23rd International Congress on Sound & Vibration
Athens, Greece 10-14 July 2016
ICSV23

ACOUSTICAL INFLUENCE OF DIFFERENT LOCATIONS OF THE CHOIR IN THE CATHEDRAL OF GRANADA FROM A SUBJECTIVE AND OBJECTIVE OVERVIEW

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The choir is a space that greatly influences the design and architectural configuration of a cathedral. Cultural influence, the reform of the liturgy and agreements reached during ecclesiastical councils in the last centuries have promoted a relocation of this space. Since its origins, it has been a privileged and reserved enclosure, providing a private character. This space is reserved for the clergy for prayer, preaching, or chant, promoting churches as places where music can be heard. The Renaissance cathedral of Granada in Spain is one of the most important historic religious spaces in southern Europe. Over time, the choir was moved up from the central nave to the back of the presbytery to be finally distributed inside the cathedral. Virtual modelling using geometrical acoustic prediction is a very helpful tool to investigate these choir locations in the acoustic behaviour of the cathedral. Hence, based on experimental acoustic measurements carried out previously, sound space reconstruction was recreated virtually. The creation of a virtual model of its sound field led to the implementation of the three main documented changes. In this paper, the role of the choir within the liturgy was considered in terms of acoustics and the acoustical performance of the evolution of various interventions was analysed. The impact of the relocation of choral space is evaluated from a perspective that analyses the relationship between subjective qualities and the acoustic parameters measured. In addition, the acoustical suitability of the cathedral in terms of the performance of different music motifs is also considered. Therefore, a comparative analysis in terms of temporal design, incorporating the study of early reflections together with the type of music is addressed to investigate the influence on the acoustical performance of the cathedral.

1. Introduction

Speech and music, especially choral music, are two of the main functions carried out in Christian spaces of worship [1]. For this reason, in recent years there has been a notable increase in the analysis of acoustical conditions of churches, in order to establish their suitability, in addition to assessing and promoting their acoustical heritage value during major liturgical celebrations.

The cathedral type stands out in Western religious architecture as it is the main Christian church, given its spatial and functional complexity and its unique size. The interior configuration and organization of these churches depend on the liturgical function carried out and vary depending on how the space is used by the clergy and the faithful, as well as by the form and location of the choir. Alterations of these variables over time could lead to major spatial and functional transformations inside the cathedrals. The cathedral of Granada is one of the most important examples of the vital role of the choir in the cathedral space. The triple intervention carried out changing the position of the choir throughout its history brought about major spatial, functional and acoustical changes.

The interpretation of music in cathedrals can be classified into different types of chant and instrumental music, with acoustical demands varying depending on the music motif. Different studies have explored this matter in depth, determining that the ideal acoustical conditions in a church space display greater flexibility than that required in concert halls. In fact, some research has proven the subjective preference for acoustics with higher reverberation than that recommended for other types of spaces [2,3].

This paper carries out an acoustical assessment of the different spatial transformations of the cathedral of Granada depending on the location of the choir, and introducing the musical condition using a form of spatial-functional identification. The results section is analysed in terms of a temporal design approach, considering the four orthogonal parameters defined by Ando [4]. This new approach requires an experimental study based onsite acoustic measurements, as well as the use of simulation techniques for the assessment of the sound perceived depending on the type of music: choral or instrumental.

2. Spatial and functional analysis of the cathedral of Granada

2.1 Description of the cathedral

The cathedral of Granada, considered one of the most important religious spaces in southern Europe, is a renaissance church with a basilica floor plan, divided into five vaulted naves, a transept that sections the naves transversally, a polygonal ambulatory, and chapels along the perimeter.

The original design by Diego de Siloé in the 16th century aimed to distance itself from the conventional Gothic solution by incorporating the concept of centrality in the head of the temple. However, the solution finally adopted in the cathedral placed the choir in the centre of the space. The central nave was divided into two differentiated spaces, one for the clergy and another for the congregation. The main structure of the building and most surfaces are coated with plaster, with a variety of different finishes. Table 1 shows the main geometric data of the space.

Table 1: Geometric data of the space.

Volume (m^3)	Maximum measurements of the cathedral			Naves	Chapels
	Height (m)	Length (m)	Width (m)		
≈160500	35 / dome: 47	106	63	5	19

2.2 Spatial transformations of the cathedral

The choir is a unique space designed for the representation of chant. The three main different positions of the choir brought about major spatial transformations in the cathedral:

- Configuration M1. Originally the choir space was placed in the middle of the central nave, which it divided into two large differentiated areas. The choir space is designed as a fundamental part of the cathedral of Granada given its influence on the interior space of the church and the location of the congregation. Its presence constituted a physical obstacle to the congregation's view of the high altar (Fig. 1.a).
- Configuration M2. An intervention was proposed in the early 20th century suppressing the choir from the central nave to install it in the main chapel, providing an optimal spatial-functional relationship. However, this modification meant that the two organs which had previously been on the walls of the former choir were left hanging. In addition, including the choir in the presbytery, previously conceived as an open space visible from the ambulatory, would eliminate the concept of centrality (Fig 1.b).
- Configuration M3. The final intervention was carried out in the late 20th century. The choir was eliminated from the main chapel and the openings which connected this space with the ambulatory were reopened, allowing connection with the congregation. The result of this process of spatial and functional evolution is an open floor plan that is completely interconnected in all areas. The new location for orchestras and choral groups is established in the transept area and is studied in detail in this paper.

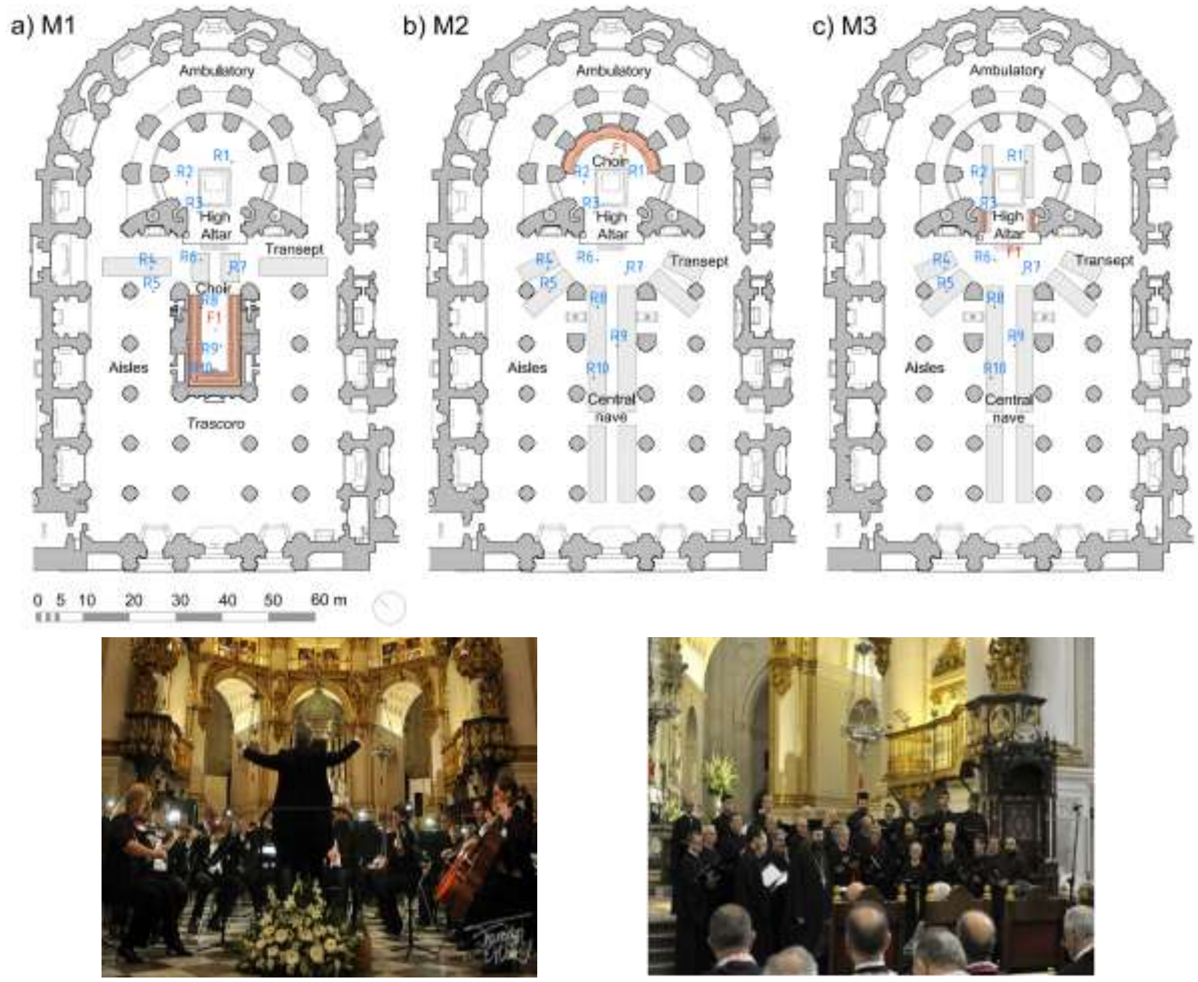

Figure 1: Historical configurations of the cathedral of Granada a) year 1619 (M1); b) year 1929(M2); c) Current conditions, since 1992 (M3); d) Position of orchestra and choir at present.

3. Methods

The methodology followed for the assessment of the perceived acoustical sensation of the different historical configurations of the cathedral of Granada is described according to the music motif performed, categorized into choral (Alleluia and Gregorian chants) or instrumental (Bruckner's Romantic Symphony). Several details relating to the musical pieces selected should be noted: the first chant is characterized by voice modulation; the second is a fragment performed by a choir with four unaccompanied voice parts, with a series of crescendos and diminuendos; finally, the piece for orchestra selected is characterized by a suitable equilibrium in spectral terms and is characterized by a slow initial part moving on to a crescendo [3]. Firstly, a set of onsite acoustic measurements was conducted, based on the guidelines set in ISO 3382 [5], in order to characterize the acoustic sound field of the temple. The calibration process of the virtual model reproducing the current conditions of the space became possible thanks to the development of this experimental technique. In addition, the creation of virtual models of the space in three different historical configurations was necessary in order to research the acoustical influence of the relocation of the choir. The predicted values were provided using the commercial package Catt-Acoustics v9.0c, based on geometrical acoustics (GA) theory. Finally, the values were obtained for temporal and spatial factors depending on the music motif performed: choral or instrumental, in order to carry out a comparative analysis between the acoustical environments of the three scenarios. This was done in two phases: it was firstly necessary to consider the same sound source in the three configurations for the representation of the same music motif, and subsequently the same configuration (M3) was considered using three different pieces of music.

3.1 Experimental technique

Acoustic measurements were conducted at night time in the unoccupied cathedral of Granada. The excitation response of the cathedral was generated by emitting sine swept signals using an omnidirectional dodecahedron sound source (AVM do-12), with frequency increasing exponentially over time. The duration of the sweep was set to 20 s and covered the octave bands from 63 to 16000 Hz with a power amplifier (B&K 2734). Sound source and receiver positions were placed throughout the audience area, at a height of 1.50 meters and 1.20 meters from the floor surface, respectively. Room impulse responses were acquired using a multi pattern microphone (Audio-Technica AT4050/CM5) which directivity switched from omnidirectional to bidirectional in a figure of eight. Consequently, all the acoustical parameters needed for the purposes of calibration were obtained using signal processing.

3.2 Calibration of the model and acoustic simulation

As regards the level of detail used in the construction of the model, it should be noted that the geometry was simplified and cornices and other elements lineally measuring under 50 cm were not included. Although it was necessary to reduce the number of planes, the geometrical base of the model was respected at all times. Values obtained from the acoustic measurements meant that the calibration of the model represented the space accurately. The process was basically generated by adjusting absorption and scattering coefficients and comparing various acoustical parameters using an iterative process. These factors were selected following a visual inspection of the surface of the space. The best adjustment result was obtained with a suitable selection of the characteristics of the stone and its absorption and scattering coefficients.

Conventionally, the calibration process and the acceptance of the model are completed by obtaining JND differences below 1 for T_{30} (5%), and less than 2 when assessing other parameters. However, the calculations for spaces with high reverberation must be more flexible given that the threshold for subjective sound perception shows differences, as reflected in different studies [3]. Figure 2 shows the spectral results of the model tuning process of T_{30}, C_{80} and Ts. A fair adjustment of reverberation time T_{30} with differences of less than 1 JND in all octave bands is observed. As regards the other parameters, it was observed that spatially averaged simulated values were rather similar to measured values, with the exception of low frequency values, where occasional discrepancies appeared, especially for Ts, slightly exceeding 2 JNDs. It must be noted that some studies have proven that GA techniques are sufficiently more accurate and widely used in the prediction of mid-high frequency behaviours of rooms [6], than low frequency results, where the Finite Element Method is the best calculation option.

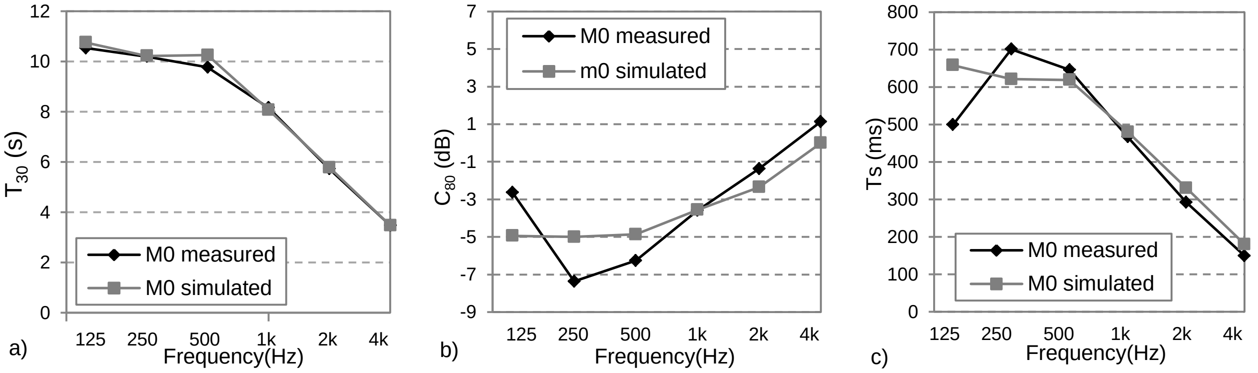

Figure 2: Spectral behaviour of spatially averaged acoustical parameters: a) T_{30}; b) C_{80}; c) Ts.

3.3 Temporal and spatial factors

In this study, based on Ando's model of hearing [7], it is taken into consideration the subjective preference of the listener as an overall impression of the acoustical environment and determines the acoustical quality of the cathedral.

In fact, previous research shows that processing sound capabilities by each hemisphere, had a noticeable influence in terms of the description of subjective parameters, categorized into temporal and spatial factors. On the one hand, delay of first reflection (Δt_1) and subsequent reverberation time of the signal (T_{sub}) are included in the first group. Δt_1 values were analytically obtained using the acoustical software and T_{sub} coincides with reverberation time. On the other hand, the second group contained the listening level of sound (LL), which coincides with SPL (A-weighted), and Inter Aural Cross Correlation (IACC), which measures the difference in signals received by both ears. Consequently, the four orthogonal parameters based on brain activities were considered in developing this research.

The same source position and different music motifs (vocal and instrumental concerts) were investigated for the three historical configurations of the cathedral. As fundamental attributes are contained in each sound field, it was possible to check the optimum acoustical design stage and the most suitable type of music. In this research, the repertoire selection for the analysis was made up of two types of chants, Alleluia and Gregorian, together with instrumental music (Bruckner's Romantic symphony). A value of 26 and 90 ms was used for Gregorian and Alleluia chants, respectively and a value of 136 ms for orchestral music.

3.3.1 Subjective preferred conditions

The deviation from the preferred conditions is evaluated by the linear scale value of preference (S_i) for each parameter, whose sum results in the total value S. The obtainment of optimal design values was needed to calculate this new parameter, as is explained in detail in [4]. This is related both to delay of first reflection and to the actual duration of autocorrelation envelope (τe). In this sense, in order to determine the subjective sound quality of the cathedral, the definition of the hypotheses of study together with the repertoire that will be performed are needed.

Musical performances in cathedrals vary greatly since these spaces have become one of the venues for promoting vocal and instrumental concerts. A comparative analysis was carried out in terms of temporal design, incorporating the study of early reflections (Δt_1) analytically determined using image source model, as well as the type of music. Based on the assumptions set forth in previous studies, a simplified approach is used in which the preferred delay time (Δt_{1p}) is equal to the τ_e value, depending on the type of music considered [3]. $[T_{sub}]_p$ also depends on τe and is assumed to be approximately $23\tau e$; LL_p, was assessed in a specific point of the enclosure, in this case approximately 15 metres from the source. In the case of IACC, the dissimilarity of signals arriving at both ears is preferred, thus the preferred value is assumed to be 0. However, research currently being developed shows that this fact is not emphasized when the listener perceives the sound in a reverberant space like a cathedral. This allowed the acoustical suitability of each configuration of the cathedral to be checked.

4. Results and discussion

In this study, acoustical influence is assessed in terms of temporal design of different historical configurations with different positions of the choir. The analysis of the sound field was carried out considering the sound source position in front of the transept, where cantors and orchestra are placed during events and concerts. Firstly, variations of each orthogonal parameter, categorized into temporal (Tsub, Δt_i) and spatial factors (LL and IACC), depending on the choir location and the type of music, are described. Parameter values were obtained following the acoustic simulation of different configurations. Consequently, it was possible to observe which model was acoustically more suitable when the same position of sound source is considered, by representing the influence of these parameters on the linear scale value.

4.1 Analysis of different configurations

Figure 3 shows general variations that were observed in receiver points when considering the different historical configurations. In order to carry out this comparative analysis Bruckner's Romantic Symphony was considered, given that orchestral music is one of the main representations occurring in source A1. As regards spatial factors, it should be noted that IACC is the factor with the most negative influence on subjective preference, nearing -1 on the scale value for almost all points considered. This demonstrates that left and right signals in the cathedral are substantially similar. This is because the sound sensation in the cathedral approaches the binaural sensation in the form of monophonic behaviour, as IACC values were close to 1. No significant influence is observed due to the type of configuration analysed. In the case of LL it is observed that the negative effect is greater in the points closest to the sound source (R6 and R7, Fig. 1). This occurs in all three models, although it is slightly less noticeable in configuration M1 as the distribution is more uniform in the central nave given the central location of the choir. As stated previously, LL_p is calculated at a distance of 15 metres, and as a result, points that are excessively close record high SPL values which differ from the optimal value by almost 8 dB (Table 2).

In this case, the same musical repertoire and, consequently, the same τe was selected in obtaining the parameters for the three models. However, varying the position of the choir has a strong effect on the arrival of the early reflections at some points. The variations in temporal factors can be understood better when different musical representations are considered. Nevertheless, a significant negative effect is observed in the early reflection delay, as Δt values obtained differ greatly from those preferred for the orchestral representation of Bruckner's Romantic Symphony ($\tau_p \approx 136$ ms). On the contrary, this entails a preference for a relatively high reverberation, slightly higher than 3 seconds, a preference which could even increase given the high reverberation of the space and its acoustics, described earlier as ‘church’ acoustics.

It should be noted that $S_1+S_2+S_3$ obtain a sum of less than 0.5 in the scale value of R5, as its strategic position between two pillars generated a positive effect on the results. In general, it could be stated that configuration M2 provides the lowest scale value, assuming the best acoustical quality at points located in the estimated occupancy areas. Figure 4 a-b) depict variations of scale value in terms of delay time of first reflection and distance between source and receiver. As was to be expected, in the case of Bruckner's Romantic Symphony, S decreases as the delay increases, nearing the preferred values. The opposite occurs when the S-R distance is taken as factor of reference, given that conditions worsen as distance increases.

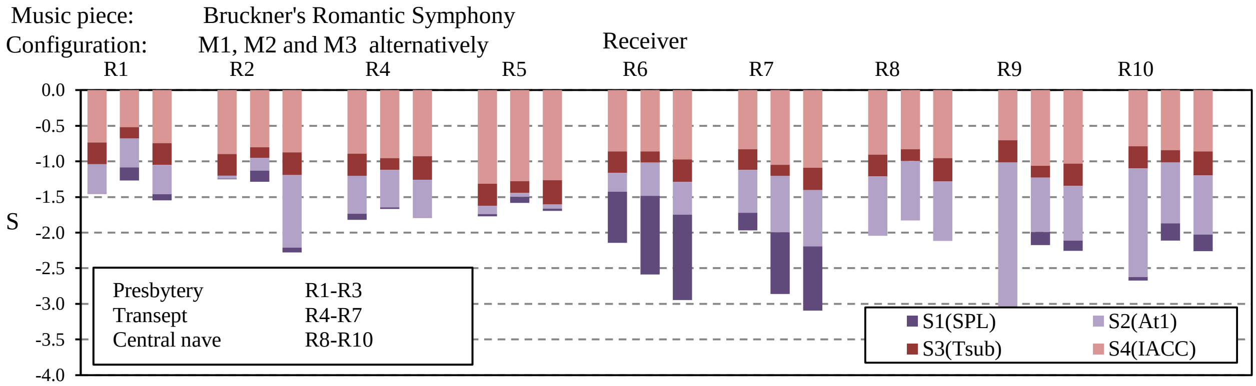

Figure 3: Influence of different configurations of the cathedral in the orthogonal parameters considered on the linear scale value of each receiver, from the same sound source (A1).

Table 2: Variation ranges defined by the differences between the maximum and minimum values.

Hypotheses	SPL (dB)	Tsub (s)	IACC	Δt1 (ms)
M1	6.1	0.44	0.53	77.3
M2	8.04	0.35	0.53	21.4
M3	8.18	0.33	0.27	77.5

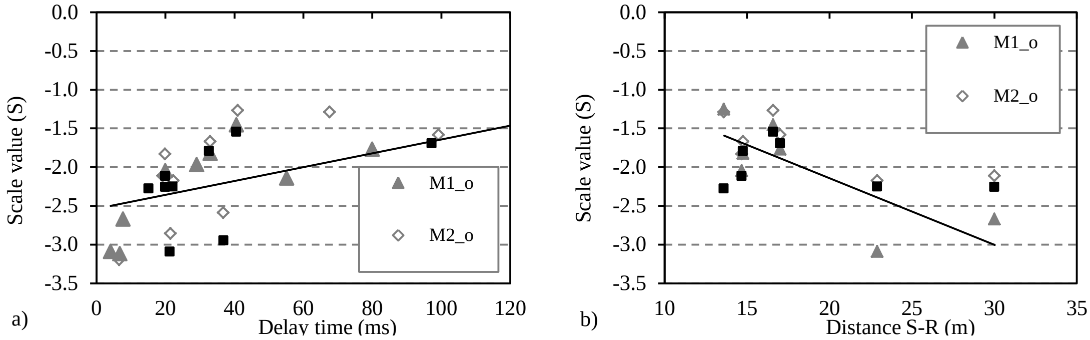

Figure 4: Representation of scale value of preference (S) depending on delay time Δt (a); S-R distance (b).

4.2 Analysis of music motifs

For this analysis the same configuration (M3), representing the current conditions of the cathedral, was considered with various pieces of music in order to assess how the type of music affects the same scenario. As stated before, Alleluia and Gregorian chants, together with Bruckner's Romantic Symphony were the selected repertoire, since sound source A1 represented the real position of a choir group or an orchestra. Accordingly, a different τe was chosen for each music motif. This choice has strong consequences on the sum of each scale values (S_i). In this analysis, early reflections remain constant as it is the same configuration, suggesting a constant value of spatial factors. However, as temporal data contains information about important musical qualities, the two temporal factors has a significant influence in the variation of S.

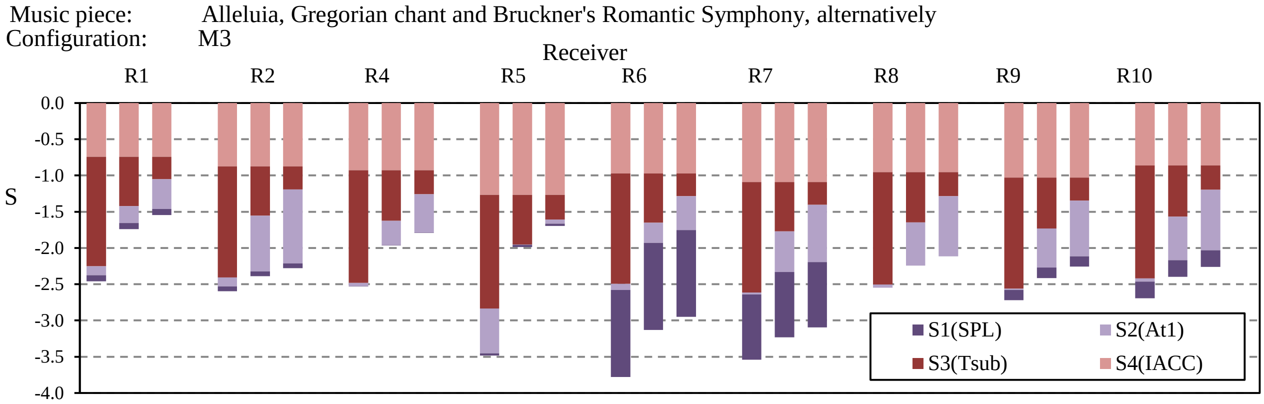

Figure 5: Influence of different music motifs on the orthogonal parameters considered on the linear scale value of each receiver. Configuration M3 and sound source A1.

Based on the assumption that optimum reverberation time value for Alleluia is lower than a second (T_{subp} ≈0.60 s), it can be stated that T_{sub} had the strongest negative influence on total scale value (Figure 5). A reverberant cathedral is far from reaching such low values. Nevertheless, a positive effect is observed in S_2, since it was observed that delay time values do not greatly differ from those considered optimum for this activity (τ_p≈20 ms), while giving the poorest acoustical quality.

The opposite effect occurs when orchestral symphony is performed, due to the longer τe requirement preferred for this type of music, featuring slow symphonic passages for wind and string instruments. In this case, T_{subp} were longer, reaching better optimum design objectives in the cathedral.

However, except in some specific points, in general, early reflections usually arrived within 20-30 ms, a value differing greatly from that of τ_p , which was the largest of the three models, resulting in significantly worse behaviour. Figure 5 shows the influence of the type of music and it has been verified that the effect of reverberation is more perceptible. Thus, longer optimum reverberation values are better suited to the acoustical behaviour of the cathedral.

5. Conclusions

Three major interventions changing the position of the choir have been carried out in the cathedral of Granada. This study assesses the subjective acoustical influence of the spatial transformation within the cathedral throughout its history. In addition, the acoustical performance of choral or instrumental music in the cathedral was also evaluated in terms of subjective preference. The analysis and discussion of results took place using a temporal design approach.

It is known that the fundamental attributes are contained in the simplest sound field, which consists of direct sound, and a single reflection representing a set of reflections. It was thus possible to check that configuration M2, with the choir in the main chapel, provides the best acoustical suitability in terms of temporal design in occupied zones. Closing off the main chapel by changing the position of the choir brings about a slight increase in subjective preference at most points considered, while the value of S mainly diminishes in temporal factors.

As for the variation observed at each point when the type of music is varied, it should be noted that there is a subjective preference for certain types of instrumental pieces over sung pieces, as the wider reverberation has a positive effect on low-pitched fragments with a slow tempo featuring wind or string instruments. Generally, T_{sub} has a worse effect on chants, however, a high reverberation time close to 10 s has a negative effect on all types of music. Besides, it should be noted that the scale value associated with Δt_i factor increased for orchestral music, where preferred conditions differed from those obtained. In light of the results, it can be confirmed that the cathedral is acoustically more suitable when optimum reverberation values are longer, since the negative effect of the early reflections is not as significant.

Further research must be carried out to provide a detailed analysis of the acoustical influence of the three spatial transformations, taking into account objective acoustical parameters and determining variations in terms of JND by zone.

Acknowledgments

This work has been financially supported by the Spanish Government, with reference BIA2014-56755-P and FPU12/04949.

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