On the assessment of the multiplicity of spaces in the acoustic environment of cathedrals: the case of the cathedral of Seville.

Highlights:

- Acoustic assessment of the cathedral of Seville is carried out
- Different spatial configurations and their acoustic environment are analysed
- Acoustic influence of audience, decoration and music motifs is evaluated
- Adaptation of acoustic environments for the same piece of music is developed
- A subjective preference for slow tempo and musical bass passages is observed

On the assessment of the multiplicity of spaces in the acoustic environment of cathedrals: the case of the cathedral of Seville.

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Abstract

Depending on the type of configuration to be adopted there are multiple forms of occupation of a cathedral which can significantly influence the acoustic environment. As a result, several activities with different acoustic requirements, including preaching and the musical performance of a song or piece can coexist during the same ceremony. Therefore, the requirements needed to achieve suitable acoustic conditions may vary depending on the type of configuration.

This article presents the development of the multiple spaces inside the cathedral of Seville, the largest Gothic church in the world. The aim is to evaluate the acoustic environment of the cathedral, which has an exceptional multifunctional character, in terms of the different configurations generated inside for concerts and other unique ceremonies, as well as the varied arrangement of the sound sources to meet the requirements of these events. The in situ acoustic measurement carried out in the cathedral enabled the assessment of the current acoustic conditions. In addition, the use of virtual simulation tools made it possible to recover the sound of past times and to establish its potential in future intervention projects. The evaluation of various configurations established the effects of the occupation, of decoration in the acoustic environment, and of different choral and instrumental musical motifs. This analysis was carried out taking into consideration the objective acoustic parameters contained in ISO 3382 and a subjective approach to the temporal and spatial factors. According to this analysis in a large multifunctional building such as the cathedral of Seville there is no general preference for a specific music motif given that the subjective perception of the sound field depends on the type of configuration, while occupation varies depending on the purpose of the event.

Keywords: Virtual acoustics, religious music, worship acoustics, cultural heritage, cathedral of Seville.

1. Introduction and objectives.

The acoustic complexity of cathedral spaces is due partly to their geometry, materials, and multifunctional character. The wide range of options for the occupation of a cathedral requires the potential evaluation of the suitability of these churches as venues for events, depending on aspects such as the position of the sound source [1], the configuration of the space [2], the percentage of occupation [3] and the decoration [4, 5], as well as the type of activity carried out [6, 7], both choral and instrumental [8]. In recent years, there has been an increase in the number of studies on the acoustic conditions of worship spaces [1, 2,9], mainly examining their current state [10, 11, 12]. However, there is little research analysing the behaviour of these spaces in the past, taking into account the multiple configurations within the single space [6].

From an architectural perspective, the choir of the cathedral is crucial in generating and transforming interior church spaces. On occasion, the shape and location of the choir lead to major modifications of the interior spaces, as in the case of Seville cathedral, which follows what is known as the "Spanish configuration" [13]. Several Spanish cathedrals, following the recommendations of the Council of Trent, moved the choir space from the centre of the nave to other locations around the presbytery, prompting major spatial and acoustic transformations [2]. In other European typologies the positioning of the choral space marks the main difference in relation to the Spanish model. Unlike the Spanish model, the other two European models allow for the occupation of large audiences along the central nave in all kinds of celebrations, with the source located on the Main Altar.

In the cathedral of Seville, the choir is located in the centre of the church, dividing the central nave into two differentiated areas. One of the areas in front of the presbytery creates a space for preaching where the voice can carry from the pulpits reaching the audience in an acceptable manner. As analysed in a previous study [14], the position of the choral space prevents the depth of the central nave from being used making it necessary to find a configuration that can accommodate a large audience. The different forms of occupation in the cathedral have created multiple spatial configurations to adapt the acoustics of the space to the necessary requirements to ensure suitable acoustic conditions [15].

An acoustic model was used for the development of the study, and was calibrated based on onsite measurements inside the cathedral, following the methodology established for this type of large historical space [8,16,17]. In addition, virtual simulation tools were used to create past configurations, allowing the recovery of sound from past eras [14, 15,18], and the discovery of a method for achieving suitable acoustics in future intervention projects, obtaining the results of the acoustic parameters analysed.

The main aim of this article is the objective and subjective assessment of this acoustic environment for music in the multiple spaces that are part of a Spanish cathedral, in this case Seville, the largest Gothic church in the world. Given the multifunctional nature of the cathedral, the results are evaluated for different configurations with various source positions established. Equally, this paper analyses the influence of the occupation and the ephemeral architecture incorporated for individual events, the performance of different pieces of music for the same scenario, and the adaptation of several spatial configurations for the same piece of music, which will allow the optimal configuration for this typology to be determined.

2. Multiplicity of spaces

Since its construction, the cathedral of Seville has become the most emblematic representative of the cultural heritage of the city, even being used as the model of the Spanish cathedral type exported to Ibero-America. This exceptional model promotes the celebration of great ceremonies, especially liturgical-religious ones, indoors. Although the cathedral was conceived as a space of great historical and heritage value, this is no impediment to its multifunctionality, which allows for the development of individual civil events. In this regard, the cathedral of Seville should be understood not as a single space, but as a series of different spaces with their own acoustic characteristics and function, both liturgical and cultural.

The interior space of the cathedral is articulated around two main longitudinal and perpendicular axes: the central nave and the transept. In addition, the central position of the choir stalls breaks up the space in the main nave, generating a new space, the *trascoro*. Figure 1 shows how the different zones inside the cathedral are organised. For centuries, the multifunctionality of the cathedral space has meant that numerous events have been held in each of the zones generated within the cathedral. In this study, numerous existing configurations have been analysed in different historical stages and in past, present, and future forms. Each configuration corresponds to a virtual model (M) acoustically analysed in the results section.

Figure 1 provides an understanding of the two ways in which the liturgical space can be analysed. These ceremonies have been developed fundamentally along the two main perpendicular axes of the interior cathedral space: the central nave and the transept. Different zones were used depending on the type of event held, as well as the occupation and space requirements. Figure 2 shows the configurations adopted inside the cathedral of Seville for the main celebrations that have taken place up to the present and analysed in this work. The sound source positions most frequently used throughout history in the most common events celebrated inside the cathedral are as follows:

- Source S1: Main Altar [19]: During the 16th century, the few documented events were held mainly in the Main Altar. This configuration follows the traditional way in which the liturgical space was used. This source position is the one used in the calibrated model reproducing the current state of the cathedral.

  Events at S1: this source was used for spatial transformations carried out centuries ago for major festivities such as the Royal Coronation in the 17th century (Model M1), and Easter, in the 16th century (Model M2) [20,21]. It is also important to note the luxurious displays set up for these festivities, transforming the inner space of the cathedral and noticeably affecting the acoustics.

- Source S2: *Trascoro*: this area was originally occupied by the congregation, who remained separate from the presbytery and choir and did not take part in the liturgy.

  Events at S2: Liturgical celebrations held, both ordinary and annual [22], evaluating the occupation and the position of ephemeral architecture (Models M3 and M4).

- Source S3: Transept [11]: this source position noticeably increases the areas suited to the presence of the audience, taking advantage of the depth of the transept nave.

  Events at S3: it should be noted that at present configurations are adopted for holding massive concerts, with an audience of up to 2000 (Easter Miserere model M5 and the Messiah model M6) [23]. Two configurations conceived as future interventions and incorporating proposals for improvement compatible with the heritage character, are also analysed (Models M7 and M8).

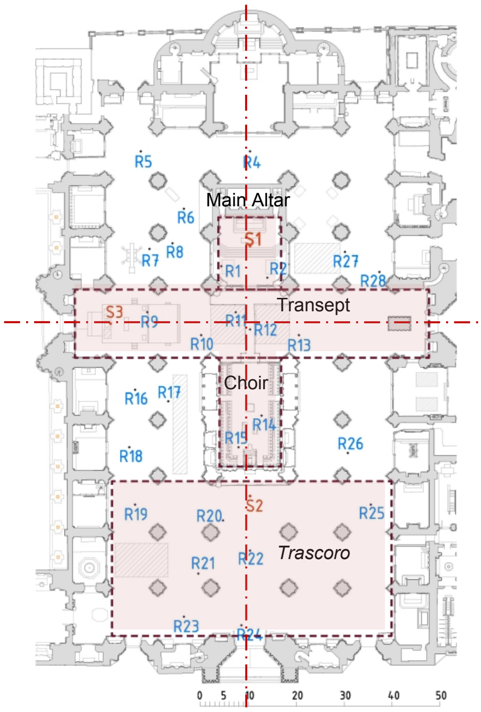

Figure 1. Plan of cathedral of Seville with delimitation of zones. Location of sound sources (S) and receiver points (R) during in situ measurements.

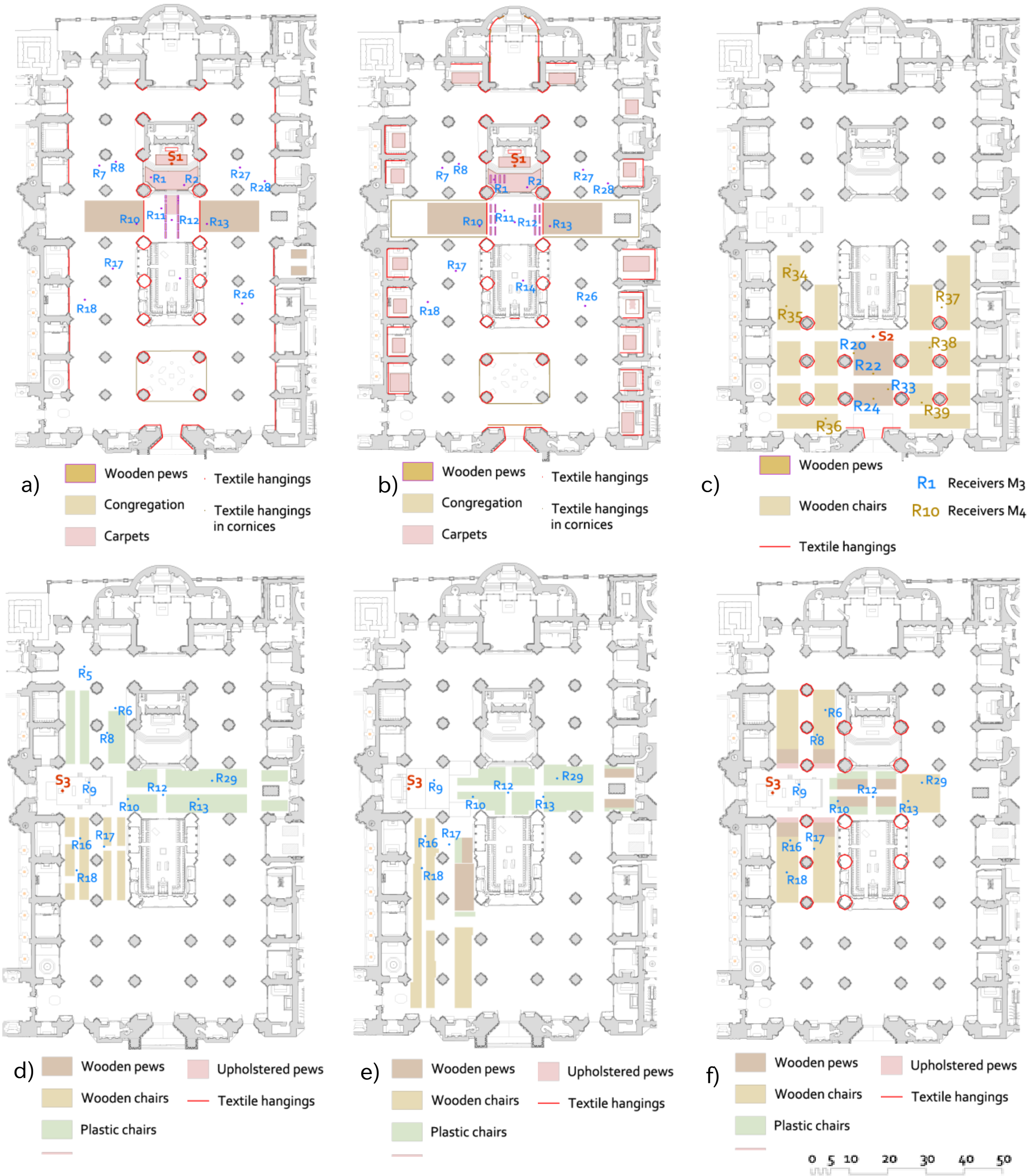

Figure 2. Configurations adopted inside the cathedral of Seville: a) M1; b) M2; c) M3 and M4; d) M5; e) M6; f) M7 and M8.

3. Methodology

Acoustic simulation based on acoustic measurement results is a highly useful tool for predicting the indoor acoustic environment of a space where it is impossible to reinstall ephemeral interventions used in the past. Thus, this technique also allows historic acoustic behaviour to be assessed by offering the chance to recover the sound field of a centuries-old space.

The methodology followed in this work begins with the development of an experimental technique that enables the evaluation of acoustic conditions of the individual spaces of the cathedral. The acoustic parameters obtained from measurements are used for the initial calibration of the simulation model for analysis. Subsequently, several acoustic models were created for the reproduction of configurations adopted at specific moments (M1-M8) in order to assess the effects of occupation, decoration and type of musical piece performed. Thus, sound space reconstruction was recreated virtually and the main acoustic parameters calculated for the comparison of the acoustic sound field of all the configurations specified. Moreover, a study of early reflections and an analysis of the relationship between subjective qualities and the measured acoustic parameters were also carried out.

3.1 Experimental technique

Room impulse responses were obtained in order to characterise the current indoor acoustics of the cathedral of Seville. In this regard, acoustic measurements were carried out at night in the unoccupied cathedral following the guidelines of ISO 3382-1 [24]. The procedure is explained in depth in [14]. Thanks to the low background noise values registered, Impulse response to Noise Ratio (INR), a parameter normally used to determine the quality of the signal recorded and to give a reliable calculation for the acoustic parameters, values over 45 dB were obtained in each frequency band, thus establishing the suitable quality of the signal recorded. In turn, this made it possible to calculate the acoustic parameters reliably [25].

A sine sweep signal was emitted from an omnidirectional dodecahedronsource S (AVM DO-12), with frequency increasing exponentially over time. Commercial software (WinMLS2004) was used together with an audio interface (EDIROL UA-101) to generate the sweep signal, with a duration set to 20 s and covering a frequency range from 63 to 16 kHz using a power amplifier (B&K 2734). The sound source was located at the three positions analysed in this study at a height of 1.50 metres from the floor. Impulse responses were recorded using a multi-pattern microphone (Audio-Technica AT4050/CM5), placed at a height of 1.20 metres at different points throughout the audience area.

3.2 Model calibration and acoustic simulations

SketchUp 3D modelling software was used to create a virtual acoustic model of the cathedral of Seville, based on plans and sections which describe the complex geometry of its interior space. The model, with an approximate volume of 200,000 m^3, was exported to CATT-Acoustic v9.0 [26] to carry out the acoustic assessment. The acoustic simulation used TUCT v1.0d software, a calculation engine known to be effective in the prediction of the acoustic parameters [27]. The number of rays used in the simulations was determined manually (300,000), after tests showed the number of rays was sufficient and converged. The length of the room impulse response, that is to say the truncation time, was also set manually, since it should be longer than the measured reverberation time (7 s).

The effects of reducing the area and sound dispersion associated with this simplification are compensated for by assigning suitable scattering coefficients to each surface. The geometrical simplification of the ornate decoration significantly reduced model computation time, allowing the sound diffusion generated by a large percentage of surfaces to be classified. There are two main reasons for scattering: i) surface irregularity, as given in absorption; and ii) surface scattering is greatly dependent on size versus wavelengths. A small irregular surface will therefore have both. However, with frequency the first consideration typically increases while the second decreases. In this regard, the small size of surfaces in relation to wavelength should be taken into consideration. In addition, scattering coefficients have frequency dependence, an important aspect in such a highly ornamented place.

In this study, the average scattering requires the application of different grade scales adopted depending on the measurements of the irregularities of the area considered. Scattering values vary from 12-18% in the 125Hz - 4kHz range, suitable only for non-ornamented medium-sized surfaces, to 55-80% in the same range when an audience is present.

It should be noted that the absorption in this model is almost the same in three quarters of the surface since stone masonry is the main material in the space. In addition, ornamentation and decoration have considerable influence on the absorption of the cathedral and by extension, on its acoustic parameters. It has been confirmed that scattering has little effect on T_{30}, although when highly absorbing surfaces are introduced in the model, scattering becomes much more important and affects T_{30}. Even with uniform absorption, as in the reference case, scattering affected prediction of measures of parameters influenced by early reflections, such as C_{80}.

A complete calculation of all the acoustic parameters was carried out to verify the acceptability of the results obtained. The simulation process for the calibration of the 3D model was based on an iterative algorithm resulting from the assignment of estimated absorption and scattering coefficients. The acoustic properties of each of the new surfaces were obtained from contrasted bibliographical sources [14]. Table 1 shows initial absorption and scattering coefficients assigned to the materials used in all configurations, along with the basis for selection. Differences in the threshold of perception between measured and predicted values of the main acoustic parameters were determined in terms of the just-noticeable difference (JND), defined as the smallest perceptible difference of a specific sensory stimulus. In this work, comparisons between measured and calculated values mainly show differences lower than 1 JND for T_{30} (5%), and less than 2 JNDs for evaluating other parameters. However, given the differences in the threshold of subjective perception the estimated consideration for widely reverberant spaces must remain flexible, as noted by Martellotta [28]. The initial acoustic model was validated following the calibration process described extensively in [14]. Figure 3 compares measured values and the corresponding values calculated under the same conditions as well as standard errors in order to confirm the basis of the calibration process. Thus, a solid basis was established for the simulation of acoustic behaviour of the past configurations adopted in the cathedral.

Table 1. Sound absorption and scattering coefficients associated with the main materials used in all configurations.

Material		125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Finishing materials							
Stone masonry* [29]	α	0.13	0.13	0.13	0.14	0.16	0.16
	s	0.12	0.13	0.14	0.15	0.16	0.17
Floor marble [30]	α	0.01	0.01	0.01	0.02	0.02	0.02
	s	0.12	0.13	0.14	0.15	0.16	0.17
Stone mouldings*	α	0.13	0.13	0.13	0.14	0.16	0.16
	s	0.20	0.25	0.30	0.35	0.40	0.45
Royal Chapel masonry*	α	0.10	0.10	0.10	0.12	0.14	0.14
	s	0.12	0.13	0.14	0.15	0.16	0.17
Windows [31]	α	0.13	0.12	0.08	0.07	0.06	0.04
	s	0.12	0.13	0.14	0.15	0.16	0.17
Wood in Choir stalls [32]	α	0.12	0.12	0.15	0.15	0.18	0.18
	s	0.30	0.40	0.50	0.60	0.70	0.80
Carpet on wood flooring [33]	α	0.11	0.13	0.28	0.45	0.29	0.29
	s	0.12	0.13	0.14	0.15	0.16	0.17
Decoration							
Wooden altarpieces [32]	α	0.12	0.12	0.15	0.15	0.18	0.18
	s	0.30	0.40	0.50	0.60	0.70	0.80
Organ [31]	α	0.12	0.14	0.16	0.16	0.16	0.16
	s	0.30	0.40	0.50	0.60	0.70	0.80
Carpets [33]	α	0.08	0.08	0.30	0.60	0.75	0.80
	s	0.12	0.13	0.14	0.15	0.16	0.17
Canvas [4]	α	0.10	0.15	0.18	0.20	0.20	0.20
	s	0.12	0.13	0.14	0.15	0.16	0.17
Cotton curtains folded 7/8 area [30]	α	0.03	0.12	0.15	0.23	0.37	0.42
	s	0.30	0.40	0.50	0.60	0.70	0.80
Densely woven window curtains 9 cm from Wall [30]	α	0.06	0.10	0.38	0.63	0.70	0.73
	s	0.12	0.13	0.14	0.15	0.16	0.17
Lightweight curtains >1 m from wall [34]	α	0.20	0.25	0.30	0.35	0.40	0.50
	s	0.12	0.13	0.14	0.15	0.16	0.17
Pews. chairs and audience *							
Wooden chairs [30]	α	0.12	0.12	0.15	0.15	0.18	0.18
Plastic chairs [30]	α	0.06	0.10	0.10	0.20	0.30	0.20
Wooden pews [30]	α	0.10	0.15	0.18	0.20	0.20	0.20
Upholstered pews [30]	α	0.30	0.32	0.27	0.30	0.33	0.33
Occupied wooden seats [30]	α	0.24	0.40	0.78	0.98	0.96	0.87
Occupied plastic seats [35]	α	0.30	0.50	0.80	0.80	0.90	0.80
Occupied wooden pews [36]	α	0.23	0.37	0.83	0.99	0.98	0.98
Standing audience (2 pers/m^2) [30]	α	0.26	0.46	0.87	0.99	0.99	0.99

*Scattering coefficients for audience 0.55, 0.60, 0.65, 0.70, 0.75, 0.80

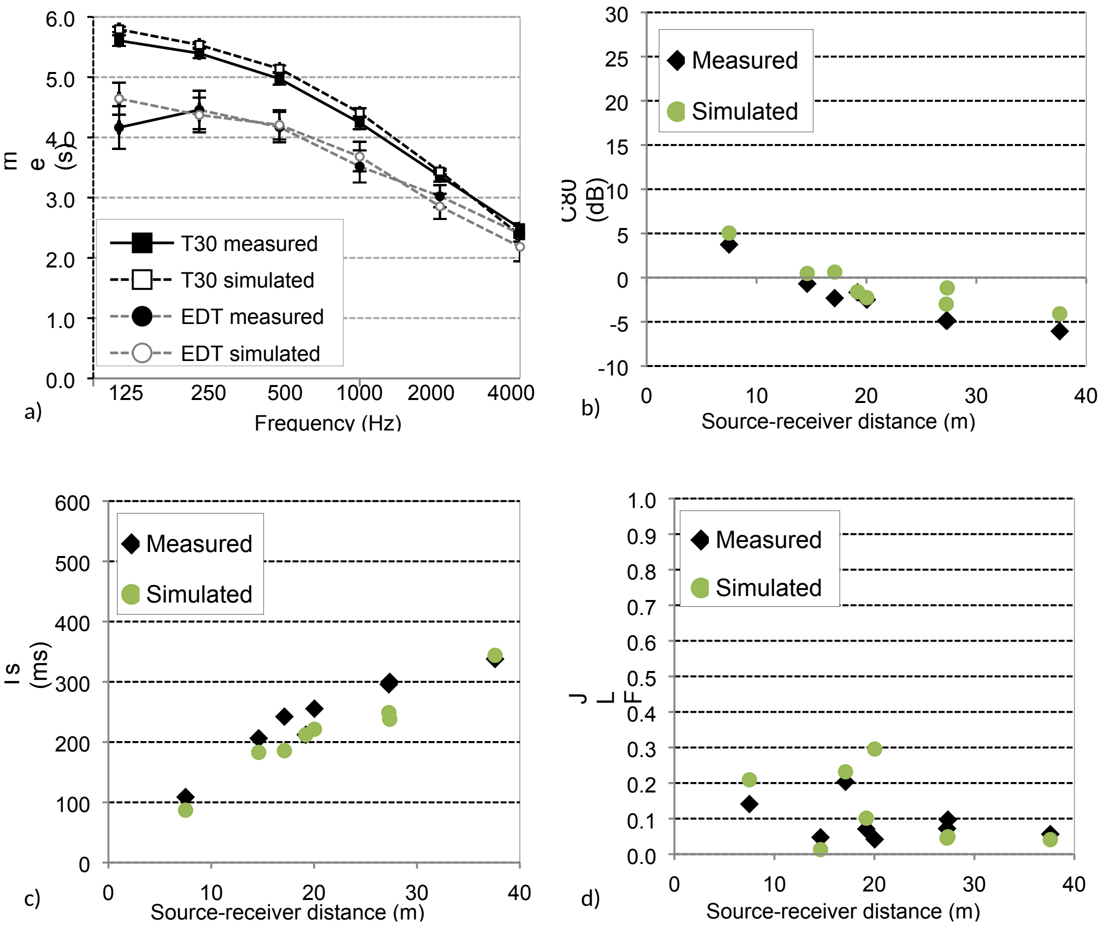

Figure 3. a) Comparison between measured and simulated values: Spectral behaviour of spatially averaged acoustic parameters T_{30} and EDT; c) Values of individual seat positions respect to source-receiver distance: b) C_{80}, c) T_s and d) J_{LF}.

New virtual models were created to reproduce past configurations adopted in the cathedral of Seville (Figure 2), with Table 2 providing descriptions of individual configurations. Some changes required the incorporation of new elements such as decoration and / or an audience area. Other interventions required variations in the sound source position depending on the different types of music performed. RIRs from all source positions enabled the development of a detailed analysis of various spatial transformations.

3.3 Acoustic parameters

Objectively, the most recurrent acoustic evaluation method and the acoustic parameters usually considered are those presented in ISO 3382-1 [23]. Based on this approach, most studies measure acoustic parameters in several positions and calculate average values and standard deviations of these parameters to describe the acoustic quality of the space [37].

In contrast, from the subjective position, scientific contributions from researchers have identified different methods for acoustic assessment. Evaluation of the acoustic behaviour of a worship space is difficult to quantify, given that certain authors have shown that it has an important perceptive consideration, as well as a variability dependent on factors such as size of the room, musical motif, or the purpose of the event. One of the most frequent evaluation methods, also used in this work, is the discrimination of the subjectively perceived sound, which is discussed in terms of JND [38]. In addition, it has been verified that spatial impression can be divided into several perceptual properties, such as spaciousness, size impression, and reverberation [39]. At present, virtual reality techniques are also applied to combine sound and visual perception within worship spaces. Postma and Katz present an overview of the different essential elements needed to achieve an immersive experience by carrying out a subjective judgement of measured and simulated RIR auralizations [17]. Ando stated that the acoustic properties at specific seats in a space should be evaluated in relation to the subjective preferences of the audience, and it was found that the individual differences in subjective preference for orthogonal acoustical parameters and the audience can potentially identify the preferred seat [40]. Ando's model of hearing is based on brain activities and implies that the sound-processing capabilities of human' brains have a noticeable effect on the description of subjective parameters.

In this work, the acoustic analysis of the multiple configurations of the cathedral of Seville was carried out by evaluating the acoustic environment both in terms of the objective acoustic parameters defined in ISO 3382-1 [24], and of the four orthogonal parameters for subjectively perceived sound in the temporal design of the sound field [40,41].

The parameters considered in the objective analysis are as follows:

- The quantification of the reverberation is presented through the analysis of the time parameters, that is to say, reverberation time (T_{30}) and Early Decay Time (EDT). T_{30} was the main factor considered in the calibration process, but also other parameters such as C_{80}, D_{50} and Ts were also taken into account [14].
- The analysis focuses primarily on the musical quality of the cathedral, given the wide variety of music performed there. This study therefore focuses on the values provided by parameters such as clarity (C_{80}), which measures the range of the listening perception for musical performance, and the centre time (Ts), associated with the balance between early and late energy reaching the receiver.

Given the links discovered between acoustic parameters and perceptive aspects of human hearing, the hearing model defined by Ando [40] was taken into consideration in subjective analysis. In this study, Ando's method was used because temporal data are considered to contain information on important musical qualities, a factor to be taken into account when assessing musical purposes of configurations adopted in the Cathedral of Seville. The following parameters are considered:

Table 2. Configurations adopted inside the cathedral of Seville

Model	Sound source	Configuration	Period	Audience	Decoration
M1	S1 – Main Altar	Royal Canonization	16th century	Medium	Dense
M2	S1 – Main Altar	Easter	16th century	Medium	Medium
M3	S2 - *trascoro*	Liturgical ceremonies	20th century	Slight	Slight
M4	S2 - *trascoro*	Liturgical ceremonies	20th century	Massive	Medium
M5 – M6	S3 - Transept	Musical concerts	21st century	Massive	Slight
M7 – M8	S3 - Transept	Improvement proposals	Future project	Massive	Medium

- Temporal factors: The delay of first reflection (Δt1), defined as the physical time between the direct sound perceived by the listener and the first reflection; and the subsequent reverberation time of the signal after the early reflections (Tsub), which coincides with T_{30} and is calculated following conventional procedures.
- Spatial factors, Listening Level of sound (LL), coincides with SPL (A-weighted) and describes the spatial distribution inside the cathedral; while Inter Aural Cross Correlation (IACC) measures the similarity in sound signals arriving at each ear of the listener.

3.3.1 Subjective preferred conditions

The spatial complexity and unique geometry and materials that characterize the cathedral of Seville make it difficult to determine the optimal values of acoustic parameters for speech or musical performance within a cathedral space. Given the shortage of references relating to subjectively preferred sound qualities in large spaces, the optimal values recommended for large concert halls proposed by Gade [42] were considered for the objective analysis, displaying some flexibility in establishing the ideal ranges of sound quality of the cathedral.

When applying the orthogonal parameters defined by Ando it is necessary to first calculate the corresponding scale value of preference (Si-value) which determines the approach to the preferred listening conditions. The majority of the preferred conditions are defined based on the actual duration of the autocorrelation envelope (τ_e), which is largely dependent on the type of sound signal emitted, that is to say, the type of music repertoire. Martellotta established a value of 26 and 90 ms for Gregorian and Alleluia chants, respectively, and 70,136 and 150 ms for orchestral music, in this case Bruckner's Romantic Symphony, Mozart's Overture, and organ, respectively (Table 3). These values confirm that subjective sensation is greatly dependent on the individual piece of music performed. In fact, subjective preferred conditions for certain acoustic parameters including C_{80} and Ts inside an ecclesial space can differ in relation to less reverberant spaces [43]. The research conducted by Ando [44] provides a detailed calculation process which was later adapted to church spaces, where a simplified approach was followed, assuming the preferred delay time ($\Delta t_1 p$) equal to the τ_e value resulting from the various pieces of music [2,40].

Table 3. Values of temporal factors depending on the individual piece of music.

Music		**$[\Delta t_1]_p$**	**$[T_{sub}]_p$**
Chant	Gregorian	90 ms	2.09 s
	Alleluia	26 ms	0.6 s
Instrumental orchestral	Mozart's Overture	70 ms	1.6 s
	Bruckner's Symphony	136 ms	3.08 s
	Organ	150 ms	3.70 s

Conventionally, the preferred listening level of sound is evaluated assuming that the sound level is at a specific point of the audience area. In the case of the cathedral, this is considered to be a point located in the middle of the audience area, 15-20 metres from the sound source. Finally, it should be noted that a recent work [45] has shown that perception of the IACC parameter in large reverberant spaces is not greatly influenced by the dissimilarity of signals arriving at each ear.

4. RESULTS.

In this section, the multifunctional character of the cathedral of Seville is evaluated through the analysis of the various configurations adopted (Figure 2, Table 2), considering different positions of sound source, occupation, decoration and musical performance. Acoustic analysis was divided into two stages: the initial evaluation of objective acoustic parameters followed by a subjective analysis, taking into consideration the temporal and spatial factors studied by Ando [29].

4.1 Acoustic assessment of the configurations

Table 4 shows the spectral values of T_{30} (s) and EDT (s) obtained from measurements, and spatially averaged for each source position considered in this research. As stated in Table 5, the multiplicity of different zones inside a single space is determined when analysing T_{30} and EDT, as mean values vary depending on the zone assessed. In the case of T30 a difference of 1 JND is observed in the *trascoro* compared to the other areas, while a difference of up to 4 JND is observed for EDT. This can be explained by the creation of a space delimited by walls, where there is an increase in the first reflections on the stone surface. The results of the parameters in ISO 3382 indicate the high reverberation of the cathedral, and are 2 seconds away from 2.8 s, the optimum value considered based on the theoretical values proposed by Beranek [46]. However, it can be observed that values are lower than those usually obtained in this type of worship space. One of the reasons for this is the high porosity of stone, a material which covers three quarters of the cathedral. The low density of early reflections in several of the points considered involves a reduction of 0.5 s in EDT with respect to T_{30}. The evaluation of C_{80} is also far from the recommended values. The results reflect the deficient acoustic conditions in the unoccupied space hypothesis.

Table 4. Spectral values of Early Decay Time (s) obtained from spatially averaged measurements (M), for each position of the source.

Sound source		**Frequency (Hz)**						**$T_{30\ m}$ EDT $_m$**
		125	**250**	**500**	**1000**	**2000**	**4000**	
S1	T_{30}	5.88	5.64	5.16	4.42	3.53	2.70	4.79
	EDT	4.57	4.53	4.02	3.33	2.68	1.99	3.67
S2	T_{30}	5.89	5.66	5.34	4.74	3.82	2.91	5.04
	EDT	5.03	5.28	4.88	4.38	3.50	2.63	4.63
S3	T_{30}	5.77	5.51	5.09	4.37	3.49	2.61	4.73
	EDT	4.70	4.90	4.54	3.89	3.27	2.57	4.22

In contrast, the assessment of the different configurations adopted in different time periods (Figure 2) is analysed taking into consideration each of the sound sources. Table 5 shows calculated values for each condition for direct comparison and to ensure the transparency of the simulated results while Figure 4 depicts the differences between spatially averaged values of all configurations expressed in JND:

- Source S1: After the evaluation of the past spatial transformations for major festivities (M1 and M2), unique differences are observed in the results. The inclusion of extensive ephemeral architecture during the Royal Canonization (M1) reduces T_{30} by 5 JNDs and by close to 4 JNDs in the case of EDT. Variations of 2 and 4 JNDs can also be observed for the other parameters, C_{80} and Ts respectively. In the case of the adoption of configuration M2, with textiles closing off the entrances to the side chapels, a greater acoustic influence is observed, with a decrease of 6 JNDs with respect to the current state model. Despite incorporating a smaller area of textile material than in M1, and the textile being of lower density, a large percentage of sound energy is obstructed inside the chapels as a result of the virtual reduction in volume due to the chapels being closed off with energy-absorbing and -transmitting fabrics. However, the occupation area, with similar percentages in M1 and M2, does not generate significant acoustic changes compared to those produced after the inclusion of decoration.
- Source S2: The configurations adopted in the *trascoro* (M3, and M4) are evaluated and following the assessment of the results it is concluded that the occupation of 160 m^2 of the central nave (M3) reduces the EDT parameter with respect to the current state model by almost 1 s. In the case of the other acoustic parameters, more satisfactory values are also obtained, with an increase of almost 2 JNDs in C_{80} in points close to the source, or of 1

JND in receivers located at 20 metres. After the addition of textile hangings on the pillars an improvement of 2 JNDs is noted in the 1 kHz band of the EDT parameter. In addition, when considering massive occupation (M4) (1000m^2 of area), there is a remarkable variation, reaching differences higher than 3 JNDs for C_{80}, with acceptable values 30 metres from the source. However, the lack of direct sound due to the presence of numerous 3-metre-wide pillars impedes suitable acoustic conditions in a large percentage of the area occupied by the audience.

- Source S3: The adaptation of the indoor space to the massive concert configurations (M5 and M6) increases acoustic absorption due to the audience. This implies a difference of up to 4 JNDs with respect to the current state model in parameters that evaluate reverberation, such as T_{30} and EDT. In the case of C_{80}, acceptable values are considered up to 30-35 m of distance from the source. In the case of Ts, the most significant differences are observed at the points located close to the source, diminishing from 25 metres.

  The partial achievement of the recommended acoustic conditions requires the incorporation of improvement proposals (M7 and M8). The delimitation of an audience area and the arrangement of an ephemeral grandstand to accommodate the furthest positions of audience (M7) reduce the objective reverberation time by up to 1 second. In contrast, the use of heavyweight textiles to cover a large percentage of the stone finishes further reduces T_{30} to 5 JNDs. This significant decrease in reverberation is the closest to the optimal values considered. In the case of C_{80} and Ts, it is worth highlighting the results obtained at the receiver points located in the stand, where the sloping surface generates an increase in early reflections. Therefore, although EDT is slightly higher than the average optimum time, the acoustic conditions of the M7 and M8 configurations can be considered to be acceptable proposals.

Table 5. Simulated results for each configuration of main acoustic parameters.

	M1	M2	M3	M4	M5	M6	M7	M8
T_{30}	3.39	3.84	4.21	3.29	3.90	3.81	3.91	3.53
EDT	3.06	3.24	3.25	2.64	3.07	3.19	2.87	2.62
C_{80}	1.81	1.19	-0.34	2.58	-0.12	-0.20	0.20	1.66
T_S	140.2	154.0	190.9	152.4	163.6	168.3	151.7	128.5

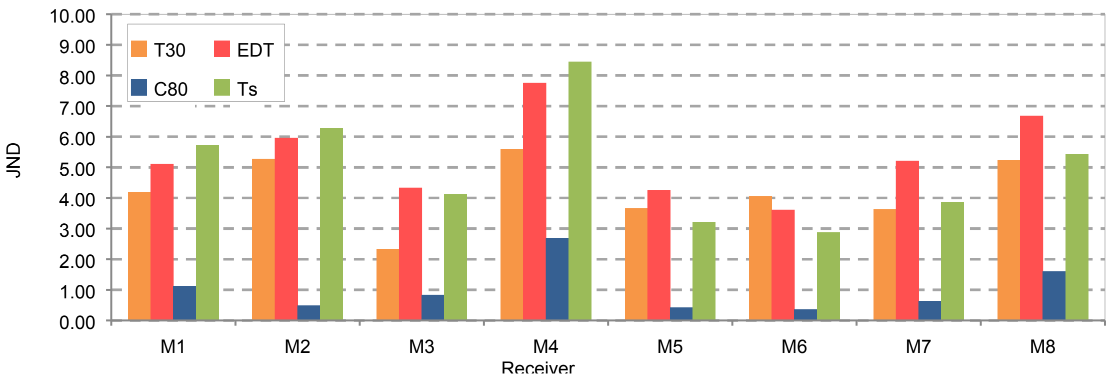

Figure 4. Differences in JND between spatially averaged values of all configurations (M1 to M8).

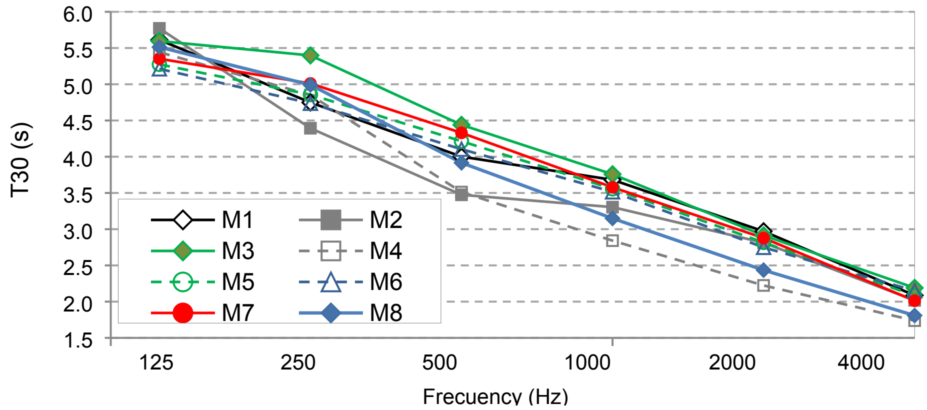

Figure 5. Spectral behaviour of T_{30} spatially averaged for each configuration.

4.1.1 Subjective assessment of the effect of audience and decoration considering various source positions

The analysis of the past configurations detailed below follows an approach which considers the temporal and spatial factors. Firstly, the analysis considers the different historical transformations with the same sound source location, so that it is possible to focus directly on the variations of the model configurations (addition of audience or decoration). Secondly, the assessment compares the results when the sound source varies the position in the cathedral, paying particular attention to the values obtained in receivers that are present in all configurations in order to be able to highlight the preferred configuration for improving acoustic conditions.

In the first part of the analysis, it was possible to observe which model was acoustically more suitable by analysing the total scale value of preference (Si). Gregorian chant was considered as a piece of music performed in S1 and S3. Therefore, the same τe was selected in the obtainment of the parameters in attaining the models, since the same piece of music was considered.

However, varying sound source positions greatly affects the arrival of the early reflections at receivers. This fact significantly affects the results of Si since the scale value determines the sum of four preferred listening conditions, assuming a direct relationship between the most preferred delay time and the actual duration of the autocorrelation envelope (τe).

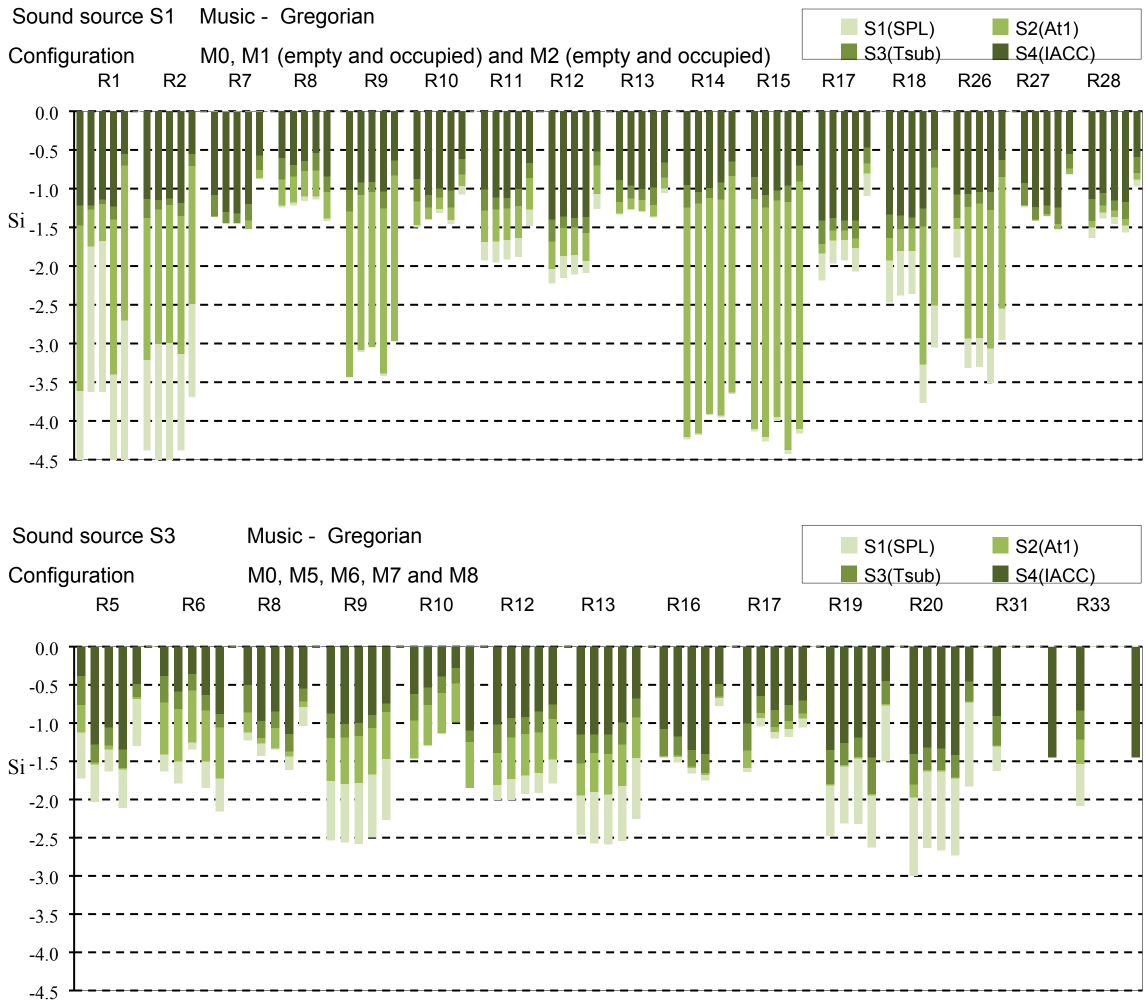

Figure 6. Influence of various configurations of the cathedral in the orthogonal parameters considered on the linear scale value of each receiver, from the same sound source.

Source S1: Figure 6 shows an increase of the negative effect, mainly on the delay of the first reflections, at the closest points R1 and R2, since the short distance S-R generates an extremely early reflection, far from the preferred value in Gregorian chant (τp≈91 ms). A similar situation can be seen in R14 and R15, located inside the choir area, where the proximity of stone walls notably affects the arrival of first reflections. Taking into consideration the influence of audience and decoration in the results, Gregorian chant involves a preferred reverberation that greatly differs from the long reverberation time obtained in the cathedral, so that Si-value of Tsub temporal factor is notably reduced after the addition of a very high percentage of decoration (M1). Variations in Tsub Si of the other configurations do not generate big differences from M1.

On the one hand, when receivers are taken into account, it is observed that the sum of Si-values in R7, R8, R10, R11, R12, R27, and R28 attain a result below 2 points, since they are located at a distance of 15-20 metres in the middle of the audience area, coinciding with the preferred sound level (LLp), which generates a positive effect on the results. In addition, when considering the total Si value of the configurations, it can be confirmed that, as in the previous analysis of objective acoustic parameters, model M2 provides the best acoustic quality with the shortest scale value.

The reduction in volume due to the location of curtains at the entrance of side chapels generates values close to 1 point in the subjective preference.

Source S3: When analysing configurations adopted along the transept, the results show visible variations between models. Consequently, despite the fact that the addition of improvement proposals (M7 and M8) reduce temporal factors scale value, since T_{sub} approaches the preferred value, the total Si (sum of temporal and spatial factors) does not always involve a reduction in the total scale value Si. Si of spatial factors makes a noticeable difference, except in the points closest to the sound source, where first reflections are extremely short. High values of the LL factor are obtained at the closest points. Values differ from the preferred value (LLp) by almost 10 dB. Generally, IACC is the parameter with the greatest negative influence on the subjective preference due to the arrival of similar signals at two ears (or at least, the perception) that provides more than 1 point of the total scale value at almost all points considered. This is due to the binaural sensation being perceived as monaural within the cathedral, since IACC values are far from 0. This fact means that an improvement of the acoustic conditions from a subjective approach is strongly dependent on spatial factors (IACC and LL).

It should be noted that when values below 2 are obtained in the total scale value, this determines a better general distribution of the audience, and therefore, a more suitable position of S3 with respect to S1 in terms of best acoustic quality.

4.2 Subjective assessment of the acoustic quality considering various pieces of music

The same configuration was considered in the assessment of the acoustic quality when different pieces of music are performed. This approach enables the evaluation of the effect of the type of music in one specific model of the cathedral of Seville. Figure 7 shows variations of each orthogonal parameter, depending on the type of music. As stated in previous sections, there are four types of music, each with a different duration of the autocorrelation envelope (τ_e): Alleluia and Gregorian as choral chants, Bruckner's Romantic Symphony and Mozart's Overture as orchestral pieces and Organ as instrumental music. Therefore, in this type of analysis, the two temporal factors, both the subsequent reverberation time and delay of first reflection have a notable effect on the variation of the total scale value (Si), whereas the selection of the same configuration means that spatial factors maintain constant values.

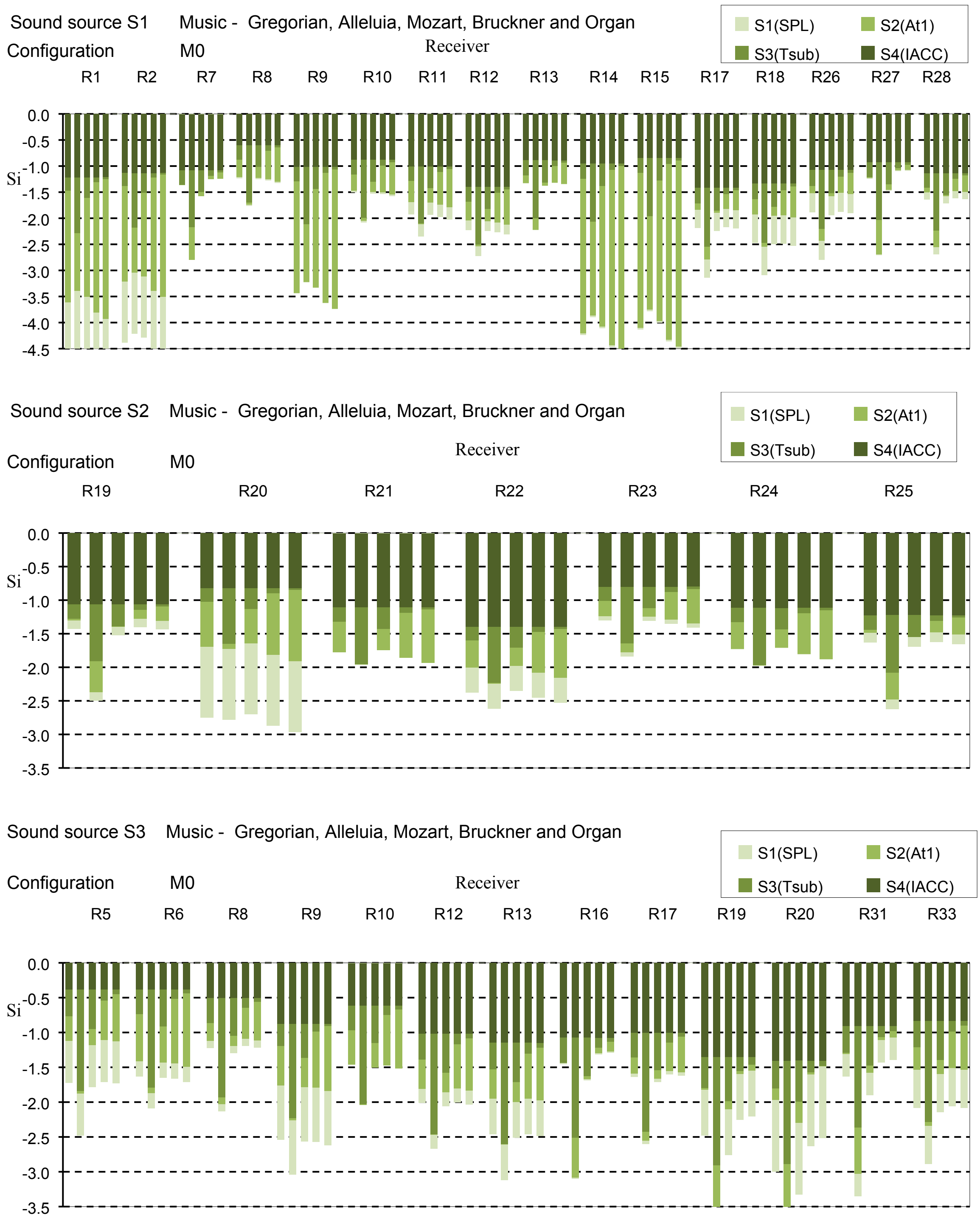

Figure 7.Influence of five separate pieces of music on the orthogonal parameters considered on the linear scale value of each receiver.

As can be observed in Figure 7, the perception of the sound field when different pieces of music are performed depends on the preferred values of temporal parameters. The mid value of reverberation time in the cathedral is almost 5 seconds, which is far from the optimum reverberation time value for the Alleluia chant (Table 1). Nevertheless, the lengthening of the syllables during the Gregorian chant drastically improves the sound quality by reducing Si-value. Generally, the longer these are, the better suited to the acoustic behaviour of the cathedral. Thus the strong negative effect of Tsub scale value determines that chants, requiring short delay time of the first reflection, are the worst option to be performed in configurations where the source is located at S1 or S3.

In the *trascoro* (S2), the orthogonal scale values of temporal factors are counterbalanced, since the presence of numerous columns diminishes the first reflection delay time in most of the receivers. In this regard, the results do not greatly differ from the optimum values for this type of music ($\tau_p \approx 20$ ms), thereby obtaining the shortest negative effect of Δt_1, which compensates for the reverberation effect. However, the long preferred τ_e required for instrumental music generates the opposite effect when an organ performance or a slow-tempo passage of an orchestra is played. Consequently, except for certain receivers, the comparison between all types of music considered in the study shows that there is no significant preference for one in particular when the performance is conducted in the *trascoro*.

Different subjective preferences can be obtained when the same piece of music is performed in a multifunctional space, but selecting a particular configuration in a different zone. In the cathedral of Seville, the acoustic behaviour of configurations located in the transept (S3) or the main altar (S1) differs from configurations adopted in the *trascoro* (S2). In the light of the results, the influence of music motifs is strongly significant and determines the scope of acoustic quality. However, it is also important to consider the location of the source in the same indoor space as it can make the best suitable performance (organ music) the worst configuration where the preference scale value moves away from the optimum conditions (Figure 7 a-c).

5. CONCLUSIONS.

The multifunctional character of the cathedral gave rise to the adoption of different spatial configurations, determined by the position of the choir and the use and form of occupation of the liturgical zones. This study assesses the multiplicity of spaces in the acoustic environment of the cathedral of Seville. In this work, a comparative study of the acoustic behaviour of configurations with different source positions was carried out to provide suitable acoustic methods for the evaluation of the cathedral and to show different proposals for future acoustic renovations. In addition, the influence of occupation and decoration was also analysed, as was the performance of different types of music in configurations adopted in the Cathedral of Seville. The procedure performed requires onsite measurements and acoustic simulations for the prediction of the acoustic indoor environment of the cathedral.

In light of the results, the objective assessment of the increase in sound absorption due to ephemeral decorations or mass occupation improves the acoustic behaviour of each of the different areas of the cathedral. Based on the work done, some points should be highlighted:

- Acoustic evaluation of such a large cathedral is made possible by assessing an analysis with a double focus, taking into consideration musical quality analysis, as it provides both objective and subjective approaches.

- Regarding decoration and space conditioning: A notable influence is observed in the acoustic parameters after the incorporation of extensive ephemeral decoration during the performance of historical ceremonies, especially after the side chapels were closed off with textile hangings, preventing or reducing the transmission of sound energy. The possibilities of space conditioning including the acoustic effect generated by the addition of hangings on the pillars noticeably improved perception by decreasing subjective reverberation. In addition, improvements in acoustic conditions are more noticeable when the textile material is close to the audience.
- Regarding audience: Massive attendance substantially improves the acoustic conditions of the cathedral for the performance of music concerts. Nevertheless, it is necessary to incorporate acoustic renovation proposals such as the introduction of a grandstand or the use of textile materials. The subjective assessment of the effect of audience and decoration considering various source positions confirms a better general distribution of the audience, and in turn, a more suitable position for the source in the transept, guaranteeing the best acoustic quality.
- Regarding the music motif: In terms of temporal and spatial factors, in the case of organ music, the late arrival of first reflections is close to the listeners' preference. This analysis establishes that in a large multifunctional building such as the cathedral, there is no general preference for a specific type of music, since the subjective perception of the sound field depends on the type of configuration and the form of occupation varies based on the purpose of the event.

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