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COMPARISON BETWEEN THE ACOUSTIC TEXTURE OBTAINED THROUGH IN SITU MEASUREMENTS AND THAT CALCULATED FROM VIRTUAL MODELS OF A PRE-ROMANESQUE CHURCH

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ABSTRACT

Acoustic Texture is a parameter related to the structure of early reflections, providing relevant information for the subjective perception of sound. Although its use is not widespread, Acoustic Texture could be a key aspect for calibrating virtual acoustic models.

This article addresses its importance by comparing the Acoustic Texture calculated from impulse responses obtained through real measurements of the pre-Romanesque church of Sant Miquel, in Terrassa, Spain, with those obtained using a virtual acoustic model of the church.

The objective is to evaluate how modeling parameters influence the Acoustic Texture by comparing it with data obtained from in situ measurements. Additionally, the study analyzes whether the processing of impulse responses (RIR) from the virtual model and the measurements allows identifying matches in early reflections, a key aspect for validating the model's accuracy.

The results aim to highlight the importance of Acoustic Texture as a relevant parameter in the perceptual evaluation of sound in historic architectural spaces. Also to offer a methodological framework that combines simulation and real measurement tools to optimize the acoustic modeling of spaces with high heritage value.

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1. INTRODUCTION AND OBJECTIVES

Acoustic texture is a term introduced by Beranek to describe the subjective impression created by the sequence and distribution of early reflections in a room [1]. According to Beranek, a well-balanced texture is characterized by a high density of early reflections that arrive in a uniform but not strictly periodic manner, without any single reflection dominating the rest. This distribution plays a key role in the perception of spaciousness and clarity in concert halls and opera houses.

Following Beranek's initial definition, several authors have expanded on the concept of acoustic texture, proposing parameters to describe its characteristics in greater detail. One of the most significant aspects is the transition time (Tt), which represents the point where early reflections cease to dominate, and the sound field starts behaving as a stochastic reverberant field. In their study, Hidaka et al. [2] analyzed Tt in depth, proposing a definition based on the correlation between the direct and early reflected sound with the later decaying reverberation. Their findings indicate that Tt is strongly related to the reverberation time (RT), with longer RT values leading to a later transition from early reflections to late reverberation. This is consistent with empirical data collected from multiple concert halls, where a proportional relationship between Tt and RT has been observed.

More recently, Bidondo advanced the study of acoustic texture by introducing a quantitative framework for its

evaluation. His work shifted the analysis from purely perceptual descriptions to numerical evaluation, incorporating parameters such as the Cumulative Number of Early Reflections (CNERs), Transition Time (Tt), and the Normalized Ordinal Distance (nOD), among others [3]. These metrics enable a more systematic assessment of how early reflections contribute to room acoustics, providing a structured methodology for texture analysis.
This study aims to investigate how the patterns of early reflections compare between real and simulated RIRs and whether these differences impact auditory perception. To achieve this, the study is based on a listening test, where participants were exposed to audio convolved with both measured and simulated RIRs of the same space (Church of Sant Miquel in Terrassa). The results of this test have been analyzed alongside the early reflection patterns extracted from the same RIRs used in the listening test, as well as from additional real measurements.
To examine the differences between early reflections in the simulated and measured RIRs, the software developed by Bidondo will be used as a first step. This tool provides a structured approach to quantifying variations in early reflection parameters between both types of RIRs. Following this, the detected early reflections will be further analyzed using a custom-developed software, which allows for a detailed examination of the pattern and distribution of individual early reflections. This two-step analysis aims to provide a more comprehensive understanding of how early reflections differ between real and simulated environments and their potential perceptual impact.
For simplicity, this study adopts a fixed Tt estimation of 80 ms, following the definition provided by Beranek, which is widely used in room acoustics literature [1].

2. METHODS

2.1 Acoustic model calibration and perceptual evaluation

A virtual acoustic model of the pre-Romanesque church of Sant Miquel in Terrassa (Fig. 1, Fig. 2) was developed using ODEON software [4]. This model underwent a rigorous calibration process, ensuring that its simulated acoustic parameters closely matched those measured in situ. The precision of the acoustic model was validated by comparing traditional key acoustic descriptors such as reverberation time (RT), early decay time (EDT), and clarity (C80), achieving differences below **1 Just Noticeable Difference (JND)** across most frequency bands and parameters (Tab. 1). The global difference between measured and simulated acoustic parameters in this calibration produces an overall error of 1.078 (JND) [4][5] This level of precision confirms the reliability of the model in reproducing the objective acoustic characteristics of real space.

Table 1. JND values for the different acoustic parameters by frequency for position F1R2. [4]

JND	250	500	1000	2000	4000
EDT	1.952	0.305	0.968	0.757	0.152
T(20)	1.289	0.775	0.084	0.312	0.453
T(30)	1.579	0.173	0.803	0.851	0.208
Ts	3.171	1.01	4.474	0.931	1.161
C(50)	0.192	0.215	1.261	0.677	0.086
C(80)	0.703	0.886	0.974	0.631	0.7586

To evaluate the perceptual quality of the auralizations generated for the Church of Sant Miquel in Terrassa [4], a listening test was designed and conducted with a total of 33 participants: 18 at the anechoic chamber of the Polytechnic University of Madrid and 15 at the acoustically treated room of the Polytechnic University of Milan. The test focused on two main perceptual criteria: authenticity and plausibility. Audio fragments—both real recordings and auralized versions using identical source-receiver positions—were presented under controlled conditions. Participants were asked to discriminate between them through structured auditory tests. The results were analyzed using Signal Detection Theory (SDT), with particular attention to the d-prime value as a measure of the participants' ability to detect perceptual differences between the stimuli.
The d-prime (d') value quantifies a listener's ability to discriminate between two stimuli by measuring the distance between the means of their internal response distributions. A higher d' indicates a greater perceptual sensitivity, meaning the participant was better able to distinguish between the compared audio samples. A value of $d' = 0$ implies chance-level performance, while increasing values reflect more reliable discrimination.
P-values were computed to assess the significance of the observed differences between conditions. A p-value lower than 0.05 was considered statistically significant, indicating that the perceptual differences identified by the participants were unlikely to have occurred by chance. These values supported the interpretation of the d-prime results, reinforcing the reliability of the

discrimination between real, measured, and simulated auralizations.
Although the acoustic model exhibited a high degree of calibration accuracy, the perceptual tests revealed significant differences in how subjects experienced the recorded and simulated sound fields. The comparison between the recorded audio (anechoic signal recorded in situ using loudspeaker playback of anechoic signals) and the measured audio (anechoic signal convolved with the measured room impulse response) (Tab.2, Tab. 3) yielded slight perceptual differences. In contrast, the differences between the recorded and simulated conditions (convolution with the simulated RIR) were considerably larger across all anechoic stimuli tested, with higher values of d′ and statistical significance.
Conventional acoustic parameters do not precisely capture auditory perception, suggesting that acoustic texture could play a crucial role in the comprehensive description of an acoustic environment.

Table 2. Authenticity Test: d' (Recorded vs Measured and Recorded vs Simulated). T2, T4, T6, T8 and T10 correspond to individual listening tests, each associated with a specific anechoic audio sample in position F1R2. [4]

d'	R-M	R-S
T2	2.87	3.19
T4	0	2.87
T6	2.49	3.19
T8	0	1.97
T10	1.61	3.38

Table 3. Authenticity Test: p-values (Recorded vs Measured and Recorded vs Simulated). T2, T4, T6, T8 and T10 correspond to individual listening tests, each associated with a specific anechoic audio sample in position F1R2. [4]

p-value	R-M	R-S
T2	5.91E-10	1.19E-11
T4	9.68E-01	5.91E-10
T6	8.47E-08	1.19E-11
T8	9.12E-01	5.07E-05
T10	2.10E-03	1.36E-12

2.2 Analysis of Acoustic Texture with Bidondo's Software

The simulated RIR was processed using Bidondo's software to analyze its acoustic texture parameters and compare them with those obtained from the measured RIR [3]. The software analyzes Tt (Transition Time), EDT (Early Decay Time), nOD (normalized Overlap Density), Late/Dir (Late to Direct ratio), CTT (Cumulative Temporal Texture), CENRS (Center of Energy of the Early Reflections Sequence), EDTt (Early Decay Transition Time), ACd (Average Curve Deviation), ATt at Tt (Average Temporal Trend at Transition Time), OD (Overlap Density) (Tab. 4). The results indicate a significant discrepancy between simulated and measured RIR, with the computed parameters showing substantial differences.
One of the most notable variations is observed in the Transition Time (Tt), a key parameter distinguishing early reflections part from the stochastic reverberation field (Tab. 4). In the measured RIR, the Tt value was 299.2 ms, whereas in the simulated RIR generated in ODEON—using Order of Transition 2 and the precision setup—Tt was calculated as only 10.15 ms. This considerable reduction may indicate that the simulation does not fully capture the prolonged presence of early reflections observed in the real environment, potentially impacting the perceived authenticity of the simulated acoustics.

Table 4. Results of acoustic texture parameters calculated in the Bidondo's Software with a measured RIR and a simulated RIR with Transition Order of 2 in position F1R2.

Parameters	Measured Results	Simulation Results TO2
Late/Dir [dB]	-4.653	-6.211
Ctt [dB]	14.3	10.92
CNERs	543	0
EDT [s]	1.205	0
EDTt [s]	1.256	0.05397
ACd [ms]	12.62	0.03647
Tt [ms]	299.2	10.15
Att at Tt [dB]	-14.3	-11.26
OD	294	67.6
nOD	0.9826	6.557

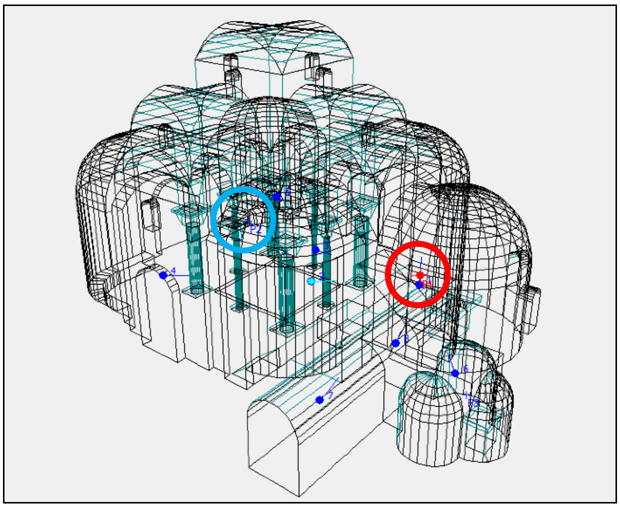

Figure 1. Virtual acoustic model of the pre-Romanesque church of Sant Miquel in Terrassa. The red circle corresponds to the position of the speaker (F1) and the blue circle corresponds to the position of the microphone (R2).

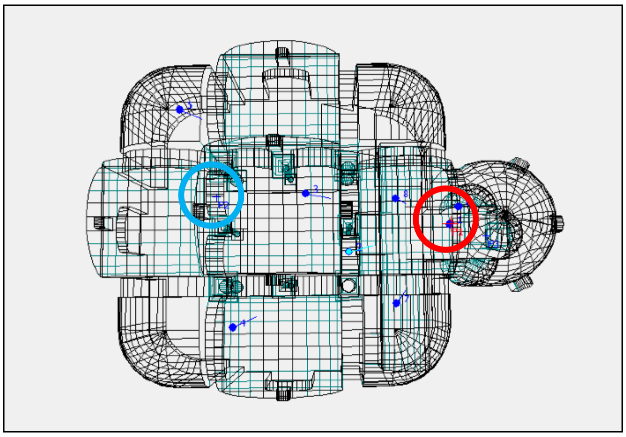

Figure 2. Floor plan of the virtual acoustic model of the pre-Romanesque church of Sant Miquel in Terrassa. The red circle corresponds to the position of the speaker (F1) and the blue circle corresponds to the position of the microphone (R2).

2.3 Detection and Analysis of Early Reflection Patterns

A custom software has been developed to detect events within a room impulse response (RIR) that can be classified as early reflections (ERs). This tool enables the identification of individual reflections based on their temporal and energetic characteristics, allowing for a detailed analysis of acoustic texture.

The objective is to extract and compare the ER patterns from both the simulated and measured RIRs, including those used in the listening test. By analyzing these patterns, the study seeks to determine whether the early reflections detected in simulations align with those found in real measurements. The RIR used in the listening test was generated in ODEON using the precision calculation setup (76960 number of late rays) and a transition order of 2.

Finally, the detected ER patterns will be compared with the results of the listening test to evaluate whether the differences between measured and simulated RIRs have a perceptual impact. This comparison will help assess the role of distribution of early reflections in the subjective perception of acoustic texture and their influence on spatial impression.

To further investigate the discrepancies observed in the perceptual tests, additional simulations were performed with varying modeling parameters.

3. RESULTS

Several configurations were tested, including different transition orders and ray tracing densities (Fig. 6, 8) yet none were able to fully reproduce the early reflection texture observed in the measured RIRs (Fig. 4). This suggests that standard calibration procedures may not be sufficient to capture the perceptual effects of early reflections, highlighting the need for improved modeling techniques that integrate acoustic texture analysis. This study underscores the importance of incorporating acoustic texture metrics into virtual model calibration.

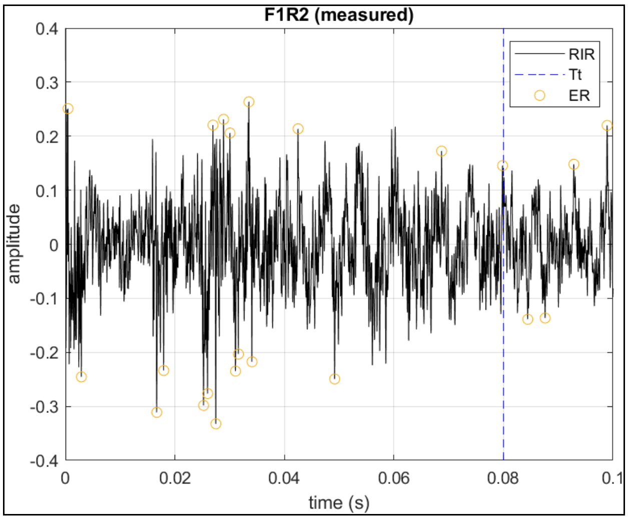

Figure 3. Measured F1R2 RIR with ER detections.

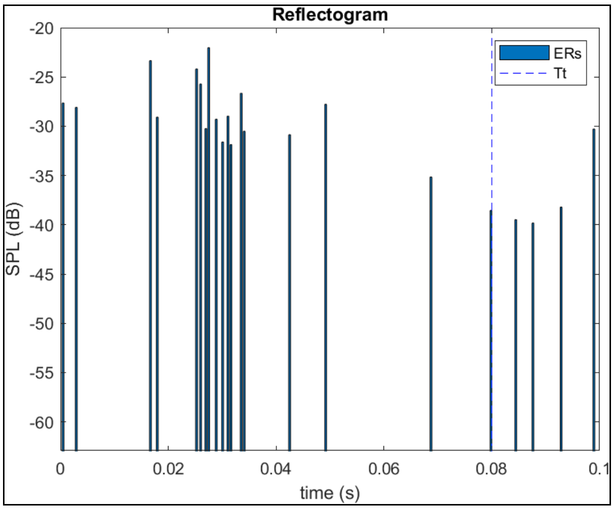

Figure 4. Reflectogram from measured F1R2 RIR.

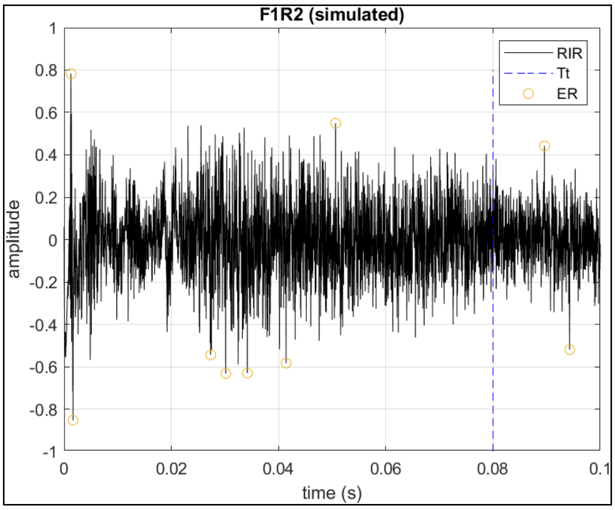

Figure 5. Figure Simulated F1R2 RIR with ER detections with Transition Order of 2.

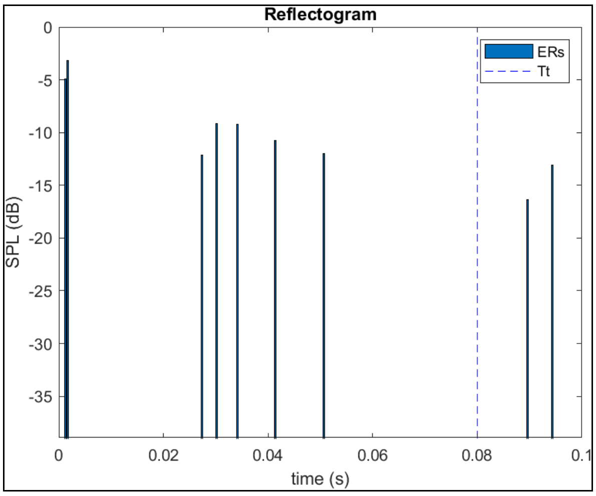

Figure 6. Reflectogram from Simulated F1R2 RIR with Transition Order of 2.

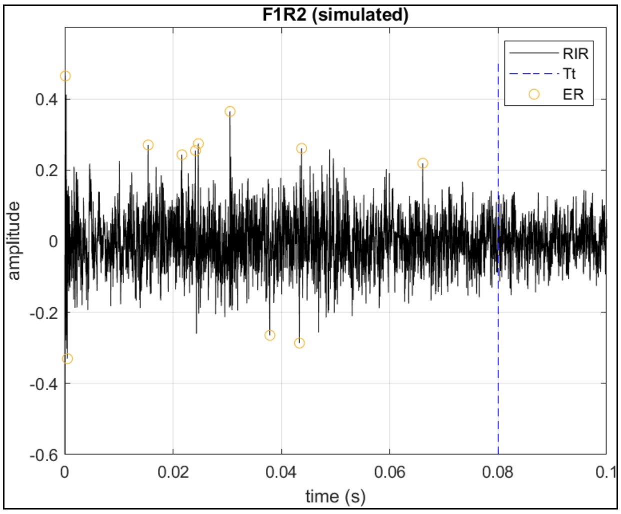

Figure 7. Figure Simulated F1R2 RIR with ER detections with Transition Order of 3.

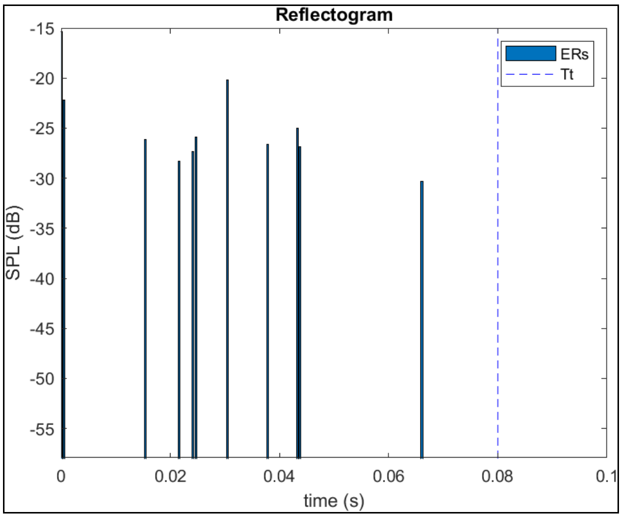

Figure 8. Reflectogram from Simulated F1R2 RIR with Transition Order of 3.

4. DISCUSSION

By calculating the reflectogram of both the measured RIR and the simulated ones with transition orders 2 (Fig. 6) and 3 (Fig. 8), several differences can be observed. Firstly, due to the greater variation in the energy envelope of the simulated RIRs obtained with ODEON (Fig. 4), fewer prominent peaks are detected by the early reflection detection algorithm. As a result, the reflectograms derived from the simulated responses show a lower density of early reflections compared to those from the measured RIRs. In contrast, the measured responses present a more homogeneous energy distribution, allowing more peaks to stand out above the detection threshold, which leads to a higher number of detected reflections. This difference highlights a potential limitation in the simulation's ability to replicate the detailed temporal structure of early reflections found in real environments.

Furthermore, the listening test results confirm that participants were able to distinguish between audio convolved with the real RIR and that convolved with the simulated RIR [4]. This suggests that the discrepancies between measured and simulated ER patterns may play a role in the perceptual differences observed.

One possible hypothesis is that current simulation methods do not fully account for the structural organization of early reflections, which could be crucial for achieving perceptual realism in virtual acoustic models. If early reflections contribute significantly to spatial perception, their inaccurate reproduction in simulations could explain why listeners perceive a difference between real and virtual environment.

5. CONCLUSIONS

The findings of this study indicate that the early reflection patterns obtained from simulated and measured room impulse responses do not show a clear correspondence in either intensity or temporal distribution. Additionally, discrepancies were found in the parameters used in Bidondo’s Software. While some localized similarities can be observed in specific regions, these are not consistent enough to affirm that the simulated model accurately replicates the early reflection behavior of the real space.

Additionally, perceptual evaluation through listening tests confirms that participants can reliably distinguish between sounds convolved with measured RIRs and those convolved with simulated RIRs. This suggests that conventional acoustic calibration methods, which primarily focus on global parameters such as reverberation time (RT) and clarity (C80), may not fully account for perceptually relevant differences in the structure of early reflections.

The results highlight the potential role of early reflections in shaping the listener’s spatial perception and suggest that their accurate reproduction may be critical for achieving a more perceptually coherent acoustic model. These findings highlight the need for more precise early reflection modeling to enhance the perceptual accuracy of virtual acoustic simulations.

6. ACKNOWLEDGMENTS

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