−11.2**	

Table 4
Summary of parameters for the Theater-26p configuration.

GROUP	Subjective listener aspect	Acoustic quantity		Octave frequency bands - (Hz)					
				125	250	500	1000	2000	4000
1	Background noise	Background level	dB	33.1	27.2	27.0	20.8	17.9	20.5
	Subjective level of sound	Sound strength	**G; (dB)**	−2.9	−2.6	**0.5**	**0.7**	0.8	0.6
2	Perceived reverberance	Early decay time	**EDT; (s)**	1.90	1.73	**1.82**	**1.85**	1.73	1.36
		Diffuse sound decay	T20; (s)	2.00	1.81	**1.85**	**1.83**	1.69	1.39
		Reverberation time	RT; (s)	2.03	1.83	**1.84**	**1.83**	1.68	1.41
3	Perceived clarity of sound	Early clarity	C20; (dB)	−8.66	−5.59	**−4.37**	**−4.46**	−4.88	−4.62
		Vocal clarity	C50; (dB)	−3.27	−1.92	**−1.40**	**−1.40**	−1.60	−0.84
		Clarity	**C80; (dB)**	−0.44	0.24	**0.18**	**0.27**	0.16	1.43
		Definition	**D50**	0.33	0.39	**0.42**	**0.43**	0.41	0.45
		Music definition	D80	0.48	0.51	**0.51**	**0.52**	0.51	0.58
		Centre time	**Ts; (ms)**	139.9	117.9	**116.9**	**115.7**	112.0	89.5
4	Apparent Source Width-(ASW)	Early lateral energy fraction	**JLF**	**0.06**	**0.12**	**0.19**	**0.13**	0.20	0.16
5	Listener Envelopment -(LEV)	Binaural coefficients	**IACC (0,50)**	0.953	0.844	**0.591**	**0.476**	**0.444**	0.356
			IACC (0,80)	0.936	0.799	**0.512**	**0.407**	**0.391**	0.303
			IACC (50,+)	0.903	0.733	**0.210**	**0.138**	**0.100**	0.086
			IACC (80,+)	0.897	0.733	**0.199**	**0.135**	**0.098**	0.085
6	Ensemble conditions	Early support	**STearly; (dB)**	−9.4	**−9.8**	**−11.4**	**−9.8**	**−8.1**	−8.9
	Perceived reverberance	Late support	**STlate; (dB)**	−8.0	**−11.5**	**−11.1**	**−11.7**	**−10.3**	−12.0

for the circus configuration. This sudden drop does not have an obvious explanation but indicates that the perceived loudness at bass frequencies is poor, since, perceived loudness increases almost linearly when G(125 Hz) increases [35,36]. As a summary it can be concluded that the circus configuration has better strength values compared to the theater configuration, although higher variability between receiver positions.

Parameters of perceived reverberance assessed in Group 2 indicate that the reverberance is better perceived in the circus configuration. Frequency averaged values for circus are always higher

Table 5
Summary of parameters for the Circus-11p configuration.

GROUP	Subjective listener aspect	Acoustic quantity		Octave frequency bands - (Hz)					
				125	250	500	1000	2000	4000
1	Background noise	Background level	dB	34.7	28.7	32.9	27.4	22.8	18.8
	Subjective level of sound	Sound strength	**G; (dB)**	−6.8	0.6	**2.5**	**1.7**	1.4	1.5
2	Perceived reverberance	Early decay time	**EDT; (s)**	1.72	1.61	**1.96**	**1.92**	1.79	1.49
		Diffuse sound decay	T20; (s)	1.55	1.78	**1.97**	**2.01**	1.80	1.44
		Reverberation time	RT; (s)	1.65	1.78	**1.98**	**2.04**	1.82	1.45
3	Perceived clarity of sound	Early clarity	C20; (dB)	−7.62	−4.83	−**5.12**	−**4.80**	−3.81	−2.34
		Vocal clarity	C50; (dB)	−1.95	−1.29	−**1.86**	−**1.88**	−0.86	0.51
		Clarity	**C80; (dB)**	1.14	1.48	**0.57**	**0.51**	1.30	2.71
		Definition	**D50**	0.39	0.43	**0.40**	**0.40**	0.45	0.53
		Music definition	D80	0.56	0.58	**0.53**	**0.53**	0.57	0.65
		Centre time	**Ts; (ms)**	120.1	109.2	**128.1**	**123.7**	107.8	82.1
4	Apparent Source Width-(ASW)	Early lateral energy fraction	**JLF**	**0.06**	**0.07**	**0.16**	**0.13**	0.15	0.17
5	Listener Envelopment -(LEV)	Binaural coefficients	**IACC (0,50)**	0.955	0.922	**0.730**	**0.700**	**0.664**	0.655
			IACC (0,80)	0.951	0.895	**0.647**	**0.561**	**0.495**	0.500
			IACC (50,+)	0.929	0.785	**0.318**	**0.137**	**0.099**	0.084
			IACC (80,+)	0.920	0.768	**0.283**	**0.132**	**0.093**	0.089
6	Ensemble conditions	Early support	**STearly; (dB)**	−10.5	−**10.8**	−**7.6**	−**7.5**	−**11.0**	−12.3
	Perceived reverberance	Late support	**STlate; (dB)**	−8.1	−**7.5**	−**6.6**	−**7.6**	−**9.8**	−12.3

than for theater, with relative differences $> 9\%$ for RT, $> 8\%$ for T20 and $> 5.7\%$ for EDT. Therefore, these three parameters evidentiate differences between both configurations.

From a spectral point of view, differences are displayed in Fig. 4. The reverberation parameters for the circus configuration are slightly higher at mid/high frequencies than for the theater configuration. At lower frequencies the behaviour is the opposite. The cause of the effect at low and medium frequencies could be explained through the loss of absorption in the circus configuration after removing the first section of stalls from the center of the stage; the effect of RT at bass frequencies does not have a clear justification a priori. Comparing the trend of the three reverberance parameters, it is noticed that the theater configuration is more stable than the circus; subjectively, and based on EDT, the behavior of the circus is quite similar to the theater, but a sudden reverberation decrease appears for bass frequencies that leads to a less flat pattern of the RT along the frequency bands and the consequent loss of bass ratio. Deviation bars indicate that the dispersion of values among the receiver positions is more important for EDT than for T20 and RT (calculated over a wider time range). The variations for T20 and RT at high frequencies are almost negligible probably due to a higher contribution of the air absorption to the total absorption.

Regarding the tonal curve of reverberation that could be associated to bass ratio (BR) and brightness (Br), the single number values shown in Table 3 reveal that the circus configuration has a lower bass ratio. Even more, the fact that the circus configuration presents values of bass ratio and brightness with values below “1” means that the reverberation at mid frequencies is slightly higher than in bass and low frequencies, as it has been formerly mentioned.

Perceived clarity of sound parameters included in Group 3 do not allow, based on the JNDs, to establish clear significant differences between both configurations. Even so, Ts and C20 parameters achieve noticeable relative differences; specifically, Ts is quite close to the value of the threshold (JND $\simeq$ 10 ms). In addition, information of the echo criteria is quite relevant for the comparison between configurations. In the Table 3 it is observed that the trend for clarity values is increasing as the time range for its calculation rises, from 20 ms to 80 ms; this fact indicates, more than a difference between configurations, the lack of abnormalities in the echogram or in the reflection processes that could mean a lack of linearity. The very low values of C80 for both configurations could be due to the distribution of materials in the room and to the relative distance between source and receivers resulting in an energetic balance between the energy arriving to the receiver position before and after 80 ms. Definition (D50 and D80) are not conclusive parameters, as non remarkable differences are observed. Centre time (Ts) is higher for the circus configuration, with a difference of the same order of the JND; consequently, this parameter may be useful to distinguish both configurations. As it can be seen in Fig. 5, the Ts frequency response for the theater configuration is flatter, but the response for the circus configuration obtains higher values at mid frequencies, specially in the bands related to the speech. Being both responses within the typical margins included in ISO 3382-1, the flat response of the theater configuration is more appropiate for music performances compared to the circus configuration where the Ts frequency response is less flat.

Regarding the echo criteria (ECmusic and ECspeech), results shown in Table 3 indicate that the median values are below the strictest values of the criteria (10%) for both configurations and for both criteria. However, maximum values of ECspeech for both configurations are above the proposed threshold; it means that, in both cases, at least there is one receiver position where an echo could be noticed for a speech signal. In any case, if the median value is set as representative of the 50% of the assessed positions, it could be said that this fact is a localized phenomenon, which is most prominent for the circus configuration. It is expected that this echo effect appears just in isolated positions of the stalls closest to the stage. Fig. 6 (left) shows, for both configurations, the minimum, median and maximum values for ECspeech, together with the threshold (factor 0.9) according to the strictest criterion (10%). In Fig. 6 (right), it is possible to observe a curved wood reflector on the vault that could be the cause of the echoes in some of the receiver positions. A further study of the premises with an acoustic simulation model may allow to discover the real effect on echoes of the curved reflector and the circular geometry.

In order to analyze in depth if this is an isolated phenomenon, the ECspeech values as a function of source distance, for each receiver position, have been considered, as it can be seen in Fig. 7. It is noticed that for the theater configuration this is truly an isolated phenomenon in a position located at a distance less than 19 m to the source; for the circus configuration, echoes also appear in two out of the eleven receiver points and for those two points

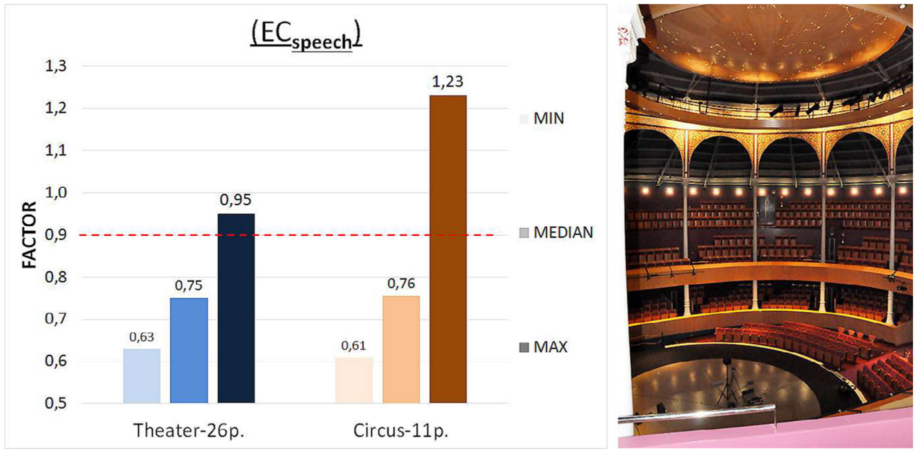

Fig. 6. Comparative statistics of probability (10%) of noticing echoes (ECspeech) (left). Detail of the curved wood reflector on the vault of the premises (right).

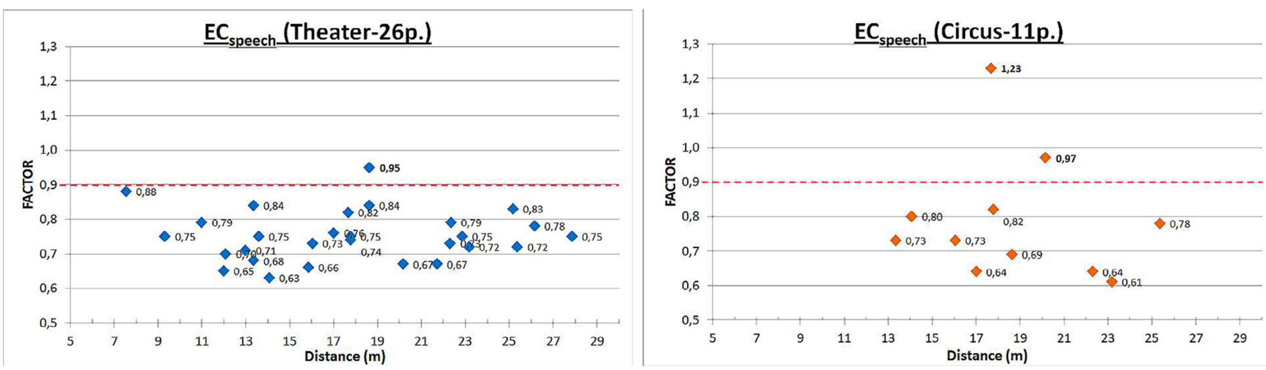

Fig. 7. Spatial location of positions with probability (10%) of echo (ECspeech).

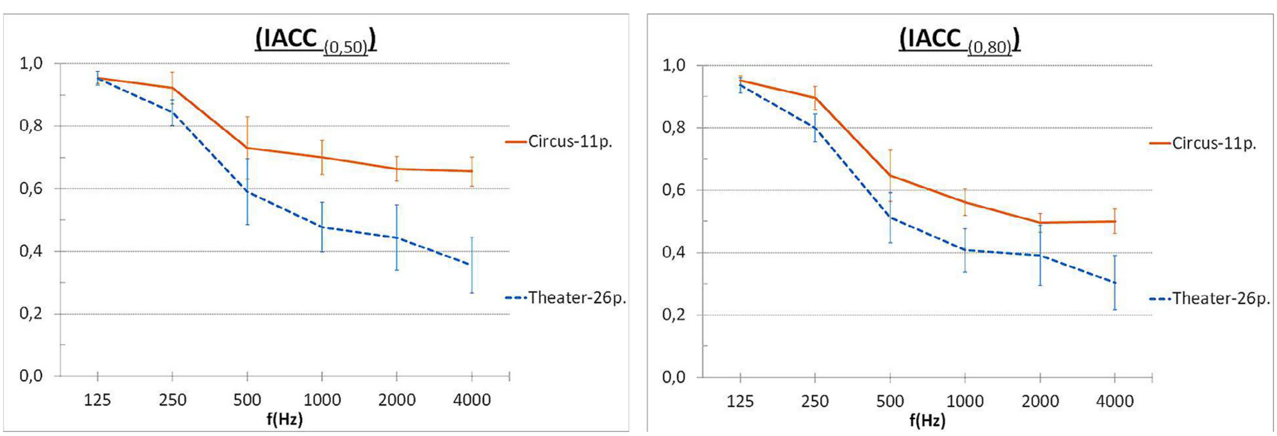

Fig. 8. Binaural parameters for early reflections: IACC(0,50) (left) and IACC(0,80) (right).

the distance to the source is also around 19 m. This induces the suspicion that it may not be by chance, but a harmful reflection could be the cause; possibly this reflection is provoked at some surface close to the vault or even at the curved reflector on the top (see Fig. 6 right).

Within the Group 4 that characterizes the apparent source width, the difference between JLF in both configurations is smaller than the corresponding JND and therefore, this parameter cannot help to distinguish between both configurations. Values for the theater configuration are slightly above those for the circus configuration. This means that the sound source would evoke the sensation of being a bit bigger in the theater configuration than in the circus. On the other hand, the source location perception would be better for the circus configuration.

Group 5 deals with the listener envelopment. The behavior of the binaural parameters is, independently of the integration interval, decreasing with the frequency. According to the data in Table 3, the IACC parameters that better differentiate both configurations are those related with early reflections, specially in the case of small integration time. For IACC(0,50) and IACC(0,80) the differences between configurations are quite above the corresponding JNDs; therefore, those parameters are chosen also as differentiating

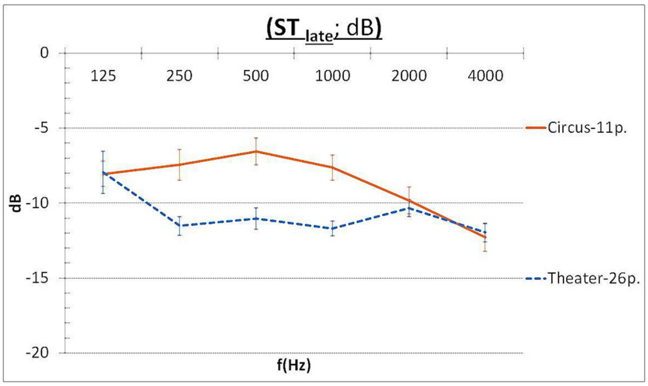

Fig. 9. On stage parameter (STlate).

parameters between both configurations. Fig. 8 shows the values for both parameters and for both configurations; it can be noticed that differences between configurations increase with the frequency, being higher for smaller integration periods. Deviation bars indicate that there is a higher dispersion of values for the theater configuration; this means that the listener envelopment perception has a stronger dependence on the relative position of the listener in the theater than in the circus. The binaural magnitudes assess the similitude of sound between both ears of a HATS; the results suggest that there is a weaker envelopment perception fo the circus configuration, as if the signal had been emitted from a monophonic source placed in the middle of the circus stage. On the other hand, the theater configuration produces a sound diffusion perception that allows a better sensation of envelopment. The differences will be more noticeable for speech signals than for music signals, although although they will be perceived in both cases [20].

ISO 3382-1 does not include JND thresholds for parameters of Group 6 to characterize the perception on the stage, and consequently, it is not possible, for this set of parameters, to compare the difference between both configurations to the corresponding JND as it was done for other parameters. However, results on Table 3 reveal that the values of early support are quite similar for both configurations, but there is a clear difference for the late support. The spectral results shown in Fig. 9 indicates that the perceived reverberation on stage is higher for the circus configuration; this could generate a non-pleasant sensation in the musicians by an excess of reverberation on the circus stage. Since the greater differences are observed in medium frequency bands, and the corresponding single number quantities are calculated using these bands (250 Hz to 2000 Hz), the difference between both configurations concerning the stage parameters is clearly seen in Table 3.

5. Conclusions

The singularity of a premises like the Circus-Theater of Albacete, that still nowadays can offer shows in theater and circus configurations, has triggered the interest to evaluate and quantify the acoustic differences between both configurations. In this work, the acoustic characterization has been carried out considering the data coming from objective “in situ” measurements for both configurations. The parameters used are those proposed in ISO 3382–1, as well as other additional parameters that are quite common in room acoustics; all the parameters are related with the listener subjective perception.

The results of the single number frequency averaged values have shown noticeable differences (above the corresponding JNDs thresholds when known) between both configurations for the following parameters: sound strength (G), early decay time (EDT), reverberation times (T20 and RT), centre time (Ts), echo criterion (ECspeech), listener envelopment (LEV) relative to the early binaural magnitudes (IACC(0,50), IACC(0,80)), and the late support on stage (STlate).

These differences indicate that a listener in the circus configuration would have a subjective perception of greater sound source strength, slightly higher reverberation, but poorer envelopment. Furthermore, concerning the stage characterization, it is observed that musicians on the circus stage would appreciate a stronger sensation of reverberation than in the typical positions of the theater configuration. On the other hand, the subjective aspects that remain common for both configurations are the perceived clarity of sound and the apparent sound width; their differences are so small that no conclusions can be made from those values.

Besides, the results for both configurations are compared with typical results for auditoria (annex ISO 3382-1), it can be stated that the characteristics of this Circus-Theater match the typical margins for an auditorium, being the most significant differences between both configurations and the reference for auditoria the sound strength and the late support parameters; in the case of the circus configuration, the late support value is slightly off of the recommended single value.

This study is the first of its kind that characterizes a premises like a Circus-Theater through “in situ” measurements for both configurations. The results, apart from stating the acoustic differences between both configurations, will allow in the future to validate and properly tune a simulation model for this premises and similar ones. The use of validated and properly tuned models is key to restoration and intervention processes, specially when altering the geometry and/or the materials is an option. Additionally, such models are essential to auralization processes, with which the acoustic perception can be evaluated for different premises configurations.

The study of this kind of premises is a new field of research with a long path ahead. This type of focalized research undoubtedly contributes to the better understanding of acoustics in different theater halls.

Author statement

All the authors certify that all of them have seen and approved the final version of the manuscript being submitted. They warrant that the article is the authors’ original work, hasn’t received prior publication and isn’t under consideration for publication elsewhere.

Declaration of Competing Interest

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

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