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Acoustics, Liturgy and Architecture in the Early Christian Church. From the domus ecclesiae to the basilica.

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Summary
In general, studies on the history of construction of Christian churches have neglected to include essential aspects such as the development of the Christian liturgy, or its relation to the evolution of spatial organization. In churches, the liturgy establishes the dynamic relationship between the different foci of the celebration: the altar, the cathedra, the ambo, the choir, places and sound sources from which word and music are proclaimed. In the historical evolution of Christian churches from their origins, liturgy, music and acoustics are clearly interconnected and related to their architecture. However, little research has been done on these interconnections. This article aims to examine them focusing on early constructions: from the domus ecclesiae to the large early Christian basilicas which preceded Romanesque and Gothic medieval cathedrals. To do so it is essential to carry out an acoustic assessment of these spaces for worship in their original historical form. Since almost all of these have disappeared or undergone considerable transformation the method of computer simulation was used to set up and analyze acoustic models for these early churches.

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1. Introduction and objectives

The history of Christian churches down to the eighteenth century is the one that best represents the evolution of architecture in Western Europe [1]. Their evolution is often analyzed in terms of architecture, style or structure, but seldom in relation to aspects such as space and function, liturgy or acoustics, forgetting in such cases that their architecture is mainly a response to the needs and activities developed in them. In spatial terms, these churches are the result of the way in which Christians understood the liturgy at each point in time.

Since the beginning of Christianity churches as assembly or meeting places have evolved around the needs and modifications of the liturgy and the ritual use of different spaces within them, producing varied architectural forms and types. To a great extent, the architectural evolution of churches can be considered as a result of the different ways of occupying interior space, a consequence of the way in which the liturgy was celebrated [2].

In churches the liturgy established relationships between the different foci of celebration: the altar (where the sacrifice was celebrated), the celebrant's chair (place of presidency) and the ambo, a raised stand from which the word of God was proclaimed. The situation of these foci within the church created liturgical spaces conditioned by the position of furnishings and liturgical objects, which defined an architectural space for practical and symbolic actions.

From the origins of the Christian church, the liturgy has been used to proclaim the word of God. The assessment of acoustic conditions in churches is therefore of great importance. The first major studies on church acoustics focused on the measurement in situ and study of reverberation time of Roman basilicas [3, 4]. Relationships were then established between reverberation time, architecture and speech [5] and more recent investigations have also dealt with reverberation time, sound pressure level and speech intelligibility [6, 7]. Recent studies have also incorporated the more common parameters for room acoustics as defined in ISO 3382-1:2009. These seek to establish relationships between spatial parameters, architectural styles and use [8, 9]; relationships between theoretical and experimental models connected with musical use [10]; or the importance of the effects of coupled spaces on reverberation time [11]. Most of these studies have provided information on the acoustic conditions of churches in their present state. However, there are few studies explaining the evolution of church acoustics as related to the evolution of liturgy, music and architecture [12, 13, 14, 15] or even other unmeasured aspects such as aural experience [16], relationships which should not be neglected. It is therefore necessary to carry out an acoustic assessment of worship spaces based on their original floor plan.

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Table I. Absorption coefficients for materials used (in brackets bibliographical reference). Scattering coefficients were set to 0.10 throughout, except for audience. *: Hung straight curtains, **: Standing congregation 2 persons/m^2 Public scattering coefficients 0.20, 0.30, 0.40, 0.50, 0.60, 0.70.

Material	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Marble floor [17]	0.01	0.01	0.01	0.02	0.02	0.02
Plaster walls [17]	0.02	0.02	0.03	0.03	0.04	0.05
Wood stage [17]	0.10	0.07	0.06	0.06	0.06	0.06
Wood ceiling [18]	0.16	0.16	0.13	0.10	0.06	0.05
Curtains* [18]	0.57	0.56	0.62	0.55	0.55	0.52
Public** [17]	0.26	0.46	0.87	0.99	0.99	0.99

Given that these early spaces have disappeared or undergone major transformations, the main object of this study is to use simulation tools to analyze the way in which acoustics evolved in the early Christian church as a result of changes in architecture, organization and purpose of the liturgy, and early music. This analysis covers the period between the early domus ecclesiae, places of worship in houses, and the large early Christian basilicas, which preceded Romanesque and Gothic medieval cathedrals. This period laid the foundations for what was to become Romanesque, the first widespread architectural style in Western Europe.

2. Methods

After an initial study of the history and evolution of church architecture in early Christian times, different architectural types were reconstructed, based on their original floor plans and their gradual transformation and adaptation to the needs of each period, mainly in terms of liturgy. This method could be described as 'acoustic archaeology' and provides information on the acoustic behavior of these spaces in the past.

An acoustic assessment of each of the stages and forms of early Christian churches was carried out using models. CATT-Acoustic software (version 8.0k) was used to carry out the simulation.

The materials of each interior surface were assigned acoustic absorption coefficients for each octave band Table I, obtained from the values found in the literature [17] or by analogy from values established in churches [18] represented in similar models with results confirmed by measurements in situ. A default scattering coefficient of 0.1 was considered for all the octave bands analyzed, from 125 to 4000 Hz, except in the audience area. The air absorption calculated by the software was considered [19] depending on the volume of the church.

The occupation of each of the models and the different positions of the sound source were studied, taking into consideration the different liturgical uses of each space [20]. To comply with the parameters defined by ISO 3382-1:2009 [21], the different positions of the sound source were simulated with an omnidirectional source at a height of 1.50 m above floor level. To simulate a standing congregation a height of 1.60 m above floor level was set for receivers.

The relationship between parameters and subjective sensation perceived complied with the ISO norm and used the following parameters:

- For the objective evaluation of room reverberation: the reverberation time (T_{30}). For the subjective assessment of the perceived reverberation: early decay time (EDT).
- For the assessment of the perceived clarity of speech: definition (D_{50}). For the assessment of the clarity of music: clarity (C_{80}. In addition, for the assessment of speech intelligibility: Speech Transmission Index (STI), as defined by Steeneken and Houtgast [22] and defined in IEC 60268-16:2003.
- Finally, for the assessment of spaciousness as relating to apparent source width: Early Lateral Energy Fraction (J_{LF}).

All the parameters have been spectrally averaged for each receiver following ISO guidelines.

To assess the sensitivity of the listeners to a change in acoustical parameters, just noticeable difference (JND) units have been calculated, as defined by ISO 3382-1:2009. The JND is the smallest perceivable change in a given measurable parameter that is perceptible by the average listener and correlates the subjective dimension of sound perception to its objective measures.

3. Christian worship buildings in the first three centuries: From the *domus ecclesiae* to the *domus Dei*

3.1. Architecture and liturgy

In the first centuries of the Christian era, the new faith was practiced within the social framework of the Roman empire. Celebrations in the early Christian community were held in houses, and since the practice of the liturgy was limited to individual and family prayer a specific meeting place was not necessary.

The religious and social needs of Christian congregations changed from the second century onward and a rich and clearly defined liturgy came into being. The usual ceremony was composed of two parts. The first of these was the reading of the scriptures, the sermon and common prayer with the participation of the faithful and catechumens. The second part of the liturgy was the mass [2].

In these early stages the mass [23] was composed of three parts: the offertory procession, the Eucharist and

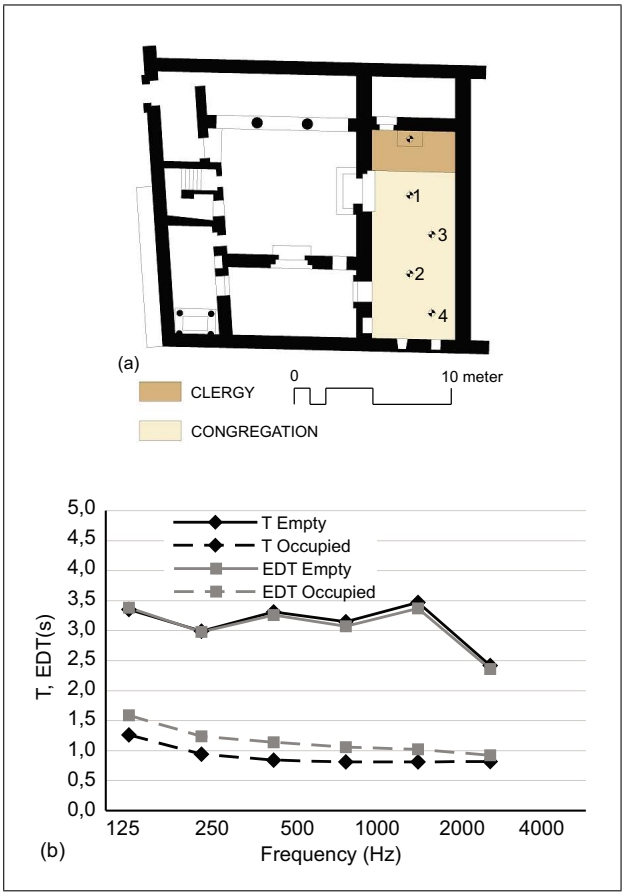

Figure 1. Domus ecclesiae. (a) Floor plan Dura Europos. (b) Octave-band values of reverberation time (T_{30}) and EDT.

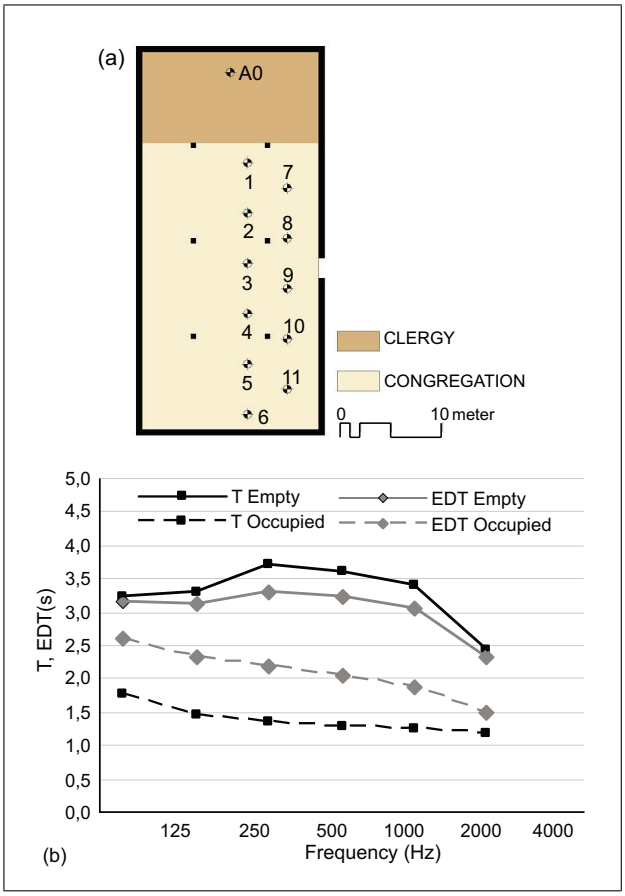

Figure 2. Domus Dei. (a) Floor Plan church of Aquilea. (b) Octave-band values of reverberation time (T_{30}) and EDT.

communion. The bishop, an important figure in the community, offered the sacrifice with the participation of the faithful, facing the congregation and surrounded by the clergy. According to Jungmann [24] all that was needed for worship was a small table for the bread and wine for consecration and a room in which to meet.

The term *ekklesia* was used to indicate a specific place where the congregation could gather to celebrate the word of God. It had to be large enough to accommodate the four basic aspects of worship (originating in the Jewish rite): a place of congregation where the faithful could pray, a place to proclaim the word of God, a place to celebrate the Eucharist and other sacraments, and a place for the exposition of the Holy Sacrament.

The first places of Christian worship were the *domus ecclesiae* (Figure 1a), houses that were originally privately owned but became the property of the Christian community, adapting to the needs of worship. The room in which the Eucharist was celebrated tended to be larger, holding fifty or sixty people divided into two groups: the clergy and the laity [25].

The *domus ecclesiae*, which was a 'house of prayer', gradually became a place which emphasized the sacred nature of the church, aiming to add pomp to religious worship. This transformation, along with the growth of Christian communities, brought about the construction of new buildings for worship: the *domus Dei*. As can be seen in the church of Aquilea (Figure 2a) these buildings were larger. The structural solution was to divide the space into four modules with three pairs of columns, forming a central nave and two side aisles. The presbytery, an area devoted exclusively to the clergy, was clearly differentiated from the area for the faithful by a small separating chancel [26].

Liturgical celebration in the *domus* was characterized by the introduction of concelebration by the priests and the faithful. All those in attendance participated actively in the prayers, readings and psalms, which were the earliest manifestation of Western sacred music. As early as the third century there are accounts of how the people responded to the verses sung by the cantor [27]. From as early as the mid-third century Greek was abandoned as a liturgical language in favor of Latin, which was understood by the entire assembly [25].

3.2. Acoustics

In the *domus ecclesiae* (Figure 1, Table II) the focus of attention was the cathedra, the seat of the presidency, and not the altar [26]. Therefore, the sound source was placed at the cathedra. The short reverberation time, with $T_{30,\mathrm{mid}}$ at mid-frequencies and EDT values close to 1 s, with a full congregation, high D_{50} and STI values of 0.60 Figure 3, and the small narrow room encouraging early reflections,

Table II. Summary of geometric data and surface percentage of each material relative to the overall surface area in models. [1] Domus ecclesiae, [2] Domus Dei, [3] Christian basilica, [4] Saint John Lateran, [5] Saint John Lateran with schola.

Model	[1]	[2]	[3]	[4]	[5]
V (m^3)	341	5105	10995	75032	74933
Floor S. (m^2)	70.22	645.45	833.73	4488.60	4488.60
Total S. (m^2)	318.91	2466.80	4200.70	20837.63	21092.40
L (m)	13.20	37.80	40.90	98.90	98.90
W (m)	5.33	15.64	16.53	34.62	34.62
H (m)	4.83	8.72	16.19	21.88	21.88
Number of planes	14	60	606	2044	2156
Number of rays	18642	47420	48919	190692	190692
Surface Material (%)					
Marble floor	21.51	26.22	32.30	37.30	37.90
Stone walls	52.98	24.71			
Plaster walls			47.79	41.30	40.82
Wood stage	2.81	26.20			
Wood ceiling	22.71	35.10	19.90	21.38	21.31
Public	17.71	18.79	8.52	6.40	9.00
Curtains				9.93	

improved speech intelligibility to favor preaching and the liturgy, one of the main aims of the domus ecclesiae.

The increase in size of the *domus Dei* (Figure 2, Table II), compared with the domus ecclesiae with similar finishes on walls and ceilings, led to an increase in reverberation time, with $T_{30,\mathrm{mid}}$ values of 1.32 s, for occupied space. There was a more significant increase in perceived reverberation since EDT values at the same frequencies increase to 2.13 s, with the reduction of early reflections. This, along with the reduction of D_{50} average values to 0.39 in the central nave and 0.34 in the side aisles (Figure 3), and of STI values (Table III) to close to 0.50, nearing the lower limit of 'fair' intelligibility [23], generally worsens acoustic conditions for preaching. Slow rhythmic recitation of the readings adapted to reverberation time is a mechanism for improving speech intelligibility in the domus Dei [28].

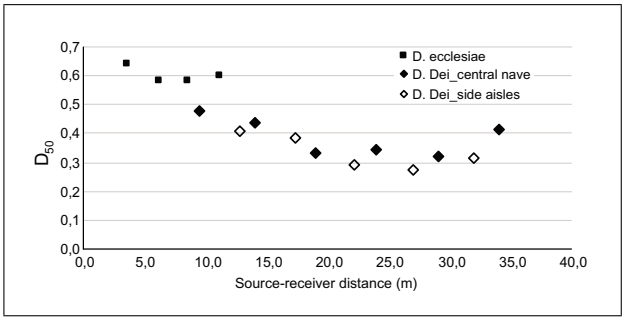

Figure 3. Domus ecclesiae vs domus Dei D_{50} as a function of source- receiver distance. Occupied domus.

4. Early Christian basilicas

4.1. Architecture and liturgy

With the edict of Milan (313) Constantine confirmed the triumph of the Church over paganism. Throughout the Roman empire the establishment of Christianity as the official religion (380) gave rise to an increase in the construction of buildings devoted to Christian worship. The *domus* were not suited to the needs of the new liturgy, which became more solemn, mimicking Roman official protocol, or to the increase in the number of faithful so that a new type of building had to be found [29]. The model adopted was that of the Roman basilica.

As stated by Zevi [30], Roman basilicas were better suited to the demands of Christianity than Roman temples, but the model still had to be transformed to satisfy these demands. On the one hand, size was reduced to suit a religion that encouraged privacy for its followers, while on the other hand, space was organized to suit the liturgy. While Roman basilicas were symmetrical around two axes with a precise geometrical center, Christian basilicas had only one axis of symmetry, which was longitudinal, as one of the two apses of the Roman basilica had been eliminated. There was also a central nave separated from the side aisles by a spaced-out line of columns, and a single deep and spacious semicircular apse covered by a half-dome. There were wooden ceilings throughout the rest of the church. This modification of the Roman basilica fulfilled the need of the faithful for a place for meeting, communion and prayer. In the assembly (ekklesia) the faithful (*fideles*) occupied the nave and the clergy the apse. The liturgy of the word was conditioned by this longitudinal space.

Simple architectural elements in the Christian basilica, furnishings and liturgical objects, gradually defined spaces associated with specific liturgical purposes: cathedra, choir, altar, and later the ambo [2]. The cathedra was reserved for the bishop when he presided the liturgical assembly. This spot, raised in the apse, was used for preach-

Table III. Summary of average values and standard deviation of acoustic parameters analyzed. Spatial average values by zone (STIavg). w. s.: with schola.

Model		Central Nave $D_{50m} \pm \sigma$	Side aisles $D_{50m} \pm \sigma$
Domus ecclesiae	A0	0.60 ± 0.03	
Domus Dei	A0	0.39 ± 0.06	0.34 ± 0.06
Basilica	A0	0.24 ± 0.02	0.25 ± 0.06
Basilica without apse	A0	0.20 ± 0.08	0.25 ± 0.01
Basilica	A1	0.37 ± 0.16	0.30 ± 0.06
Basilica with curtains	A0	0.39 ± 0.04	0.20 ± 0.04
S. John Lateran	A0	0.23 ± 0.13	0.20 ± 0.13
S. John Lateran	A1	0.13 ± 0.06	0.09 ± 0.06
		$STI_{avg} \pm \sigma$	$STI_{avg} \pm \sigma$
Domus ecclesiae	A0	0.61 ± 0.01	
Domus Dei	A0	0.51 ± 0.03	0.48 ± 0.03
Basilica	A0	0.43 ± 0.02	0.40 ± 0.02
Basilica without apse	A0	0.39 ± 0.04	0.41 ± 0.06
Basilica	A1	0.50 ± 0.09	0.43 ± 0.04
Basilica with curtains	A0	0.51 ± 0.02	0.46 ± 0.02
S. John Lateran	A0	0.44 ± 0.05	0.38 ± 0.07
S. John Lateran	A1	0.33 ± 0.04	0.33 ± 0.04
		$J_{LFm} \pm \sigma$	$J_{LFm} \pm \sigma$
Basilica	A0	0.46 ± 0.09	0.36 ± 0.13
Basilica without apse	A0	0.22 ± 0.05	0.31 ± 0.07
S. John Lateran w. s.	A0	0.11 ± 0.04	0.25 ± 0.04
S. John Lateran w. s.	A2	0.14 ± 0.09	0.30 ± 0.20
		$C_{80m} \pm \sigma$	$C_{80m} \pm \sigma$
S. John Lateran w. s.	A0	-2.71 ± 1.13	-5.21 ± 2.80
S. John Lateran w. s.	A2	-3.28 ± 1.30	-5.82 ± 2.69

ing and became the center of the liturgy. It was surrounded by the seats for the presbyters (hence the name of presbytery) along the wall on both sides of the exedra of the apse. The exedra was used for the chanting of divine office as prescribed by the Second Council of Tours (567) [31].

In basilicas, recitation as a form of expression for preaching was replaced by chanting of psalms and hymns. In the Christian liturgy this chanting was a communal expression of praise so those gathered, the celebrant, clerics and the rest of the faithful, all took part in the singing. In the fourth to the sixth centuries the chanting of each of the verses of the psalms (psalmody) was answered by the faithful with the same response after each verse (responsorial psalm) which meant that the people were able to play an active part in the ceremony [25].

Up until the fifth century the early Christian custom of placing the altar in the center of the nave was maintained. After this point it was generally placed in the center of the presbytery, midway between the apse and the central nave.

In the new liturgy, revolving around the altar, altars became a fixture, made of solid materials and associated with the relics of the martyrs. From the late ninth century onward a new element began to appear on altars, the reliquary. Accordingly altars were raised with a shrine or cer-

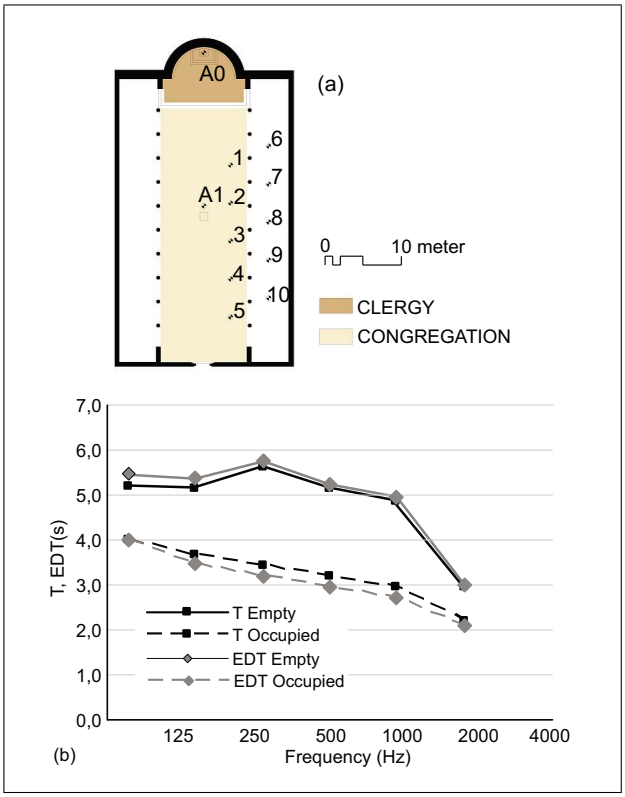

Figure 4. Early Christian basilica. (a) Floor plan. (b) Octave-band values of reverberation time (T_{30}) and EDT.

emonial canopy above the reliquary, whose dignity and liturgical importance was emphasized by these forms of architectural expression. This new type of raised presbytery, an example of which can be found in the church of Sant' Apollinare in Classe in Ravenna, was later to evolve into the presbytery above a crypt [32].

Interior spaces became compartmentalized as a result of the introduction of the different liturgical elements into the Christian basilica. This was done to define the space of the assembly, or to reserve one part of the church for the clergy and another for the faithful. Secondary elements appeared and helped define the different spaces, though borders were often set according to the range covered by voice and sight: chancels signaled the space between the presbytery and naves, transennas or low stone barriers. In the same way, curtains closed off the naves, while the congregation adapted to the dynamics of celebration, occupying the central nave and side aisles, which came to be used as spaces where people could circulate.

4.2. Acoustics

The acoustic study of the Christian basilica used a three-nave basilica model with the dimensions of the main Roman basilicas dedicated to daily liturgy (Figure 4, Table II).

The monumental and grandiose space of the new basilica, often exceeding 10000 m^3, gave rise to liturgical modifications. These churches became larger to accommodate the rapid increase in the number of faithful, housing a

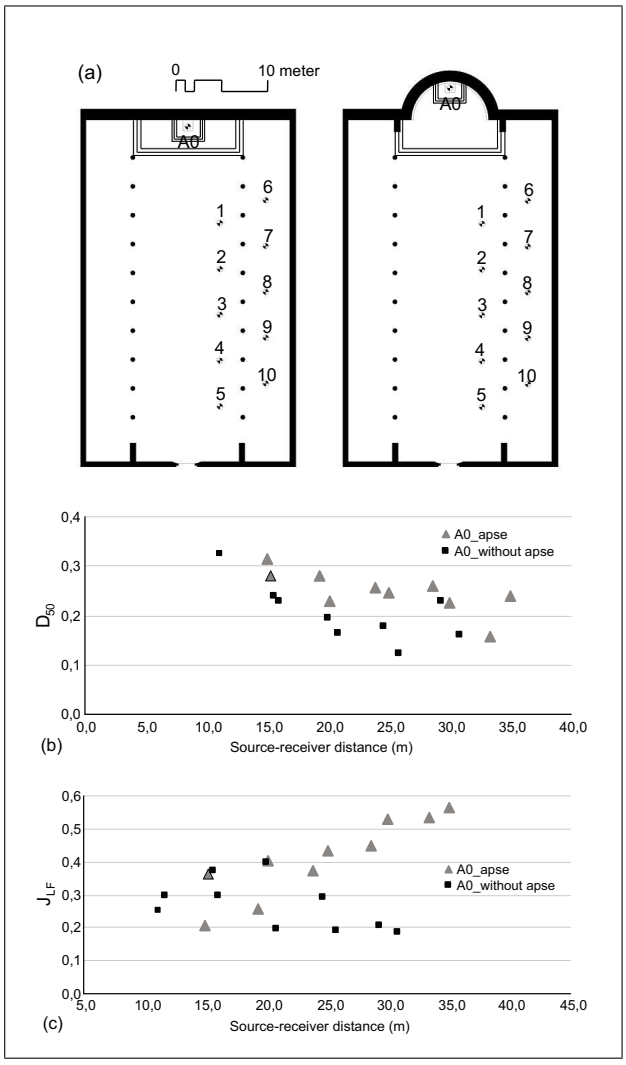

Figure 5. Early Christian basilica. (a) Floor plan with/without apse. Source in apse. (b) D_{50} as a function of source-receiver distance. Occupied basilica. (c) J_{LF} as a function of source-receiver distance. Empty room.

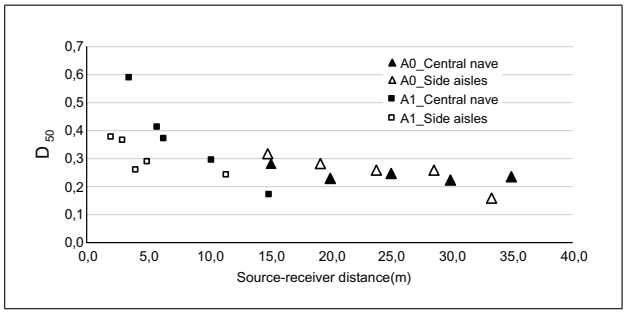

Figure 6. Occupied Early Christian basilica, sound source A0 (cathedra) and A1 (central altar). D_{50} as a function of source-receiver distance. Occupied basilica.

mass congregation and greatly transforming relationships between members of the assembly. The reverberation time $T_{30,\mathrm{mid}}$ increased to a value close to 2.75 s with the basilica fully occupied. This, in addition to similar EDT readings, hindered simple oral communication and preaching so that the sacralization which had begun with the *domus Dei* gradually increased in the new basilicas.

In the new basilica model the apse became the center of the liturgy, the place where the bishop preached from his cathedra. To assess this spot's acoustic repercussions comparisons were carried out between the behavior of a straight-ended basilica and one with an apse (Figure 5). The layout of the apse improved acoustics, both in terms of the D_{50} values (Table III), which increased by between 1 and 1.5 JNDs with the apse, and of lateral efficiency values (J_{LF}) in the central nave, averaging 0.46, above the typical range of 0.05-0.35 laid down in ISO 3382-1:2009 for performing spaces [22], with improvements of 5 JNDs in the central nave compared with the model with no apse. This is due to increased early reflections from the apse.

Despite the acoustic improvement brought about by the incorporation of the apse into the basilica model the D_{50} values tend to be low for the bishop preaching from the cathedra (source A0), with average values of 0.24, and STI values at the top of the 'poor' intelligibility range. However, for preaching from the altar in the center of the nave (source A1), a reduction in the distance between the faithful and the sound source produces improved D_{50} values both in the central nave (2.5 JNDs) and to a lesser extent in the side aisles (1 JND), as compared with the values for the bishop preaching from the cathedra (Figure 6). There was also an increase in STI values, which are barely 'fair' in terms of speech intelligibility.

The use of cantillation, solemnly singing the text in small phrases and emphasizing punctuation, rather than reciting it, was a new way to modulate the frequency of speech and improve intelligibility in the basilicas.

Curtains added between the columns around the central nave provided a new way of compartmentalizing the inside of the basilica to further highlight the separation of space into two areas, one reserved for the clergy and one for the laity. This also noticeably increased sound absorption, since there was a significant reduction in both the reverberation time, $T_{30,\mathrm{mid}}$, from 2.75 s to 1.88 s, and in perceived reverberation derived from EDT values (Figure 7). These values would all have been suitable for the responsorial chant that made the faithful feel that they were actively participating. However, these would not have provided ideal acoustics for preaching despite the fact that when the sound source is in the presbytery (source A0) D_{50} average values increase by 3 JNDs in the central nave (Table 3) compared with basilicas with no curtains. Average STI values of 0.51 provided 'fair' intelligibility.

5. Major basilicas

5.1. Architecture, liturgy and music

As the size and proportions of basilicas increased, reaching their apogee in the major Roman patriarchal basilicas, the primitive approach to church space, which had encouraged intimacy among the faithful, was lost. The emphatic value of the ritual was highlighted, reducing the active participation of the people in the liturgy [33]. The collective

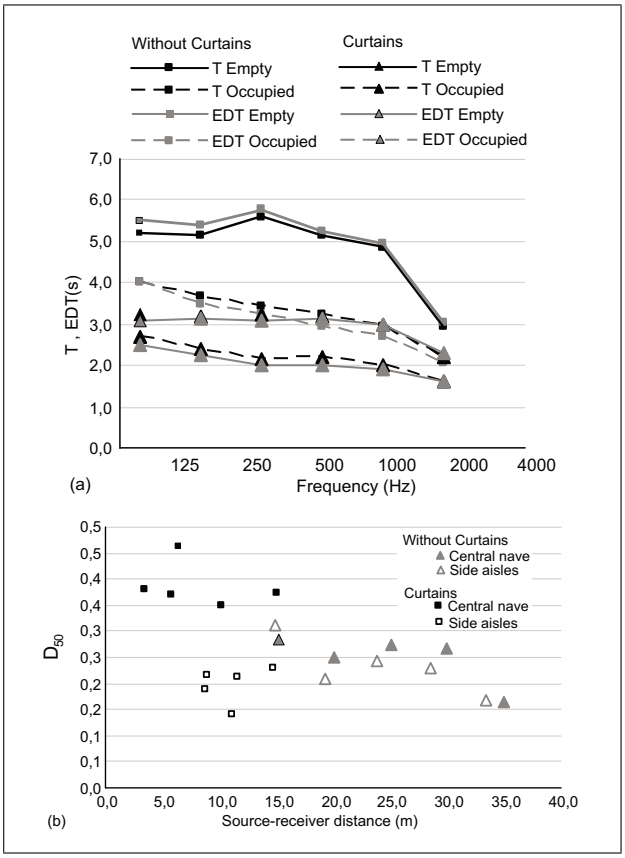

Figure 7. Early Christian basilica with and without curtains between columns. Occupied central nave. (a) Octave-band values of reverberation time (T_{30}) and EDT. (b) D_{50} as a function of source-receiver distance.

participatory worship of the assembly was gradually replaced by a clerical celebration focusing on the bishop, presbyters and deacons. In time this would turn the faithful into mere onlookers of the rite, experiencing sacraments and prayer from an increasingly individual perspective [25].

The new spaces, more reverberant than their predecessors, were better suited to the chanting of psalms than to speech. Throughout time, the psalms, a legacy of the Jewish tradition, have embodied the link between the words of prayer and the power of music. However, while the Jewish practice of rhythmic psalm chanting easily accommodated instruments, early Christians excluded instruments from worship. Sacred music was not introduced solely through melody, but rather through the words of sacred texts, used for preaching purposes. This paved the way for sung masses [34].

The connection of singing and speech brought about a superimposition of the roles of reader and cantor. Up until the fourth century the only fully defined figure in the Christian ritual was that of the reader, but there was a need for a guiding figure to further instruct the congregation. The reader-cantor had to be located in a suitable position when chanting the text. In order to increase the people's understanding of the message he faced the public, whenever possible from a high location. Documents dating back to the third and fourth centuries already mention the existence of a raised spot, with a lectern for the reader, which later gave way to the ambo, a small tribune with railings and a lectern situated between the presbytery and the nave. This location was used in equal measure for readings, responsorial chant and preaching [25].

The raised ambo in the center of the nave was better placed than the cathedra to help the person reading, chanting or preaching to be understood by the faithful, and encourage their participation. Later, in larger basilicas such as that of Saint Lawrence outside the Walls in Rome, two ambos, one for the Gospel and one for the Epistle, were set symmetrically in a central position. The Epistle ambo was higher, reached by a double set of stairs and was also used by the bishop when he was not speaking from the cathedra [2].

In the first quarter of the fifth century, Pope Celestine V introduced antiphonal or responsorial psalms to the introit of the mass. The singers had to memorize all the verses of the psalm, so that a group of specialized singers, the *schola*, was called for. From this point on, simple responsorial chant was replaced with more artistic chant, paving the way for alternating melodic chant sung by two groups of singers [35].

The role of the schola within the liturgy was to lead the singing in the assembly and it was initially situated in the apse. With the increase in the number of clergy and the more complex mass ceremonies which required more singers, the choir moved lower down from the presbytery to the central nave, to the other side of the chancel that separated the faithful from the clergy. This schola cantorum was a space closed off by a marble choir screen, with an opening that allowed access between the nave and presbytery [36].

The clericalization of the mass led to the separation of the presbytery and nave, not just by a simple chancel, but also by a double row of columns creating an *ecclesiola in ecclesia*, a place within the church that was reserved solely for the clergy [26]. Cruciform floor plans, which had begun with the introduction of transepts in the basilicas of St Peter and St Paul in Rome, appeared as extensions to the naves, allowing extra space for the clergy.

From the late eighth century on, the church evolved in terms of organization and the construction of smaller parish churches and cathedrals began. The start of the middle ages was also characterized by the increasing importance of monasteries, beginning with the foundation of Cluny Abbey (910) by Duke William of Aquitaine [37].

5.2. Acoustics

The acoustic study of the large five-nave basilica model, dedicated to the festive liturgy, was based on St John Lateran in Rome (fourth century) (Figure 8, Table II), using the reconstructions provided by Blaauw and Krautheimer [24].

Larger basilica models of the five-nave type, with little ornamentation and flat reflecting walls produce an increase in reverberation time. The $T_{30,\mathrm{mid}}$ values are over

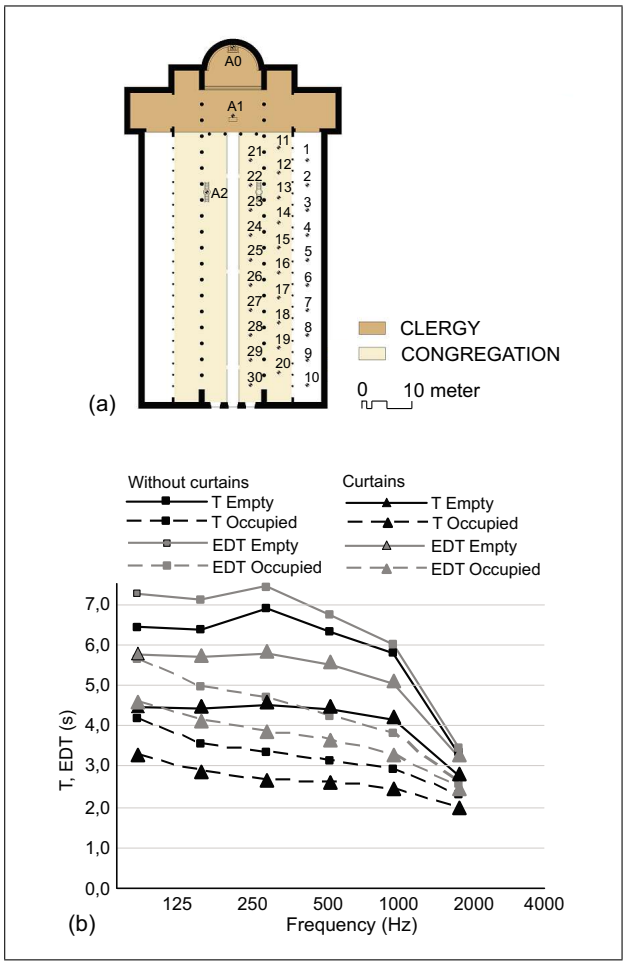

Figure 8. Major basilica, Saint John Lateran. (a) Floor plan with position of sound sources: A0 (cathedra), A1 (altar), and A2 (ambo). (b) T_{30} and EDT with and without curtains between columns in outer nave.

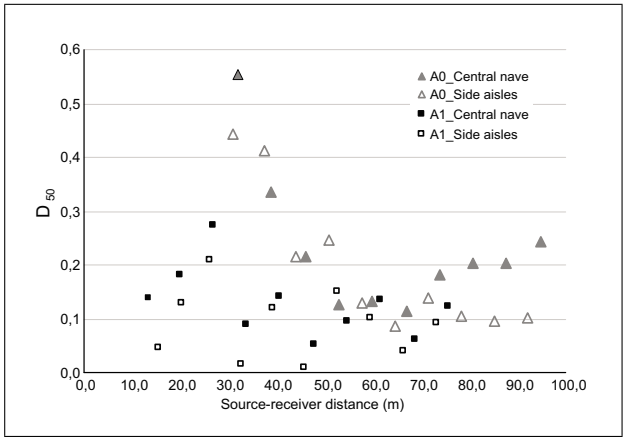

Figure 9. Major basilica, Saint John Lateran. Sound source A0 (cathedra) and A1 (central altar). D_{50} as a function of source-receiver distance. Occupied basilica.

3 s with an occupied church and the EDT values exceed those of $T_{30,\mathrm{mid}}$ by almost 1 s, indicating greater perceived reverberation, given the increased distances and few early reflections. In these large basilicas the increased distances between source and receiver and the lack of early reflections result in average D_{50} values of around 0.20 with the source situated in the apse (source A0), and average STI values of 0.44. This means speech intelligibility can be rated as 'poor-fair', which would have hindered the simple reading of the scriptures.

With the introduction of the transept the altar was moved forward from the apse area toward the central nave (Figure 8a). This relocation of the source (source A1) leads to reduced values of D_{50} with a reduction of 2 JNDs, and average STI values of 0.33, which indicate 'poor' to 'bad' intelligibility (Figure 9, Table III). The slower energy decay of Latin vowel sounds, along with their longer duration and sound level caused a temporal overlap with the following consonant, thus making speech unintelligible [38].

As in the basilica, the addition of curtains between the columns of the side aisles did not increase the sound absorption enough to improve acoustic conditions since although $T_{30,\mathrm{mid}}$ values were reduced to 2.64 s, with the church occupied there were still no early reflections.

Simple responsorial chant was replaced by sung masses which fully introduced music into church liturgy. The inclusion of the *schola cantorum* with a greater number of singers increased the number of simultaneous sound sources. The introduction of the musical liturgy [39] meant that speech was replaced by chant, and with the aid of reverberation, the church became a place for music to be heard. The slow, syllabic monotones of chant with louder passages increasing sound levels reduced the interference of reverberation and helped improve intelligibility. Gregorian chant was not a musical arrangement for the liturgy, but rather the liturgy in sung form, supported and enhanced by the great reverberation of the basilica. This added to the solemnity of Christian worship, creating an all-embracing atmosphere of spirituality to attract the faithful.

Although the separate spaces of the presbytery and transept, which were closed off for the clergy, were connected with the area for the faithful through the *schola cantorum* (Figure 10, Table II), this original floor plan did not improve the acoustic conditions in the audience area in these basilicas. The sources situated at the cathedra (source A0) or in the schola cantorum (source A2) resulted in high reverberation times, a lack of early reflections and average lateral efficiency (JFL) values of 0.11-0.14 in the central nave (Figure 11a).

For musical purposes, C80 values are within the typical range set by ISO 3382-1:2009 [22] for performing spaces and oscillate between −2.71 and −3.28 dB, depending on whether the source is positioned at the cathedra or in the *schola cantorum* (Figure 11b, Table III). According to Martellotta [40] these variations could barely be perceived in the slow musical structure of Gregorian chant where voice modulation adapted to the reverberation of the church.

These acoustic deficiencies prevented the faithful from following the liturgy, and in many parts of the church lim-

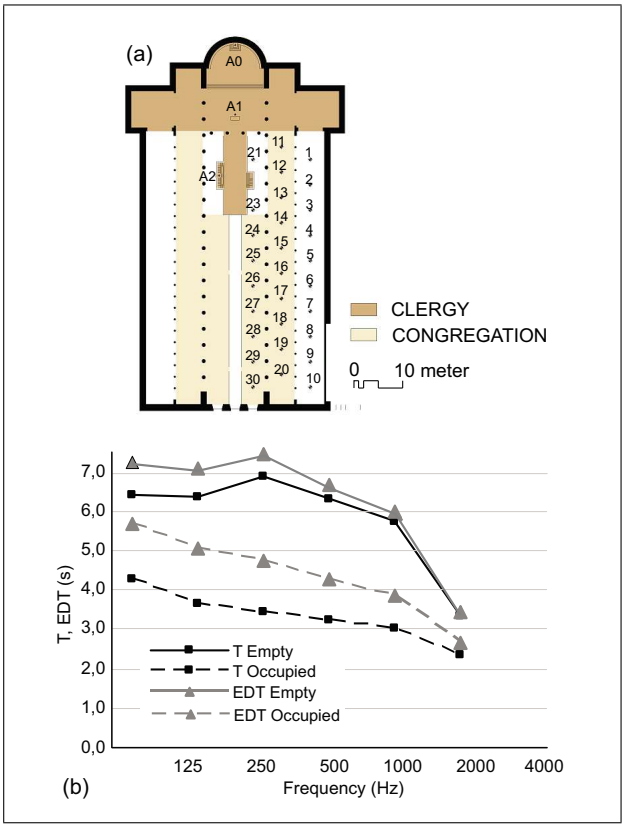

Figure 10. Major basilica, Saint John Lateran with schola. (a) Floor plan with position of sound sources: A0 (cathedra), A1 (altar), and A2 (ambo). (b) Octave-band values of reverberation time (T_{30}) and EDT.

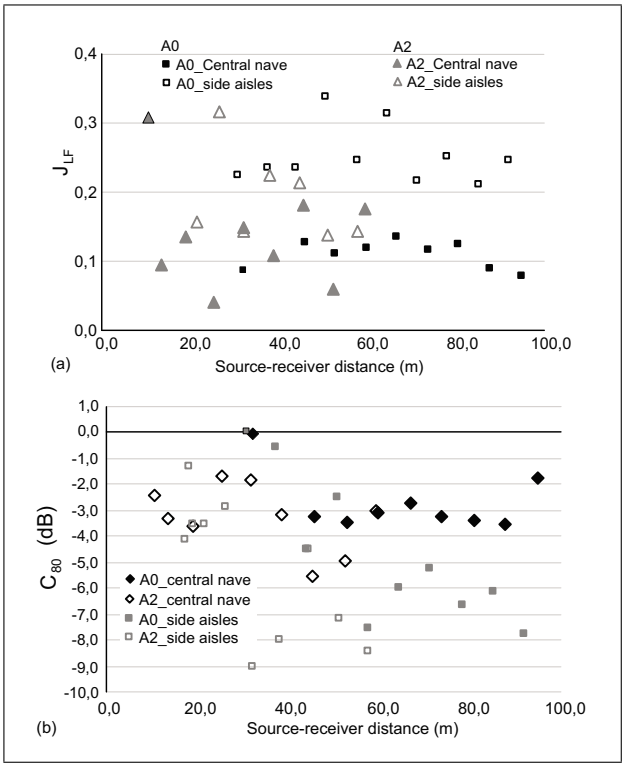

Figure 11. Major basilica, Saint John Lateran with schola. Sound source A0 (cathedra) and A2 (ambo of the schola) in central nave. (a) J_{LF} as a function of source-receiver distance. Empty room. (b) C_{80} as a function of source-receiver distance. Occupied basilica.

ited them to a visual isolation, while the spatial impression was largely due to reverberation since the congregation was unable to understand the message or locate its source.

6. Conclusions

The acoustic study of the initial evolution of the Christian church demonstrates the relationship between architecture, music and liturgy and provides a better understanding of the acoustic environment and the physical situation in these early spaces, which have now for the most part been lost.

The early Christian Church carried out its own particular search for God, from the first domus, which were considered spaces for the spoken word, to patriarchal basilicas, which were spaces for sound, from the place where the Word of God was proclaimed to the house of God in all its greatness, from divine knowledge to spiritual experience.

The early domus, with $T_{30,\mathrm{mid}}$ values under 1.0 s, with a full congregation and D_{50} and STI values of 0.60, were designed as places for meeting and preaching, and generated private spaces for the faithful, who actively participated in the rites with suitable acoustics. Following the proclamation of Christianity as an official religion, larger spaces were built to accommodate the growing numbers of faithful. These spaces show low acoustic absorption, with $T_{30,\mathrm{mid}}$ values of 3.25 s in the basilicas and higher values in the larger basilicas, and with low D_{50} and STI values. Basilicas were perceived as highly reverberant and lacking in intimacy as can be deduced from the EDT values of roughly 4.50 s at mid-frequencies with a full congregation. One of the consequences of this was a deterioration in the acoustic conditions for speech.

Christian liturgy astutely solved this by resorting first to recitation, then to cantillation and later to sacred chant. The liturgy developed trusted in the lasting spiritual effect of the music on the faithful, which reached its apogee as Gregorian chant. Basilicas magnified emotions to such an extent that Christianity came to associate reverberation with religion.

With the decline of preaching and the abandonment of the church as a meeting place, church construction entered a period where special attention was paid to the division of the assembly into faithful and clergy. This had a profound effect on the later development of medieval church types, significantly altering the initial acoustic conditions and laying the foundations for the birth of Romanesque, the first architectural style widespread throughout Western Europe.

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