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*Article*

# Analysis of Acoustic and Perceptual Variables in Three Heritage Churches in Quito Using Structural Equation Modeling

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**Abstract:** Acoustic quality is one of the aspects that contribute to the heritage of cultural and religious spaces. It is increasingly common to find scientific literature detailing the sound characteristics of places of worship, especially those with cultural and historical interests. This article presents a comprehensive acoustic characterization of three colonial heritage churches in Quito. It examines the relationship between objective and subjective parameters that influence the valuation of a space or sound environment. To analyze this relationship, the study employs Structural Equation Modeling (SEM) to evaluate three latent variables using perceptual acoustic indicators. Results from SEM showed statistically confirmed pathways between sociodemographic variables and latent perceptual constructs, which supports the notion that acoustic quality is not entirely captured by more classical measures of intelligibility or clarity.

**Keywords:** church acoustics; sound perception; structural equation modeling; colonial Quito

## 1. Introduction

Over the centuries, the church has served as a vital institution in civilization. It is a place strongly associated with religious beliefs, where believers go to seek spiritual release and tranquility. In addition to serving as a means to enhance people's spiritual well-being, these spaces also provide opportunities for verbal address, the subject of which should be clearly communicated to the audience. Furthermore, churches often hold a variety of art and music events. These include recitals of liturgical music, chamber concerts, symphonic performances, and popular or seasonal music celebrations. As cultural heritage, churches located in historic districts are invaluable. They integrate elements from architecture and urban design. In contrast, the acoustic quality parameters of churches are often not considered during this architectural process.

Restoration efforts have traditionally focused on the rehabilitation of elements such as altarpieces, altars, floors, and even coffered ceilings, as well as their decorative or pictorial elements. Although speech intelligibility may be enhanced by the use of sound reinforcement systems, the intrinsic acoustic response of these spaces—shaped by their geometry, materials, and volume—is often overlooked, despite its greater significance for the acoustic assessment of worship venues. Church acoustics represent a form of heritage that should be preserved with the same emphasis given to architecture and artistic elements.

The study of soundscapes in religious heritage buildings has gained significant attention over the past decade, driven by the interdisciplinary convergence of acoustics, architecture, and cultural heritage preservation [1,2]. Religious spaces, such as churches, mosques, and temples, serve as places

of worship and repositories of intangible cultural heritage, where sound significantly influences spiritual and communal experiences [3,4].

Acoustic characteristics of places of worship can be evaluated using a variety of methods, ranging from the numerical quantification of sound energy-related parameters to binaural recording techniques and ambisonic impulse response measurements for different combinations of sound sources and receivers. The complex architecture of churches often forces evaluators to use diverse and numerous source-receiver positions, resulting in non-comparable results. Therefore, a comprehensive understanding of the spatial variation in acoustic parameters and the selection of the most suitable technological methods are essential for accurate acoustic assessment [5]. A literature review [6] summarized decades of research on the acoustics of Western Christian churches, mainly focusing on heritage-listed sites. This review highlighted the work of research groups in several European countries, providing details of experimental procedures, results, and interpretations of how sound propagates, as well as subjective auditory experiences and computer-assisted simulation techniques. While most acoustic studies have been presented for European churches, notable research has also occurred in the Americas.

In this light, church music represents a form of domain heritage that should be equally preserved with the architectural and performance aspects, suggesting that the acoustic characteristics of worship spaces are not only contextually significant for the intelligibility of speech and the appreciation of music during religious services, but also acquire unique semiotic value specific to each geographic and cultural setting. Measurements of monaural and binaural impulse responses in distinct areas and for various liturgical functions within each cathedral confirmed that spatial distribution of reflected sound energy, reverberation time, and acoustic strength contribute meaningfully to the semiological dimension of the experience—even if these physical descriptors are not explicitly recognized by performers themselves [7]. Another study examined the acoustic properties of Toledo Cathedral in Spain, showing it to be a highly reverberant space with poor speech intelligibility. However, an analysis of its liturgical uses suggests that the cathedral is not a single acoustic space, as evidenced by the differences between the chapels and the choir [8].

One study measured the acoustic energy relationships in Gothic-Mudéjar churches in southern Spain, comparing the results of these measurements against theoretical models [9]. The authors proposed an analytical model based on measured musical clarity (C80) values. An alternative approach was presented in a study of eight Roman Catholic churches in Poland, where a comprehensive acoustic quality indicator was created by comparing multiple variables. This global indicator offers a user-friendly tool for both scientific research and practical decision-making [10].

As technology has progressed over the years, the methods for evaluating acoustics have also advanced. Initial characterizations were concerned with reverberation time (RT), early decay time (EDT), and speech intelligibility using the Speech Transmission Index (STI). Later additions included further energy-related parameters such as strength (G), lateral energy fractions (LF and LG), and speech and music clarity (C50 and C80). More recently, the interaural cross-correlation coefficient (IACC) has been used to check that sound arrives at the listener's two ears simultaneously, calling for binaural or ambisonic recording equipment as specified in the standards [11] and [12].

In addition to Christian churches, soundscapes for Buddhist temples have been evaluated, and their analysis has reported some sounds that disturb music listening as well as preferred sound sources for meditating. A study found that sound sharpness correlated most strongly with visitor's sound preferences [13]. Recently, Ma et al. [14] proposed a subjective scale for evaluating sound quality in buildings. On this scale, the three principal latent factors in the human perceptual dimensions of sound are overall sound evaluation (E: evaluation), energy content (P: potency), and temporal-spectral content (A: activity). This EPA approach (Evaluation, Potency, Activity) considers the interaction between the on-site listener and the measurement, thereby providing a valid and reliable method for quantitative analysis [14].

Despite the growing body of literature, a critical gap remains in the application of advanced statistical methods, such as structural equation modeling (SEM) [15] to analyze the relationships

between acoustic and perceptual variables in religious heritage sites. This approach offers a robust framework for modeling latent constructs and their relationships with perceptual acoustic parameters.

Building upon this background, this study aims to acoustically characterize three colonial churches in Quito, which are significant components of the city's historical heritage. By combining objective measurements with subjective evaluation scales, this study proposes a comprehensive evaluation of acoustic quality parameters for both speech and music in the evaluated churches. The goal is to use modern technology to analyze the characteristics of the overall sound field. This research aims to inform future studies on preserving the acoustics of churches as part of our cultural heritage. By comparing the sound field behavior with the experiences of on-site listeners, the study identifies key acoustic factors that influence how individuals perceive these historic spaces. Combining objective measurements with subjective assessments of the sound environment provides practical advice for adapting historic buildings for contemporary use.

## 2. Evaluated Churches

In this study, three significant heritage churches of Quito were examined: 1) La Compañía de Jesús, 2) the Metropolitan Cathedral, and 3) El Sagrario.

The Church of La Compañía de Jesús is one of the most representative of Quito's baroque architecture in Latin America. Built from 1605 to 1765, the church is an extraordinary blend of styles, including Baroque, Moorish, and Neoclassical elements [16]. Located in Quito's city center, this religious building is best known for its ornate interior, featuring gilded wood carvings, intricate altarpieces, and golden-leaf decorations. The Jesuits constructed the church as a multifaceted center for religion, education, and culture. It reflects the educational and spiritual values of the Jesuits, as well as the widespread artistic and theological interests of the Counter-Reformation era. The aesthetic of the Quito School of Art, a Spanish- and indigenous-influenced regional style, can still be observed in the form of many church frescoes, sculptures, and ornamental details [17]. Conservation and restoration efforts carried out over the last few decades have enabled the preservation of its historical and artistic heritage, making it a reference for researchers and experts in heritage protection [18].

The Metropolitan Cathedral is another important religious site in Quito and can be found in the city's main square in the colonial quarter. Constructed from 1562 to 1806, the cathedral reflects the evolution of architectural styles from the colonial period to the early Republican era. It features a blend of Gothic rib vaults, Baroque ornamentation, Mudejar ceilings, and Neoclassical facades. This diversity of styles demonstrates how the European model of architecture was gradually adapted to local building practices. Since the Spanish conquest, the cathedral has remained an integral part of the city's religious, cultural, and political life [19]. This richness of artistry also extends to the interior, where there is masterful woodwork and stone carvings, as well as a number of Quito School artworks. The cathedral also contains the tombs of several significant historical figures. Although there have been several earthquakes in the area, the building itself has undergone several careful renovations and reinforced its construction, preserving its spiritual and architectural essence intact.

Another well-known colonial religious structure is the El Sagrario Church, also located in Quito's Old Town. Envisioned initially as a subsidiary chapel of the Metropolitan Cathedral, El Sagrario developed its own architectural identity and artistic importance as a separate parish church. The church was constructed in the 16th-18th centuries (Renaissance for construction and Baroque for decoration). It features a very coherent composition style with a concordant yet dynamic architecture. On the surface are classical-style columns and intricate iconographic details cut from polished volcanic rock. Within, the visitor finds an overwhelming visual feast of gilded altarpieces, mural paintings, and a soaring dome that filters the light. El Sagrario is a key element of Ecuador's national heritage, providing examples of the art and cultural interaction that characterized Andean colonial architecture [20]. Table 1 shows the general attributes of the studied churches, Figure 1 presents a schematic diagram of the churches, and Figure 2 shows general views of the evaluated sites.



Table 1. Main attributes of the studied churches in Quito, Ecuador.

Church	Architectural Style	Volume (m³)	Dimension L x W (m)	Height (m)	Description
La Compañía	Baroque, Rococo. 16th century	30,240	63 x 30	16	Plank hardwood flooring, Gold leaf coffered ceiling, Gold leaf altarpieces wall, Stone and plaster columns.
Metropolitan Cathedral	Baroque, Rococo. 16th century	31,500	70 x 25	18	Plank hardwood flooring, Wooden coffered ceiling, Plaster walls with oil paintings, Stone columns.
El Sagrario	Baroque, Rococo. 18th century	16,512	43 x 24	16	Suspended plank flooring, Plaster ceiling, Gold leaf altarpieces wall, Stone and plaster columns.

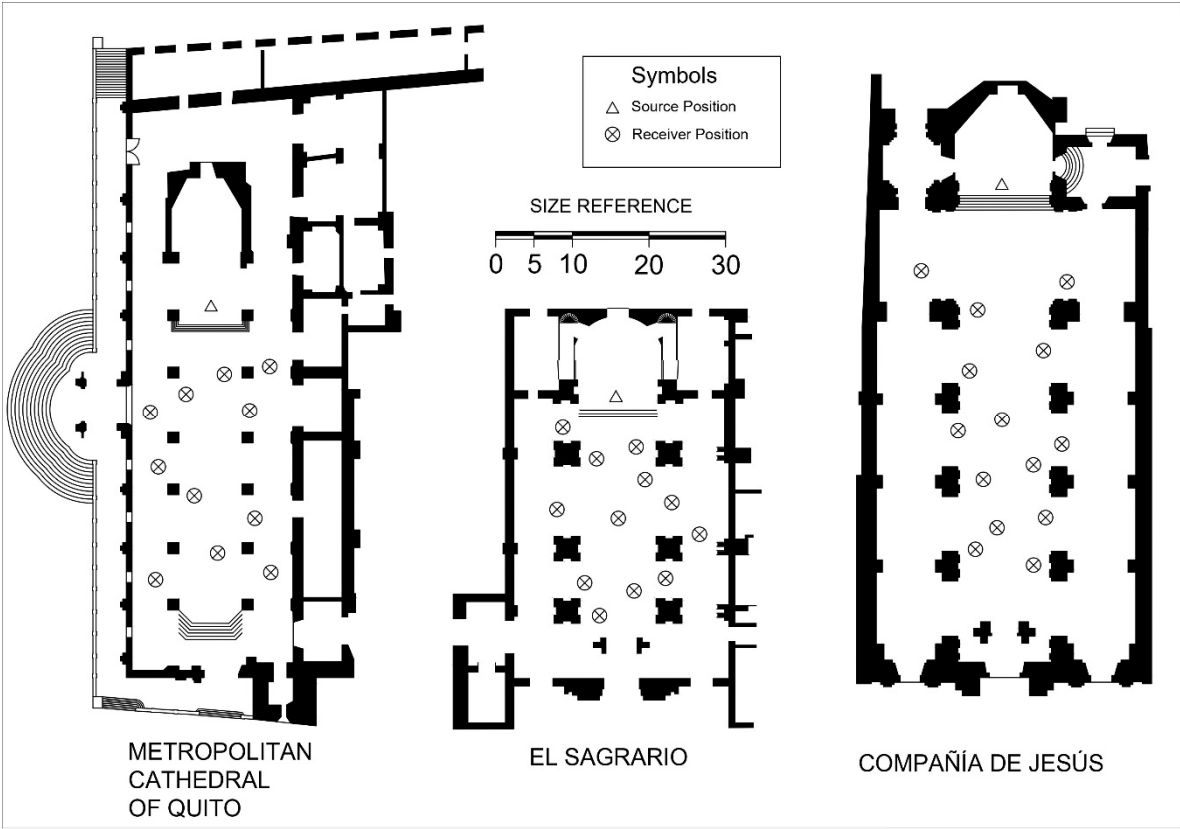
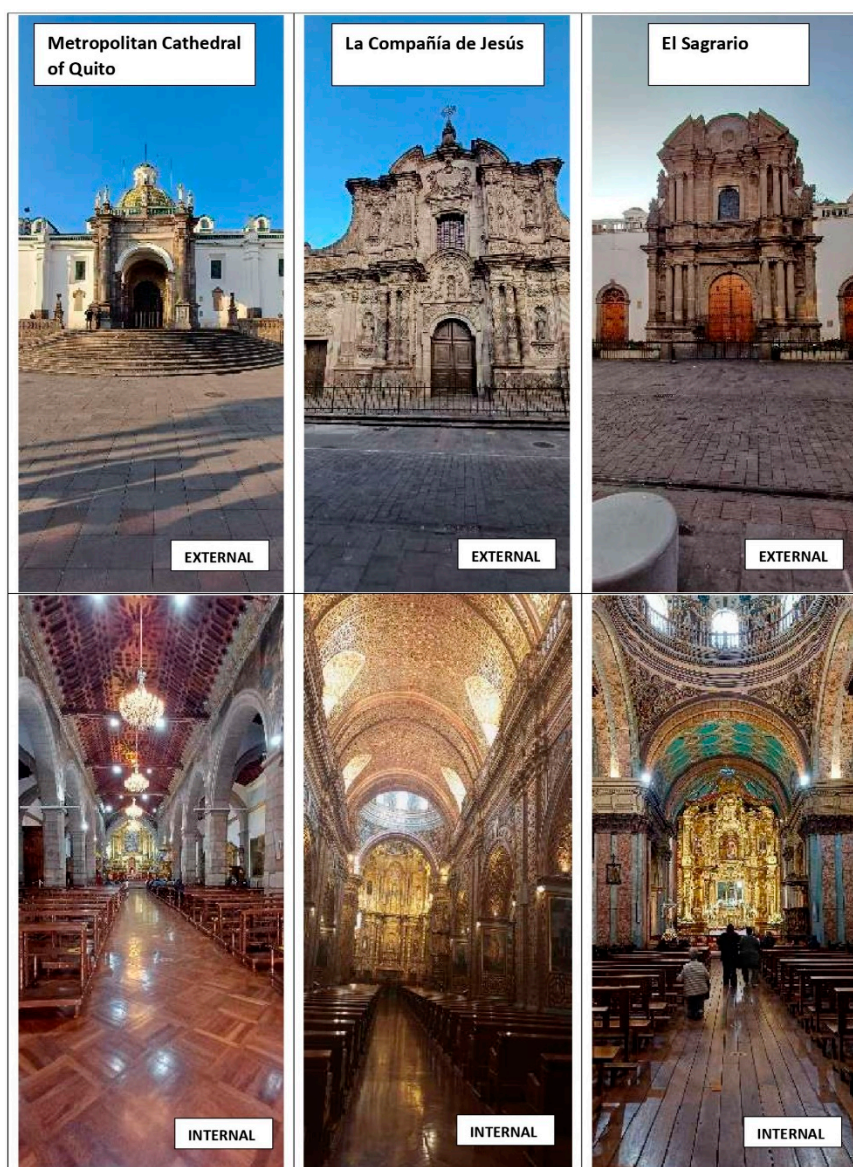


Figure 1. Ground plan of the three churches studied, including source and receiver positions used.



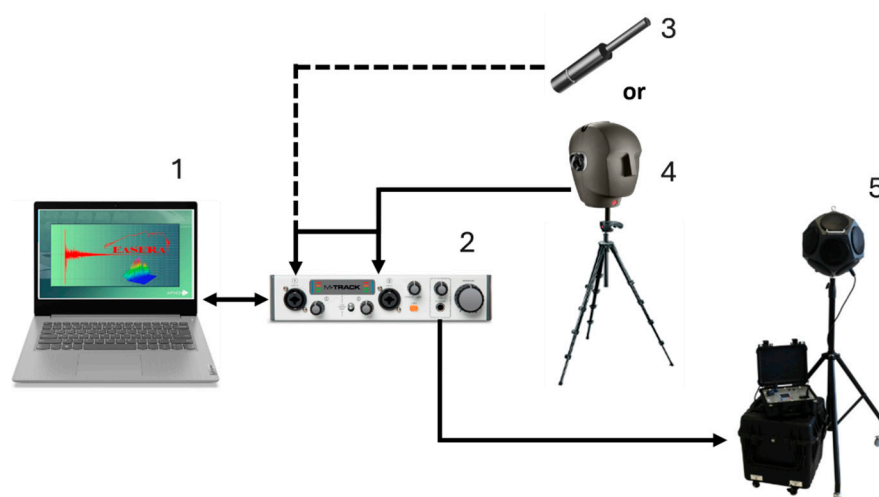
**Figure 2.** Photographs of the exterior and interior of the churches.

### 3. Methodology

The methodology includes three key components: acoustic evaluation through in-situ measurements, subjective assessment via opinion surveys, and the development of a Structural Equation Model (SEM) based on the EPA approach to analyze the relationships between perceptual and acoustic variables.

#### 3.1. Acoustic Assessment

The acoustic evaluation followed a rigorous methodology to analyze the sound characteristics of the selected religious sites. To ensure controlled conditions, acoustic measurements were conducted during technical visits when the space was unoccupied by the public. An omnidirectional sound source (CESVA BP012) was used, driven by its dedicated amplifier and connected to an M-Audio MTrack II interface, as shown in Figure 3. Calibration was performed in situ before each measurement using software (EASERA v1.2) to ensure consistent excitation levels. The source was positioned at the altar, as it is the central location for religious ceremonies.



**Figure 3.** Diagram of measurement's setup. Elements: 1. Computer running software (EASERA v1.2); 2. M-Audio Mtrack II Audio Interface; 3. Measurement microphone (Beyerdynamic MM1); 4. Binaural dummy head (Neumann KU100); 5. omnidirectional sound source (CESVA BP012).

Receiver positions ranged between 15 and 22 per site, distributed along the central nave, considering the geometry of the space. Their placement followed the recommendations of [12], ensuring a homogeneous random distribution while avoiding symmetrical positions. Each point was measured using both a microphone (Beyerdynamic MM1) and a binaural dummy head (Neumann KU100). The microphone was primarily used to evaluate temporal acoustic parameters, including Reverberation Time (RT), Early Decay Time (EDT), Speech Clarity (C50), Musical Clarity (C80), Definition, the sound pressure level within the first 80 ms after the initial arrival of the signal (L80), and Speech Transmission Index (STI). At the same time, the binaural dummy head captured spatial attributes, including the Interaural Cross-Correlation Coefficient (IACC) in full early and late mode.

Acoustic excitation was performed using an exponential sine sweep generated by software (EASERA v1.2), with a sampling rate of 44.1 kHz. The impulse responses were captured over the whole audible frequency range, ensuring broadband acquisition was suitable for room acoustic analysis. Each receiver position was measured five times to ensure data reliability and accuracy. The software automatically processed the impulse responses and calculated the acoustic parameters. Statistical post-processing involved averaging five measurements per point and aggregating data across three predefined zones—near, mid, and far (relative to the altar)—to derive representative values for each area and the entire venue.

Acoustic measurements were conducted under the normal conditions of each space without modifications. To minimize external noise interference and environmental fluctuations, several measures were implemented, including in situ calibration, closure of the venue to the public during measurement sessions, and scheduling data collection during periods of minimal or no external activity. These procedures provided a comprehensive and reliable assessment of the acoustic environment within the analyzed religious spaces.

### 3.2. Subjective Assessment

To explore the perceptual and affective responses to the acoustic environment of the heritage churches under study, a subjective assessment was conducted through on-site surveys. Participants completed questionnaires immediately after visiting the churches, which contained a range of contextual scenarios. Specifically, participants were surveyed following religious services, guided or independent tourist visits, and non-formal religious or touristic visits (e.g., private prayer or casual entry). This approach ensured the inclusion of a broad spectrum of acoustic perceptions shaped by different functional and experiential conditions within the sacred spaces.

3.2.1. Participants’ Sample Size

Applying the guideline of six subjects per parameter resulted in a minimum sample size of 115 participants per site. To enhance the consistency of the perceptual data and meet the statistical requirements of the analysis methods used, we distributed a greater number of surveys—at least 400 for each religious site [21]. This decision follows methodological recommendations indicating that larger sample sizes enhance the stability of factor analysis results and support the practical application of the semantic differential technique.

On the other hand, the EPA approach specified in this study consisted of three latent variables, each measured through two observed indicators, yielding a total of six observed variables [14]. Following best practices in SEM, a minimum sample size was estimated based on two commonly accepted criteria: at least ten respondents per observed variable and at least five respondents per estimated parameter.

Thus, a total of 1,214 visitors participated in the survey, distributed across the sites as follows: the Cathedral (n = 409), La Compañía (n = 403), and El Sagrario (n = 402). The participants included individuals visiting for both religious and touristic purposes, representing a balanced distribution of male and female respondents. Age groups ranged from 15 years to over 65 years, allowing for a diverse understanding of sound perception across different life stages. The data was collected through face-to-face surveys conducted using digital forms between March and November 2024, ensuring a comprehensive capture of visitor experiences under varying temporal and environmental conditions. Considering that the model includes six factor loadings, six error variances, and three latent covariances, a total of 23 parameters were estimated (see Table 2 parts II and III). Accordingly, the minimum recommended sample size was calculated to be 60 based on the parameter-based criterion and 60 based on the variable-based criterion. The final sample size far exceeded the minimum requirements, thereby ensuring robust model estimation and high statistical power.

Table 2. Elements of the applied questionnaire.

Part	Question (Latent variable)	Scale type
I: Personal background/sociodemographic	Gender, Age, Educational level, Occupation, Family size, Residence Zone, Frequency of visit, Purpose of visit	Categorical
II: Acoustic perceptions	Speech clarity, Musical clarity, Quality, Intelligibility, Reverberation/Echo	Five-point Likert scale
III: Soundscape perceptions	E: Opacity, Brightness, Treble, Bass, Understandable, Confusing P: Silence, Noise, Lightness, Intensity, Strength, Weakness A: Tranquility, Noise, Relaxation, Strain, Pleasure, Displeasure	Five-point Likert scale

3.2.2. Questionnaire Design

The survey was structured into three main sections to capture participants' profiles and their experiences with sound perception, as presented in Table 2. The first section gathered personal and socio-demographic information, including age, gender, purpose of visit (touristic or religious), and frequency of visits to religious sites. The second section focused on general perception related to the acoustic environment, using a 5-point Likert scale where 1 represented "Strongly Disagree" and 5 "Strongly Agree." The third section explored perceptions associated with the latent variables defined in the EPA approach. This part contained 18 semantic differential indicators, all rated on a 5-point scale. For example, for the indicator "Pleasantness," participants rated their experience from 1 ("Not pleasant at all") to 5 ("Very pleasant"). This structured approach enabled a detailed assessment of



how visitors perceived the sound environment within religious spaces, providing insights into both subjective evaluations and broader perceptual patterns.

Table 3 presents the complete set of input variables used to construct and estimate the structural equation model designed to explore the relationships between architectural/acoustic indicators, perceptual sound descriptors, and sociodemographic factors. It contains three main thematic blocks: (1) demographic and socioeconomic aspects, (2) architectural/acoustic perception ratings (General Opinions), and (3) perceptual responses subdivided according to the circumplex structure of soundscape dimensions—Evaluation, Potency, and Activity. Each variable was categorized by its thematic module and included the corresponding label and coding scale.

Table 3. Input variables used in the model.

Module	Variable	Range - Codes
Sociodemographic	Gender	Female (0) - Male (1)
	Age	15–25 (1), 26–35 (2), 36–45 (3), 46–55 (4), 65 (5), >65 (6)
	Educational level	Categorical
	Occupation	Categorical
	Family size	Categorical
	Residence zone	Categorical
	Frequency of visit	Categorical
	Purpose of visit	Categorical
Acoustic perceptions	Speech clarity	Lowest (1) - highest (5)
	Music clarity	Lowest (1) - highest (5)
	General quality	Lowest (1) - highest (5)
	Intelligibility	Lowest (1) - highest (5)
	Reverberation/Echo	Lowest (1) - highest (5)
Soundscape perceptions (Evaluation)	Opacity	Lowest (1) - highest (5)
	Brightness	Lowest (1) - highest (5)
	Bass	Lowest (1) - highest (5)
	Treble	Lowest (1) - highest (5)
	Confused	Lowest (1) - highest (5)
	Understandable	Lowest (1) - highest (5)
(Potency)	Quiet	Lowest (1) - highest (5)
	Loudness	Lowest (1) - highest (5)
	Light	Lowest (1) - highest (5)
	Intense	Lowest (1) - highest (5)
	Weakness	Lowest (1) - highest (5)
	Strength	Lowest (1) - highest (5)
(Activity)	Noise	Lowest (1) - highest (5)
	Tranquility	Lowest (1) - highest (5)
	Tense	Lowest (1) - highest (5)
	Relaxed	Lowest (1) - highest (5)
	Unpleasant	Lowest (1) - highest (5)

Pleasant	Lowest (1) - highest (5)
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3.3. Structural Equation Modeling

To investigate the correlations between objective acoustic behavior and subjective sound quality perception in churches, the current study employs SEM with three latent variables: EPA [14], where Evaluation (E) characterizes the global affective judgment of the acoustic scene (e.g., Pleasant-Unpleasant, Relaxed-Tense), Potency (P) indicates the perceived intensity and dominance of the sound in the environment (e.g., Weak-Strong, Quiet-Loud), and Activity (A) represents the spectral content (e.g., Flat-Sharp, Low-High).

Firstly, an exploratory factor analysis (EFA) was performed to extract the primary latent constructs from a set of measured indicators without a preconceived structure. Next, to assess the discriminant validity and factorial validity of the constructs, Confirmatory Factor Analyses (CFA) were carried out and confirmed using composite reliability (CR) and average variance extracted (AVE). Discriminant validity was established as the maximum shared variance (MSV) for each factor was lower than the AVE. Finally, an advanced SEM model was formulated to validate the hypothesis path by estimating the regressor coefficient loadings on the structural model. Structural equation models were processed and analyzed using the Lavaan library [22] in R-Studio (v2025.05). SEM allows the use of mediation analysis and then estimates the loadings of the total effects involving both latent and explanatory variables.

The literature indicates that several studies have applied latent variable analysis within SEM frameworks to assess auditory perception in urban soundscapes [23–26], as well as in building environments [14]. However, this methodology remains unexplored, mainly in the specific context of heritage churches. Recent contributions have sought to integrate objective acoustic measurements with subjective assessments of auditory perception [27,28] or with user-reported perceptions of churches as tourist destinations [29]. Based on the EPA approach proposed for assessing sound quality in buildings, the present study tests a conceptual SEM based on the three hypotheses illustrated in Figure 4, specifically adapted to the context of heritage churches:

- H<sub>A</sub>: Perceived Activity inside churches is positively correlated with Potency of sounds.
- H<sub>B</sub>: Perceived Potency of sounds influences sound evaluation.
- H<sub>C1</sub>: Sociodemographic characteristics of participants influence Activity, Potency, and Evaluation of sounds in churches.
- H<sub>C2</sub>: The geographical residential location of participants influences the Activity, Potency, and Evaluation of sounds inside the churches.

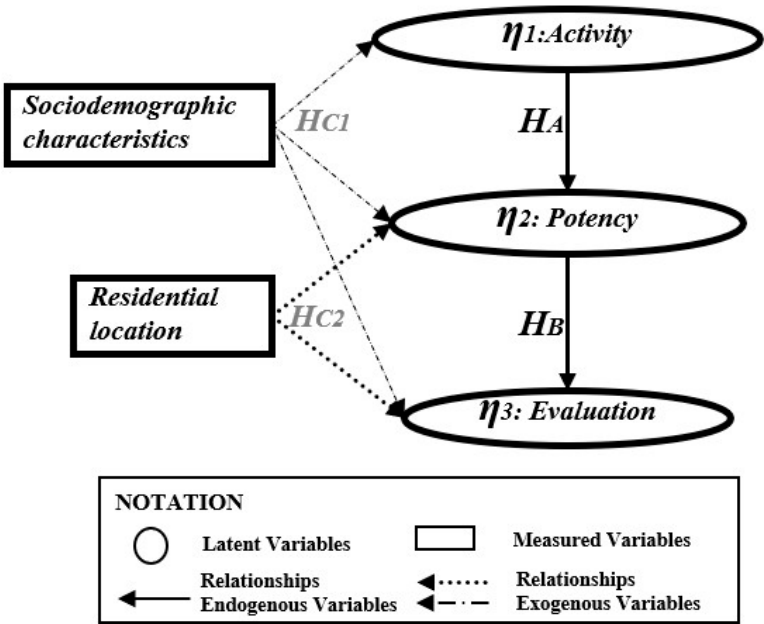


Figure 4. Proposed theoretical model.

4. Results

Table 4 summarizes the acoustic analysis of the three heritage churches, where different reverberation and clarity behaviors were identified. RT varied between 2.1 s (La Compañía) and 2.6 s (El Sagrario), though La Compañía also showed the lowest EDT (2.4 s), which might denote just a little better sound decay control. Clarity indices were negative in all sites, with La Compañía church exhibiting the highest Music Clarity (C80 = −2.0), indicating a better musical acoustic environment. Definition values were consistent at 0.3, and L80 levels were highest in La Compañía (100.0 dB), suggesting a stronger early energy contribution. STI and RASTI values were generally moderate (STI ≈ 0.4), as were the %AICons values (17.8–20.2%), suggesting moderate levels of speech intelligibility. IACC values were relatively stable for the early and late reflections; full-range IACC was highest in La Compañía (0.4), indicating a somewhat stronger spatial impression.

Table 4. Average results of the acoustic parameters (standard deviation).

Parameters	Metropolitan Cathedral	La Compañía	El Sagrario
RT[s]	2.4 (0.06)	2.1 (0.08)	2.6 (0.03)
EDT [s]	2.5 (0.07)	2.4 (0.23)	2.6 (0.06)
C50	-4.7 (0.52)	-4.3 (0.11)	-4.5 (0.38)
C80	-2.8 (0.36)	-2.0 (0.11)	-3.6 (0.90)
D	0.3 (0.02)	0.3 (0.05)	0.3 (0.02)
L80 [dB]	97.7 (0.63)	100.0 (0.73)	99.3 (0.27)
AICons [%]	20.2 (0.66)	17.8 (0.30)	17.8 (0.24)
STI	0.4 (0.02)	0.4 (0.04)	0.4 (0.01)
STI (Male)	0.4 (0.02)	0.4 (0.04)	0.4 (0.01)
STI (Female)	0.4 (0.02)	0.4 (0.04)	0.4 (0.01)
RASTI	0.3 (0.01)	0.4 (0.04)	0.3 (0.03)
IACC (Full)	0.3 (0.05)	0.4 (0.07)	0.4 (0.03)
IACC (Early)	0.5 (0.07)	0.5 (0.07)	0.5 (0.05)

IACC (Late)	0.3 (0.07)	0.3 (0.04)	0.3 (0.02)
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Figure 5 shows RT values across 1/1 octave bands, capturing the frequency-dependent decay characteristics of the sound field. Complementarily, Figure 6 shows the IACCs, also in 1/1 octave bands, which provides insights into the spatial immersion of the acoustic environment from a binaural perspective.

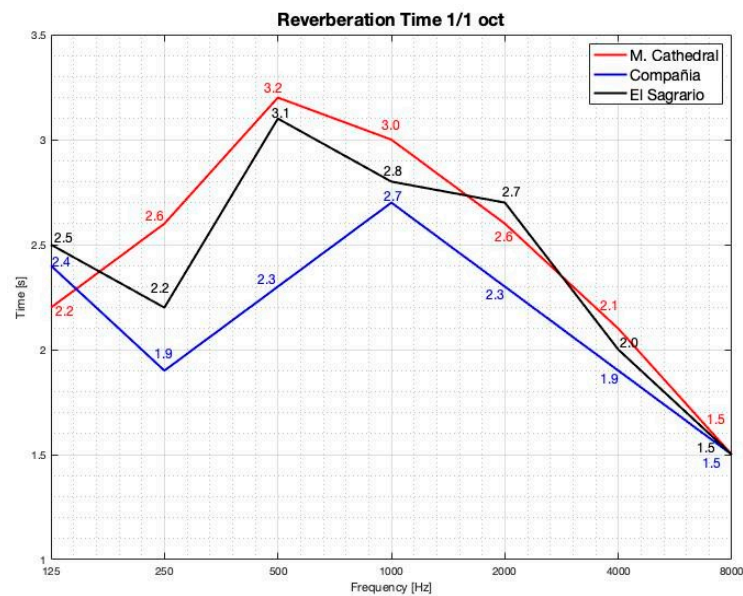


Figure 5. Reverberation time (RT) measured in one-octave frequency bands at each church.

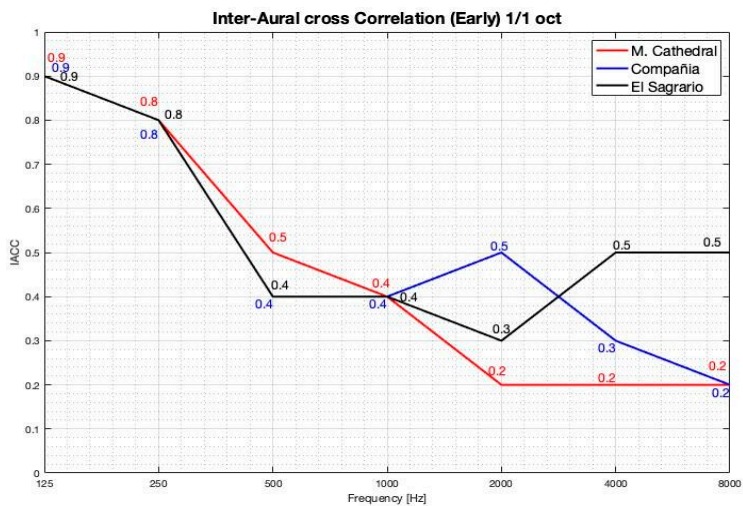


Figure 6. Interaural Cross-Correlation Coefficient (IACC) measured in one-octave frequency bands at each church.

The Metropolitan Cathedral exhibited the highest RT across most frequency bands, peaking at 3.2 seconds at 500 Hz, which suggests a particularly reverberant space, ideal for the performance of liturgical music but detrimental to the intelligibility of spoken language. El Sagrario presents an intermediate acoustic profile, with reverberation times comparable to the Cathedral at mid-to-high frequencies but slightly reduced at low frequencies. On the other hand, La Compañía presents the lowest reverberation times in general, and especially at low frequencies (1.9 s at 250 Hz), indicating a more damped acoustic environment, which may favor the clarity of spoken words. These differences arise from the varied architectural and material properties of the three buildings.



As for IACC, large values indicate an enhanced auditory spaciousness. La Compañía generally shows the highest IACC across most frequencies, as well as the mid-high range, which can be as high as 0.4-0.5. These results indicate better performance in generating an enveloping sound field, which increases the perception of spatialness. By contrast, the IACC values are higher in the Metropolitan Cathedral and El Sagrario, specifically, below 1 kHz, the IACC values are higher in the Cathedral, while above 4 kHz, El Sagrario exhibits the highest values, denoting a directional sound field and less perceptual space. These data support the acoustic singularity of La Compañía in terms of spatial sensation.

A principal component analysis with varimax rotation was conducted to identify orthogonal factors and their primary indicators. The Kaiser–Meyer–Olkin Index ( $KMO = 0.94$ ), along with the Measure of Sampling Adequacy (MSA) for each indicator, was used to assess sample adequacy [30]. All indicators surpassed the acceptable threshold of 0.7 based on MSA values, confirming their suitability for inclusion in the analysis.

The SEM development underwent a multi-stage validation process, which included EFA, CFA, and SEM path modeling techniques. The EPA approach determined that Activity ( $\eta_1$ ), Potency ( $\eta_2$ ), and Evaluation ( $\eta_3$ ) represent the fundamental latent variables characterizing the acoustic quality perception within heritage churches

Several models were tested for the EFA, and Table 5 presents the results of the EFA that showed the highest association. Three clear factors emerged from the EFA with eigenvalues above 1, explaining 74% of the total variance. The variance distribution was 35% for Factor 1 (*Activity*) and 19% for Factor 2 (*Potency*), while Factor 3 (*Evaluation*) explained 20%. The principal factors extracted from the EFA align with those identified in previous studies [31]. The *Activity* showed high loadings from *Noise*, *Tense*, and *Unpleasantness* indicators, which exceeded 0.89, while *Potency* revealed strong loadings from *Loudness*, *Reverberation*, and *Strength* indicators. The *Evaluation* dimension relied on indicators like *Speech* and *Music Clarity* and *Brightness* together with *Understandability*.

Table 5. Results of the Exploratory Factor Analysis (EFA).

Indicators	MSA	Factor loading	Variance explained (%)
<b>Factor 1: Activity</b>			35
I3. Noise	0.82	0.89	
I4. Tense	0.74	0.94	
I7. Unpleasantness	0.75	0.93	
<b>Factor 2: Potency</b>			19
I8. Reverberation/Echo	0.89	0.62	
I10. Loudness	0.71	0.83	
I14. Strength	0.87	0.7	
<b>Factor 3: Evaluation</b>			20
I15. Speech clarity	0.78	0.89	
I16. Music clarity	0.78	0.83	
I19. Brightness	0.78	0.81	
I23. Understandability	0.78	0.89	

CFA confirmed the structure because every standardized factor loading proved statistically significant and surpassed the advised threshold of 0.70 except for one marginal instance. Table 6 demonstrates that the average variance extracted for each construct exceeded 0.50, thereby confirming convergent validity. The measurement of internal consistency proved strong as CR and Cronbach’s alpha values exceeded the accepted 0.70 standard [32].

Table 6. Results of the Confirmatory Factor Analyses (CFA)

Latent variable	Std. factor loading	AVE	CR	Cronbach's alpha	MSV	ASV
Activity $\eta_1$		0.851	0.851	0.94	0.891	0.868
I3. Noise	0.900					
I5. Tense	0.934					
I7. Unpleasantness	0.934					
Potency $\eta_2$		0.536	0.536	0.744	0.845	0.840
I8. Reverberation/Echo	0.706					
I10. Loudness	0.935					
I14. Strength	0.485					
Evaluation $\eta_3$		0.726	0.726	0.908	0.891	0.853
I15. Speech clarity	0.883					
I16. Music clarity	0.791					
I19. Brightness	0.850					
I22. Understandability	0.912					

To validate the hypothesis, the structural relationships among the latent and observed variables were analyzed, as presented in Figure 7 and Table 7. The values of the goodness-of-fit metrics for the conceptual model are shown in Table 8. Regression results (see Table 7) indicated that all structural paths were statistically significant ( $p < 0.001$ ). For example, Activity was a significant predictor of Potency, and Potency significantly influenced Evaluation, suggesting a mediated mechanism whereby negative emotional responses (e.g., Noise, Tense) intensify the perceived acoustic environment, subsequently shaping global evaluative judgments of sound quality. Table 8 indicates an acceptable model fit. Although the Tucker–Lewis Index (TLI) and the Root Mean Square Error of Approximation (RMSEA) values are slightly outside the ideal ranges, they still fall within acceptable limits for complex models. The Standardized Root Mean Square Residual (SRMR) falls within the recommended values. Overall, the model exhibited a satisfactory fit to the data.

Table 7. SEM Measurement and Regression.

Measurement	Estimate	Standard Error	p-value	Standardized estimate
Activity $\eta_1$				
I3. Noise	1.023	0.03	< 0.001	0.9
I5. Tense	0.954	0.02	< 0.001	0.934
I7. Unpleasantness	0.868	0.02	< 0.001	0.934
Potency $\eta_2$				
I8. Reverberation/Echo	0.645	0.03	< 0.001	0.709
I10. Loudness	1.041	0.03	< 0.001	0.929
I14. Strength	0.346	0.02	< 0.001	0.491
Evaluation $\eta_3$				
I15. Speech clarity	0.686	0.02	< 0.001	0.851
I16. Music clarity	0.656	0.02	< 0.001	0.79
I19. Brightness	0.923	0.03	< 0.001	0.851
I22. Understandability	0.9	0.02	< 0.001	0.913

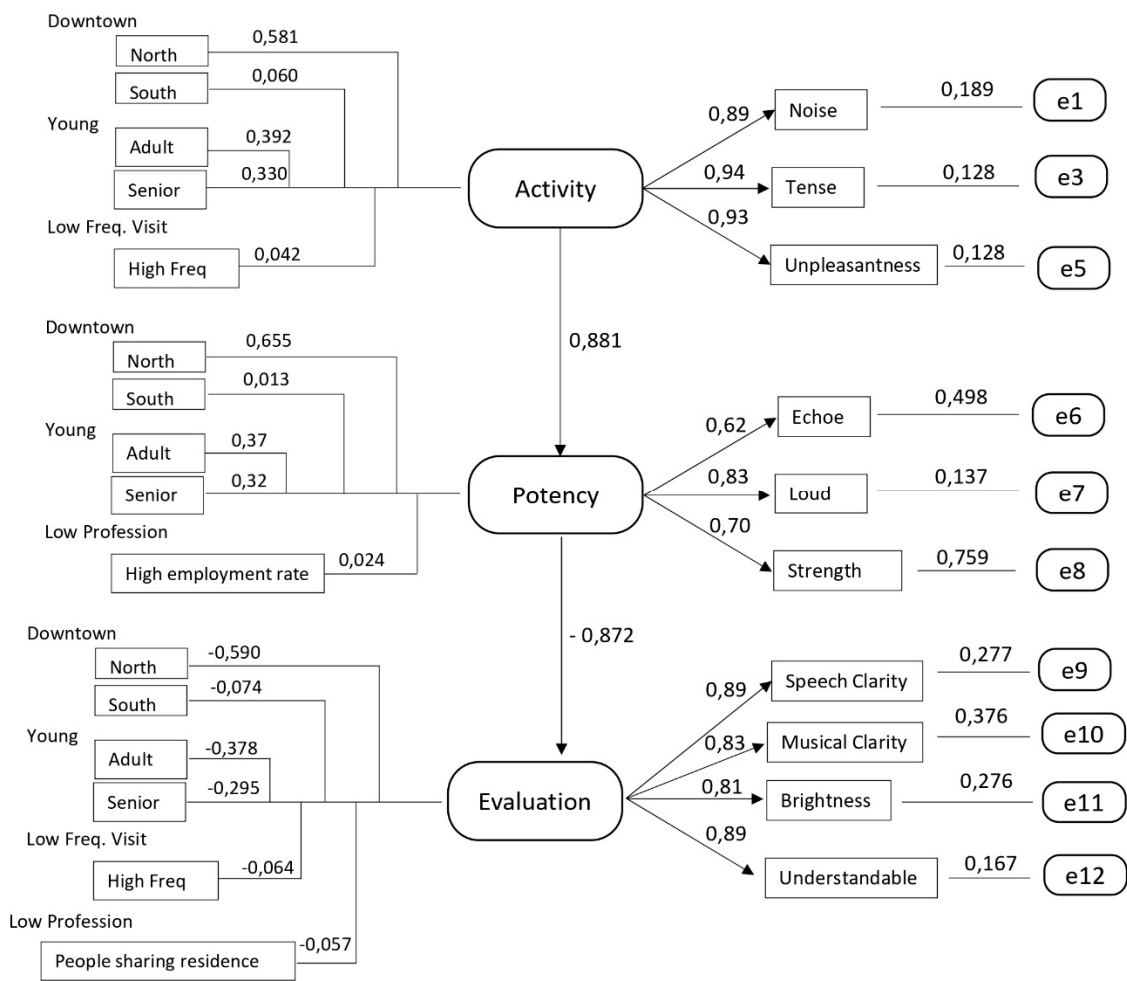


Figure 7. Structural model results.

Table 8. Goodness-of-fit of the tested model and recommended values (N=1,214).

Model fit metric	$\chi^2_{SB}/df$	CFI	TLI	RMSEA	SRMR
Modified model	8.84	0.905	0.873	0.082	0.047
Recommended	< 5.0	>0.90	>0.90	< 0.08	< 0.05

SEM results confirm the hypothesized relationships among the latent constructs derived from the EPA model (see Table 9). Specifically, perceived *Activity* significantly and positively influences *Potency* ( $\beta = 0.881$ ,  $p < 0.001$ ), while *Potency* exhibits a strong adverse effect on *Evaluation* ( $\beta = -0.872$ ,  $p < 0.001$ ), suggesting a mediating mechanism through which spectral characteristics of sound modulate the perceived intensity and, ultimately, the affective appraisal of the acoustic environment in heritage churches. Sociodemographic factors, such as age and frequency of visits to the assessed churches, were also significant. Adults and seniors reported higher perceptions of *Activity* and *Potency* but tended to evaluate the soundscape more negatively (e.g., adult  $\rightarrow$  Evaluation:  $\beta = -0.378$ ,  $p < 0.001$ ). Additionally, geographic location was a significant factor. Participants residing in both the northern and southern areas, compared to those living in the central zone where the churches are located, consistently perceived higher levels of *Activity* and *Potency*, and tended to evaluate the acoustic environment more negatively. These findings highlight the significance of physical acoustic parameters and listener context in shaping subjective sound quality evaluations in religious spaces.

Table 9. Hypothesis testing results.

Hypothesis	$\beta$	S.D.	T-value	p-Value	Decision
H <sub>A</sub> A → P	0.881	0.015	56.958	<0.001***	Accepted
H <sub>B</sub> P → E	-0.872	0.02	-52.89	<0.001***	Accepted
H <sub>C1</sub> Age (adult) → A	0.392	0.137	7.257	<0.001***	Accepted
H <sub>C1</sub> Age (senior) → A	0.33	0.14	6.20	<0.001***	Accepted
H <sub>C1</sub> High freq. visits → A	0.042	0.09	2.54	<0.05**	Accepted
H <sub>C1</sub> Age (adult) → P	0.374	0.16	6.82	<0.001***	Accepted
H <sub>C1</sub> Age (senior) → P	0.32	0.15	5.89	<0.001***	Accepted
H <sub>C1</sub> High employment rate → P	0.024	0.11	1.43	1.43	Rejected
H <sub>C1</sub> Age (adult) → E	-0.378	0.14	-6.93	<0.001***	Accepted
H <sub>C1</sub> Age (senior) → E	-0.295	0.14	-5.50	<0.001***	Accepted
H <sub>C1</sub> High freq. visits → E	-0.064	0.09	-3.70	<0.001***	Accepted
H <sub>C1</sub> People sharing residence → E	-0.057	0.04	-4.30	<0.001***	Accepted
H <sub>C2</sub> Location (North) → A	0.581	0.083	18.05	<0.001***	Accepted
H <sub>C2</sub> Location (South) → A	0.06	0.116	2.31	<0.05**	Accepted
H <sub>C2</sub> Location (North) → P	0.655	0.10	19.57	<0.001***	Accepted
H <sub>C2</sub> Location (South) → P	0.013	0.12	0.54	0.54	Rejected
H <sub>C2</sub> Location (North) → E	-0.59	0.09	-17.98	<0.001***	Accepted
H <sub>C2</sub> Location (South) → E	-0.074	0.12	-2.83	<0.001***	Accepted

4. Discussion

The research findings demonstrate the efficacy of using the EPA approach to study acoustic perception within heritage churches. The latent construct *Activity* captures negative emotional responses (such as *Noise* and *Tense*), *Potency* measures the perceived intensity of sound (such as *Loudness* and *Reverberation*), while *Evaluation* assesses the comprehensive quality of hearing (like *Clarity* and *Brightness*). The structure illustrates how acoustic perception is formed through physical sound measurements and emotional and cognitive reactions to auditory surroundings, which underlie the sound experience in sacred spaces.

The acoustic measurements revealed that three churches exhibited moderately long RTs ranging from 2.1 s to 2.6 s, with La Compañía demonstrating slightly superior acoustic behavior across several parameters, including C80 and IACC. These values align with those reported in [7], who observed excessively high RTs in Andalusian cathedrals—exceeding 8 seconds in some cases—yet highlighted the significance of architectural features and spatial source positioning (e.g., retro-choir) in mitigating these effects. In this study, the placement of the sound source at the altar, together with the natural material absorption characteristics, likely contributed to its comparatively better speech intelligibility and spatial impression. However, the dimensions of the analyzed churches in this study were significantly lower.

Despite low STI values (≈0.4), the perceptual clarity reported by participants—particularly in La Compañía—suggests a decoupling between physical and subjective intelligibility, reinforcing the observations made by Abadía [31], who found low D50 values (<50%) across several Jesuit churches, yet moderate to high subjective ratings for clarity. This discrepancy highlights the influence of non-acoustic factors, including visual cues, source distance, and cognitive adaptation, on shaping sound perception in sacred contexts.

From the SEM analysis, three latent constructs were clearly identified—Activity, Potency, and Evaluation—explaining a cumulative 74% of the total variance. The high factor loadings and



satisfactory goodness-of-fit indices support the structural validity of the model. Notably, the strongest loading indicators for Activity included *Noise*, *Tense*, and *Unpleasantness*, reproducing the semantic scales validated in [14], which emphasized the importance of affective dimensions in shaping environmental sound judgments. Similarly, *Potency* was closely associated with *Loudness* and *Reverberation*, while *Evaluation* included indicators related to *Speech Clarity* and *Understandability*.

The structural relationships among latent variables revealed that *Activity* significantly predicts *Potency*, and *Potency*, in turn, significantly influences *Evaluation*, validating the hypothesized mediation pathway. This suggests that emotionally charged reactions (e.g., stress, discomfort) intensify the perceived sound environment, which subsequently affects the overall evaluative judgment. Such mediation aligns with the conceptual structure proposed in [14] and is further supported by the high AVE and CR values observed in the CFA.

The path from *Potency* to *Evaluation* suggests that the mere intensity or dominance of sound may not be inherently negative; instead, it becomes evaluatively salient when modulated by emotional or contextual cues. This finding aligns with Abadía's study [33], which suggests that spatial volume and materiality play a defining role in listener impressions, independent of reverberation time alone. Moreover, the relatively high IACC values in La Compañía reinforce the importance of spatial characteristics in enhancing the immersive quality of the acoustic experience, a dimension highlighted by Farina [34] in the context of binaural measurements.

The study reinforces the concept that acoustic quality in heritage churches cannot be fully understood through objective metrics alone. The perceptual experience is shaped by a complex interplay of physical, emotional, and contextual factors that SEM can effectively capture. These insights have practical implications for acoustic heritage conservation, soundscape-based assessments, and the integration of perceptual models into building acoustic standards.

While this study provides valuable insights into the perceptual and acoustic dynamics of heritage churches, several limitations must be acknowledged. First, the acoustic measurements were taken in unoccupied conditions, which may not accurately reflect how sound absorption and diffusion behave with live audiences present. Even though statistical averaging and zone-based aggregation were applied to approximate typical usage scenarios, dynamic occupancy remains a variable that could impact the generalizability of the results. Additionally, the perceptual data were gathered immediately after individual visits rather than during services, potentially underrepresenting the full-range of soundscape experiences. Additionally, although the SEM demonstrated strong explanatory power, it was limited to three latent constructs (EPA). It may not account for other dimensions, such as cultural context, visual-auditory interaction, or temporal variation in sound perception.

Future research should expand the model by including additional variables such as spatial congruence, expectation bias, and ritual familiarity. These enhancements could improve the understanding of how sacredness, history, and religious significance influence soundscape evaluation. Longitudinal studies tracking acoustic perception over time—or during different liturgical events—could also offer deeper insights into the dynamic relationship between sound environments and human experience. Further integration of binaural recordings, immersive auralizations, and virtual reality simulations could help assess design interventions or material additions in a non-invasive way, particularly in sensitive heritage contexts.

## 5. Conclusions

The acoustic characterization of three heritage churches in Quito revealed not only the objective physical conditions of these spaces, as identified by reverberation times, clarity indices, and speech intelligibility values, but also provided valuable insights into how these conditions are perceived by users/visitors through systematic subjective evaluation. The EPA approach to auditory perceptions revealed that, although the spaces were generally perceived as imposing and culturally resonant (*Potency*), the listeners found them somewhat confusing or lacking in clarity (*Evaluation*) and experienced a dense or saturated acoustic environment (*Activity*). These subjective perceptions

complement the quantitative acoustic metrics and confirm the limitations posed by speech intelligibility, as well as the perceived magnificence and envelopment of sound, which are hallmarks of sacred spaces.

To investigate the relationship between acoustic and soundscape perceptual descriptors, an SEM approach was employed as a robust analytical tool to examine the intricate nature of ecclesiastical acoustics. Key results from SEM demonstrated statistically confirmed pathways between sociodemographic variables and latent perceptual constructs, supporting the notion that acoustic quality is not entirely captured by more classical measures of intelligibility or clarity. A further positive predictor for Evaluation was Potency, which suggests that loudness and spatial spread can be beneficial within the conditions of a liturgical space. In contrast, the Activity factor -which describes auditory dynamism and temporal density- was negatively correlated with it. This study demonstrates that the combined use of quantitative measures and auditory perceptions is crucial when examining acoustic heritage. In addition to being a robust approach, SEM provides a conceptual framework to bridge the gap between measurable acoustic events and human sensory perception. The methodology developed in this study can be applied to future research in the architectural acoustics of culturally significant contexts. It advocates for refined interdisciplinary frameworks that recognize the diverse acoustical identities embedded in historical sacred spaces.

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Abbreviations

The following abbreviations are used in this manuscript:

AVE	Average Variance Extracted
C <sub>50</sub>	Speech Clarity
C <sub>80</sub>	Music Clarity
CFA	Confirmatory Factor Analyses
CR	Composite Reliability
EFA	Exploratory Factor Analysis
EPA	Evaluation Potency Activity
G	Strength
IACC	Inter aural cross-correlation coefficient
RMSEA	Root Mean Square Error of Approximation
RT	Reverberation Time
SEM	Structural Equation Modeling
SRMR	Standardized Root Mean Square Residual
STI	Speech Transmission Index
TLI	Tucker–Lewis Index

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