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ACOUSTIC EVALUATION OF THE CATHEDRALS OF MURCIA AND TOLEDO, SPAIN

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Cathedrals are complex buildings, each of which is the product of a joint effort and whose construction process has covered an extended period of time. Not only are such historic monuments symbols of a national cultural identity, but also symbols of a European collective identity. The acoustic environment of cathedrals is considered part of its intangible heritage. The Gothic cathedrals of Murcia (c. XIV-XVI) and Toledo (c. XIII-XV) correspond to the so-called Spanish style, in which the choir is located in the middle of the main nave. Their enormous volumes, constructive solutions, and finishing materials give them a highly reverberant character. This paper presents the experimental results, obtained through the application of a previously developed methodology for the acoustic characterisation of these reverberant spaces. The spatial distribution of several objective parameters is analysed in order to assess the acoustic quality for both musical and speech reproduction of their main temples. Various source positions are considered in the study.

Keywords: cathedral acoustics, room acoustic parameters

1. Introduction

The seventy-eight cathedrals of Spain form part of the most important elements of Spanish monumental heritage. Cathedrals are complex buildings resulting from a collective and prolonged-in-time effort. These historic, but fully alive buildings exert a cultural projection towards their interior, with a remarkable accumulation of goods, and also towards the exterior surroundings, as spatial references of the cities shaping their urbanism. Cathedrals have been clearly affected by the change experienced in the concept of heritage, whereby the restriction to the artistic and religious scope has been overcome, with a clear extension towards its environment in a broad sense and to its anthropological and symbolic aspects. These places of worship are also affected by the social cultural demand, that is, the heritage tourist, which in these emblematic religious buildings presents a major challenge. These concepts can be extended to encompass the entire European cathedral heritage, as symbols not only of a national cultural identity, but also as symbols of a European collective identity. In this context, the techniques of studying and analysing their present and previous acoustic conditions (archaeological acoustic research), supported by the documentary research, provide a scientific element to this integral concept of architectural heritage.

The propagation of sound in religious venues, especially churches, has been the object of study of various research groups covering several countries, with a great variety of contributions, such as the analysis of the sound field as a function of distance to the source [1,2], acoustic measures relating to ecclesial furniture [3], influence of occupation [4], aspects of subjective preference [5], the relationship between acoustics and liturgical uses [6], and the use of simulation techniques for different purposes [7,8]. In these large reverberant spaces, room impulse responses (RIRs) [9] and parametric and sensory evaluation [10] need to be tailored for their suitability to the long reverberation times in relation to concert halls and auditoriums [11]. For a number of decades, the acoustic study of cathedrals has remained an object of multidisciplinary interest, and hence certain pieces of work on emblematic European historic cathedrals should be pointed out, such as St. Paul's in London [12], St. Peter's Basilica in Rome [13], and Notre Dame in Paris [14].

In this paper, we present the results of two Gothic Spanish cathedrals, in accordance with the methodology and analysis previously carried out in the Andalusian cathedrals [15,16]. Certain elements of comparison have been introduced between these two cathedrals and the Andalusian cathedrals in relation to temporal and energy parameters in order to assess the musical and spoken-word perception in their interior.

2. Description of the spaces studied

2.1 Murcia Cathedral

The city of Murcia is located in the southeast of Spain and its cathedral is located in its historic centre. The construction process of this Gothic temple began at the end of the 14th century, and ended with the raising of the Gate of Apostles (transept on the south side) in 1488. In its history it has suffered additions: the chapel of Velez, (15th century); the bell-tower (16th and 17th centuries) and the new main façade (18th century), which unifies various artistic styles (Fig. 1). After the fire of 1854, the cathedral required a new Neo-Gothic altarpiece and a great organ for the choir.

This cathedral presents a Latin-cross floor plan, whose area is 84 m long and 51 m wide, constituted of 3 longitudinal naves with 5 lateral chapels in each nave, with the choir placed in the centre of the main nave (Spanish configuration). The lateral aisles are articulated by pointed arches giving access to the lateral chapels, on which is located a broken impost in the windows. The ribbed vaults that cover the side aisles are mostly supported on wide polygonal base pillars with columns at the corners. At the head of the temple, an ambulatory is articulated with 9 small chapels surrounding the heptagonal apse where the main altar is located, which has a large altarpiece from 1863 (Fig. 1). The approximate volume of the cathedral is 115,000 m^3 and its maximum height is 32 m.

2.2 Toledo Cathedral

The cathedral of Toledo (Fig. 2) is located in the historic centre of the city. The first stone was placed in 1226, and, in 1493, with the closing of the last vaults, this great construction was concluded. The temple has a clear French influence, due to the Gallic origin of its first architect. During the sixteenth to eighteenth centuries, different work was carried out, according to new styles. The interior space is composed of 5 naves, supported by 88 columns and 72 vaults, with an area of 120 m long and 60 m wide. The side aisles, somewhat wider than the other two, extend behind the Main Chapel surrounding the chancel and create a U-turn with a double semi-circular aisle (Fig. 2). The 15 chapels of the ambulatory are of various sizes and, in certain cases, the reforms over time altered the layout of a number of the chapels. Its large retrochoir is of remarkable beauty. The approximate interior volume of this cathedral is 125,000 m^3 and it has a maximum height of 31 m.


Figure 1: Murcia cathedral: (left) View of the façade, (right) view of the apse and the high altar.

Figure 2: Toledo cathedral: (left) View of the façade, (right) view of the space from the retrochoir.

In both cathedrals, the most dominant finishing materials and decorative furnishings are: stone columns, vaults and walls; marble flooring; hardwood choir stalls and wooden pews; wooden and marble altarpieces; stained glass windows; canvases and paintings; and wrought-iron grids.

3. Acoustic measurements

For the description of the acoustics of cathedrals, it is essential to address the various uses of each enclosure. Nowadays, in addition to the liturgical function, with its spoken and sung passages and those of a musical nature, certain musical events not directly related to their religious character are held in cathedrals, such as cultural activities where sound perception plays a primary role.

3.1 Measurement positions

Due to the multifunctional character of these spaces, 5 common source positions are set up in accordance with [16]: on the symmetry axes of the high altar (SA), on the pulpit (SP), in the choir (SC), at the organ position (SO), and in the retrochoir (SR). Additionally, several source positions have been considered in order to cover particular configurations of the space in each temple, as well as to characterise singular spaces, such as main chapels. Various common zones of use were also delimited, which are conditioned by the configuration of the space, especially due to the location of the choir which divides the central nave, thereby reducing those areas with visibility from the source: Zone A (ZA), which corresponds to the high altar; Zone B (ZB), which corresponds to the choir; Zone C (ZC), which includes the pew area located in the transept (mostly concentrated in the central nave) and in both sides of the high altar; Zone D (ZD), which integrates part of the lateral naves in the area next to the choir where a number of pews are generally placed; and Zone E (ZE), which refers to the retrochoir. Additionally, Zone F (ZF) is delimited as including the ambulatory, but in these cases it is not considered due to the limited visibility from the sound positions included in the analysis. Each delimited zone (Fig. 3) is influenced by certain positions of the sound source, which is directly related with the location of the congregation or the audience in each case. This information, which is summarised in Table 1, is the key to determining the position of the receiver points to be characterised when the source is located at each position.

Table 1. Number of receiver positions characterised in each zone of influence considering each common sound-source position, in the cathedrals of Murcia (MU) and Toledo (TO)

Source	Zone A		Zone B		Zone C		Zone D		Zone E		Total	
	MU	TO	MU	TO	MU	TO	MU	TO	MU	TO	MU	TO
SA	3	4	4	4	8	8	-	-	-	-	15	16
SP	3	-	4	4	12	11	1	1	-	-	20	16
SC	2	-	4	4	4	4	-	-	-	-	10	8
SO	3	1	4	4	8	7	-	-	-	-	15	12
SR	-	-	-	-	-	-	-	-	4	8	4	8

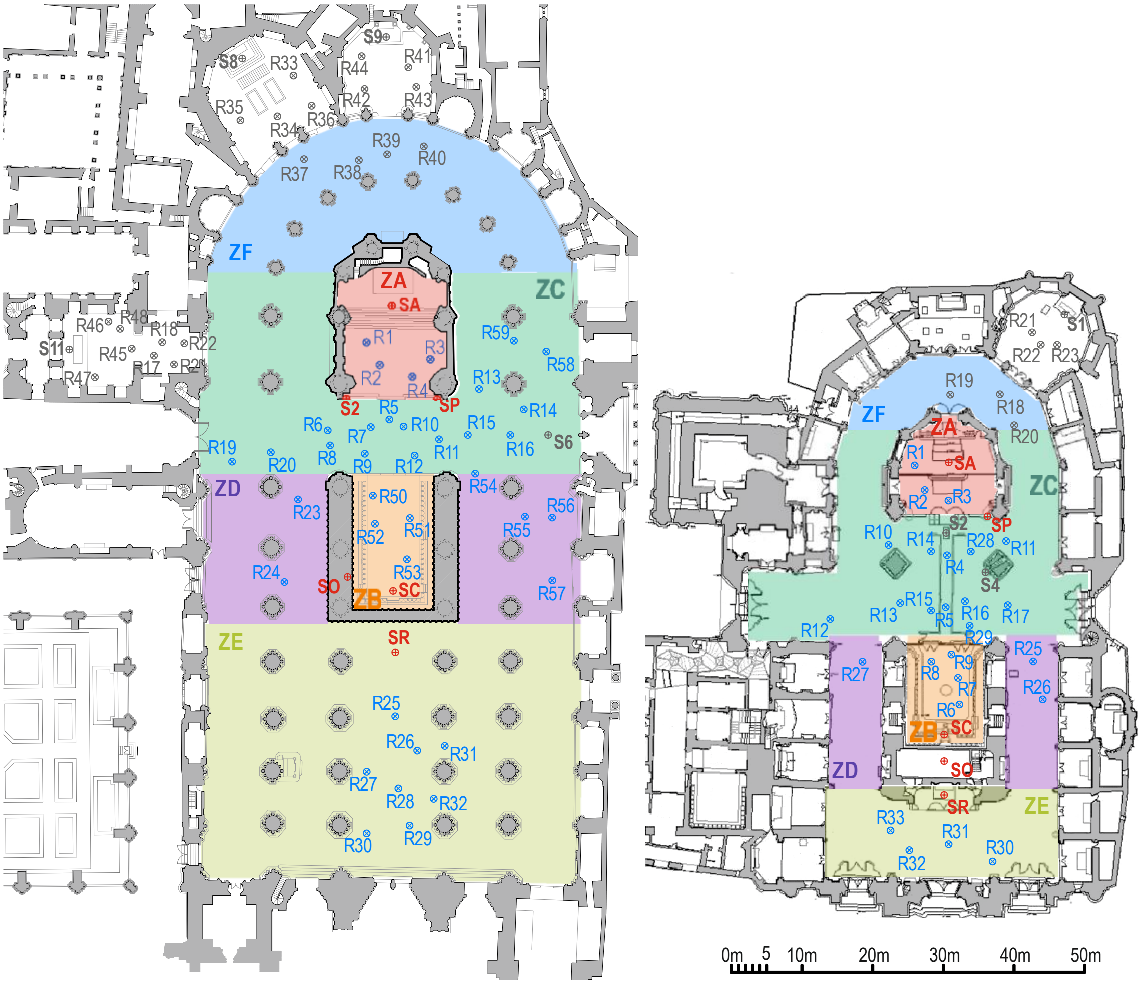

Figure 3: Floor plan of the cathedral of Toledo (TO) (left) and the cathedral of Murcia (MU) (right) with source and receiver positions, as well as the delimitation of the zones (in colours).

3.2 Electroacoustic measurement chain

Experimental measurements were carried out by following the procedure established in the standard [11] and specific guidelines [9,15]. Specifically, the process of generation, acquisition, and analysis of the acoustic signal was performed by using a commercial software tool, EASERA v1.2, through an AUBION x8 multichannel sound card. All RIRs were obtained from sine-swept signals, in which the scanning frequency increases exponentially with time.

The frequency range, the level, and the duration of the excitation signal were adjusted so that the frequency range would cover the octave bands from 63 to 16000 Hz, and the impulse response to noise ratio (INR) would be at least 45 dB in each octave band to guarantee accuracy of certain parameters, such as T_{30}. The generated signal was emitted through an AVM DO-12 dodecahedral sound source with a B&K 2734 power amplifier. For Murcia cathedral, a self-amplified Beringher Eurolive B1800D-Pro subwoofer was incorporated in order to improve the low-frequency results. At each reception point, monaural and binaural RIRs were measured by using several types of microphones. For the monaural RIRs, an Audio-Technica AT4050/CM5 microphone was used. The configuration between omnidirectional and figure-of-eight of this multi-pattern microphone can be easily changed in order to simulate the spatial impression of the listener through the lateral acoustic energy perceived. For the binaural RIRs, a Head Acoustics HMS III (Code 1323) dummy head was used. The external polarisation voltage source required for each type of microphone was used in each case: the 4-channel microphone preamplifier Soundfield SMP200 and the 4-channel microphone power supply Brüel & Kjær Type 2829, respectively. The background noise level was recorded with an SVAN 958 analyser, of SVANTEK.

4. Results and discussion

4.1 Reverberation time of the Cathedrals

The reverberation time of a room, T_{30}, can be considered the most important parameter for characterising its acoustic behaviour, providing a general idea of the listening quality of the space depending on the purpose of such room. Table 2 includes the spatially averaged values of T_{30} of the cathedrals studied, considering all the source-receiver (S-R) combinations measured in the main temple during the experimental campaign, since, as expected, the variation of the reverberation time with the sound-source position is negligible (average standard deviation from the mean remains lower than 0.1 s). A previous study on the acoustic characterisation of several liturgical spaces of Toledo cathedral [17] reported similar results of the T_{30} (in ref. 17 see liturgical space named LS4).

Table 2. Spatially averaged values of the reverberation time (T_{30}) in seconds (s) measured in the cathedrals under study, considering all source-receiver combinations

Cathedral	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
MU	4.51	4.59	4.56	4.24	3.46	2.54
TO	6.98	6.87	6.64	5.75	4.51	3.08

Several authors have previously reported the reverberation time of other large places of worship [13,18-20]. Although diverse methodologies were applied to conduct these investigations, the results of the reverberation parameter are comparable since all were based on a common standard [11]. In order to compare reverberation conditions in the cathedrals under study with those obtained in previous studies performed in similar buildings, volume appears to be the simplest architectural feature to establish a coherent comparison in general terms. Figure 4 shows T_{30m} values measured in those churches whose volume is greater than 25,000 m^3, with the sound source placed at the high altar, and includes our field measurement results (Spanish cathedrals, represented with a triangle in the figure). It can be observed how the T_{30m} measured in the set of characterised temples varies across a broad range (approximately from 2 to 12 s), with Murcia and Toledo cathedrals located in the middle part of the graph. This graph does not show a clear relation between the two variables, which emphasises the fact that the reverberant characteristics of a room are not only influenced by the volume and the geometry of the space, but also by the choice of construction and finishing materials, which has been well known since the publication of work by Sabine. It can be observed how the majority of the temples, including Spanish cathedrals, have a T_{30m} higher than 4 s, which can be considered above the typical recommended values both for music and especially for speech. However, when dealing with this kind of buildings, providing recommended values becomes difficult, since reverberation perception is strongly influenced by psychoacoustic factors, such as the feeling of involvement.

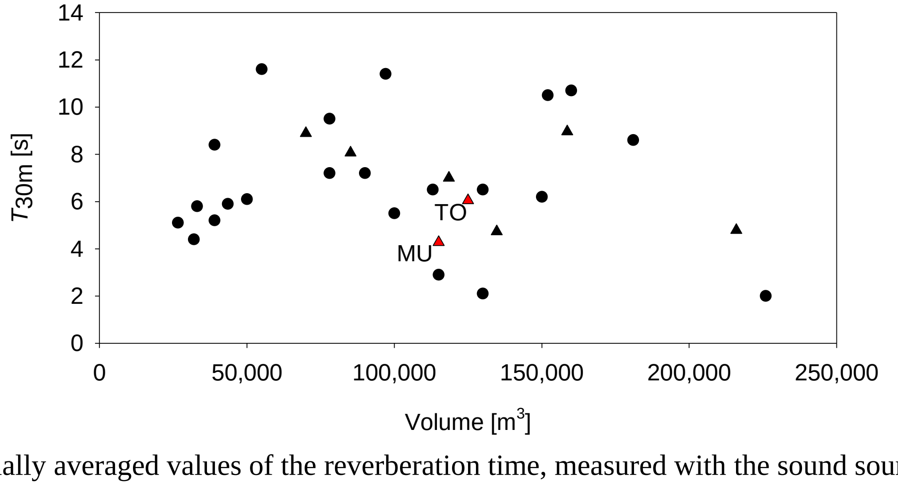

Figure 4: Spatially averaged values of the reverberation time, measured with the sound source located at the high altar, on the symmetry axes of the temples. Triangles correspond to Spanish cathedrals.

4.2 Acoustic evaluation: comments on acoustic data

The acoustic environment of the cathedrals under study was assessed through the analysis of the RIRs measured at the receiver points located in the different areas of influence associated with each source position, characterised in accordance with Table 1.

Firstly, only SA is considered since it is the most relevant position, both in religious ceremonies and in cultural activities. Table 3 summarises the spatially and spectrally averaged values of the acoustic parameters measured in each temple with the sound source placed at that position. Listeners located throughout zone C, B and D (Fig. 3) perceive a speech intelligibility rated as *poor* (STI < 0.45 and D_{50m} < 0.30) in MU, while in TO, this level can be considered *acceptable* [21]. Furthermore, in TO, EDT_m values are significantly lower than T_{30m} values, thereby decreasing the feeling of reverberance, owing to the nearness of their position to the source and/or to the hard reflecting surfaces that surround them. The poor perception of musical clarity for choral, chamber, and classical symphonic music [5,22] is denoted by the low C_{80m} values (especially in MU where, on average, C_{80m} is below -6 dB). J_{LFm} averaged values are slightly lower than required for a good spatial impression (SI) (values of at least 0.17 to 0.20 are required), possibly because lateral reflections tend to be scattered and weakened by the lateral chapels [18], while $IACC_{Em}$ values in both cathedrals are of the order of those obtained in the best subjectively valued concert halls [23]. In the near future, the binaural RIR will be used to implement auralisations for a more accurate representation of the acoustic sensation in listening tests.

Table 3. Spatially and spectrally averaged values of the acoustic parameters measured in each cathedral, with the sound source placed at the high altar (SA)

Cathedral	EDT_m [s]	T_{Sm} [ms]	C_{50m} [dB]	C_{80m} [dB]	D_{50m} [-]	J_{LFm} [-]	$IACC_{Em}$ [-]	$IACC_{Lm}$ [-]	STI [-]
MU	3.88	295.73	-8.22	-6.55	0.19	0.16	0.57	0.15	0.41
TO	3.92	247.33	-3.14	-1.43	0.35	0.15	0.46	0.12	0.46

In order to compare the acoustics in regard to the 5 common source positions, Figure 5 shows the spectrally averaged results measured at each source-receiver combination in each cathedral, for 3 monaural parameters, EDT, C_{80}, J_{LF}, and also for the speech intelligibility parameter, STI, in order to assess the various subjective aspects of the quality of sound. Analysing the spectrally average values of these parameters, which vary significantly with distance, it can be observed how EDT_m values are significantly lower than T_{30m} values when the source-receiver distance is less than 15 m in MU and less than 30 m in TO, except in the retrochoir. This suggests that early reflections have no significant influence in receiver positions located further than such distances from the sources, which implies, in

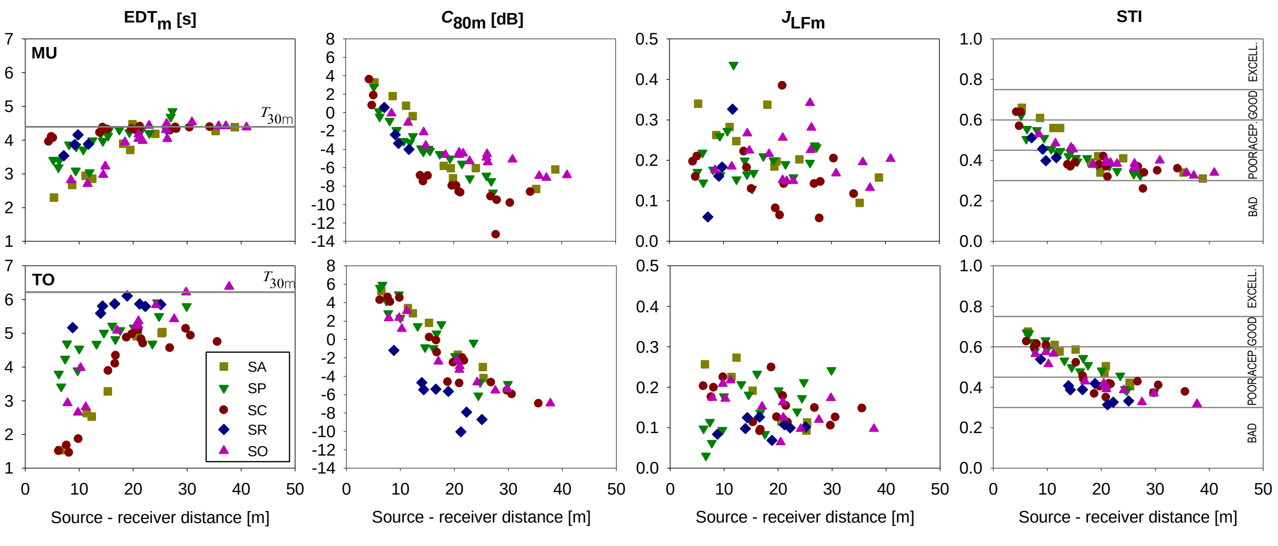

Figure 5: Acoustic parameter values, spectrally averaged, measured at each receiver point for each source-receiver combination in the cathedrals studied, as a function of source-receiver distance.

general, C_{80m} values of under -5 dB at those receiver points. Nevertheless, the maximum S-R distance at which the acceptable range of speech intelligibility can be reached is strongly dependent on both the cathedral and the source position under discussion.

Regarding SP, both music and speech perception in ZB and ZC are improved with respect to the conditions obtained with SA, mainly due to the reduction of the source-receiver distances [7].

The choir is a key element in the spatial distribution of the interior of Spanish cathedrals due to its location in the middle of the central nave, which subdivides the space, and where liturgical and cultural events with reduced attendance are held. Therefore, its acoustic environment is assessed independently. Although the choir is not a wholly independent space since it is partially open to the rest of the temple, it can be considered as a reduced-size "volume" inside the cathedral, where sound-absorbing materials, such as wood and upholstery, are present in greater proportions and distributed more homogeneously than in the rest of the temple. When both the source and the receivers are located inside the choir (corresponding to SC and Zone B, respectively), then S-R distances are considerably reduced and there is a noticeable increment of the early lateral reflections. Hence, the mean perceived reverberance is reduced in the choir (reductions in EDT_m values of approximately 1 s), the perceived clarity of both music and speech is greatly improved (reaching values rated as *acceptable/good*), and the feeling of spaciousness and envelopment are also favoured (Table 4).

The retrochoir is also configured as a “semi-independent” space within the Spanish cathedrals where Mass, special services, and concerts of diverse types of music are held. In general, in the retrochoir, the S-R distances involved are smaller and congregants are subject to less influence from the naves, lateral chapels, vaults and domes. Specifically in MU, as in other Spanish cathedrals [16], greater values of the musical clarity and speech intelligibility are achieved (Fig. 5) when both source and receivers are located in the retrochoir. Nevertheless, due to the great dimensions of the retrochoir of TO, this "space" fails to show any significant improvement in acoustic conditions.

Table 4. Spatially averaged values of the acoustic parameters measured in the interior of the choir of Murcia (MU) and Toledo (TO) cathedrals, with the source position SC

		S-R dist. [m]	T_{30m} [s]	EDT_m [s]	C_{80m} [dB]	D_{50m} [-]	T_{Sm} [ms]	J_{LFm} [-]	STI [-]	$IACC_{Em}$ [-]
MU	SC_R06	5.32	4.09	2.30	3.29	0.62	109.3	0.34	0.66	0.35
	SC_R07	8.69	4.16	2.67	1.79	0.53	134.9	0.26	0.61	0.45
	SC_R08	11.17	4.19	2.94	0.74	0.48	155.4	0.28	0.56	0.46
	SC_R09	12.40	4.39	2.86	-0.39	0.41	175.9	0.25	0.56	0.40
TO	SC_R50	15.30	6.13	3.28	1.80	0.52	164.0	0.19	0.59	0.39
	SC_R51	12.29	5.98	2.53	2.85	0.53	137.9	0.27	0.58	0.36
	SC_R52	11.37	6.01	2.64	3.40	0.60	127.8	0.23	0.61	0.43
	SC_R53	6.46	5.94	1.54	5.25	0.69	81.3	0.26	0.68	0.39

5. Conclusions

Their enormous volumes, constructive solutions, and finishing materials give these cathedrals a highly reverberant character with, in general, unfavourable conditions for music and speech perception. Considering the various liturgical and cultural uses of the cathedrals under study, several source positions and various zones of use are established. The choir can be considered as a reduced-size "volume" inside the cathedral. When both the source and the congregants are located inside the choir, the mean perceived reverberance is considerably reduced, the perceived clarity of both music and speech are greatly improved, and the feeling of spaciousness and envelopment are also favoured. The retrochoir is also configured as a “semi-independent” space within these cathedrals.

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