

AURAL DIGITAL TWIN FOR AIRCRAFT CABIN DESIGN

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Abstract

This paper presents the development of an aural digital twin for aircraft cabin design, integrating vibro-acoustic simulations with immersive real-time audio rendering. The proposed approach enables the spatial reconstruction of the acoustic field across the entire cabin through an interpolation-based auralization strategy. The methodology was applied to a business jet and a regional turboprop configuration, representing different cabin layouts and acoustic conditions. Simulation results were transformed into auditory signals and rendered within an immersive virtual environment, combining visual and auditory components to enable the perception of position-dependent noise variations. A human-centred experimental campaign was conducted to assess both the realism of the virtual environment and the users' ability to perceive spatial differences in the acoustic field. Results showed that, while the overall realism of the experience was positively evaluated, participants' perceptions of spatial variation remained limited and highly variable. These findings indicate that although the proposed framework effectively reproduces global acoustic characteristics, the spatial resolution achieved through impulse-response-based reconstruction is insufficient to ensure robust perceptual discrimination across the cabin.

Keywords: Auralization, Cabin design, Human-centred approach, Noise reduction

1. Introduction

The development of new technologies, aircraft configurations, materials, and design methodologies has led to significant progress in reducing cabin noise in recent years. In particular, the introduction of advanced solutions such as acoustic metamaterials and innovative propulsion systems has opened new possibilities for controlling and shaping the internal acoustic environment [1]. Despite these advances, the methodologies used to assess the impact of noise on passengers and crew have not kept pace. Current evaluation approaches remain largely based on global quantitative indicators, which provide only a partial representation of the acoustic experience [2]. This limitation is mainly due to the nature of cabin noise, which, except in extreme cases, does not represent a safety issue but rather a comfort-related problem. As a consequence, its assessment is intrinsically complex, as comfort depends not only on overall sound levels but also on spectral characteristics, spatial variability within the cabin, and interactions with other sensory inputs [3, 4, 5].
In this context, two main approaches can be identified:

- Human-based approaches, in which users are described through objective parameters that define their response to acoustic stimuli (e.g. physiological limits, audible frequency ranges, or frequency-dependent sensitivity of the auditory system). These methods provide robust, quantitative evaluations and are essential to define acceptable operating conditions. However, they neglect subjective perception and therefore offer only limited insights into how different acoustic configurations are actually experienced.

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- Human-centred approaches, in which users are directly immersed in the acoustic environment to be evaluated. In this case, comfort is assessed through subjective responses, typically collected via questionnaires or psychometric measurements [6]. Although inherently subjective, these approaches can yield meaningful and generalisable results when based on statistically relevant samples, providing a more realistic description of perceived acoustic conditions.

The implementation of human-centred methodologies in aircraft cabin design has been facilitated by the development of virtual and augmented reality technologies, which allow the creation of immersive virtual mock-ups without the need for full-scale physical prototypes [7]. Within this framework, auralization is a key component, enabling the reconstruction of an audible environment from numerical simulation data and serving as the auditory counterpart of visual virtualisation [8, 9, 10].
Previous works have demonstrated the feasibility of combining numerical vibro-acoustic simulations, convolution-based audio rendering, and immersive environments to create virtual representations of limited cabin sections, thereby supporting preliminary human-centred evaluations [11, 12, 13]. However, these implementations are typically restricted to localised portions of the cabin and do not fully capture the spatial variability of the acoustic field experienced by passengers.
In the present work, the focus is extended to the spatial characterisation of cabin noise across the entire passenger compartment. Particular attention is devoted to position-dependent effects, such as those associated with proximity to propulsion systems, which can lead to significant variations in perceived noise along the cabin [2, 6]. The objective is therefore to capture these spatial gradients and reproduce them within the virtual environment, allowing users to directly perceive differences in acoustic conditions as a function of their position. In addition, the proposed methodology is extended to multiple aircraft configurations. Alongside a business jet, a regional turboprop aircraft is considered, introducing a more acoustically demanding scenario with different noise sources and a different cabin layout in terms of passenger density and spatial organisation [4]. This extension enables assessing the robustness of the approach across different aircraft types and operating conditions.
Within this framework, the paper presents the development of an aural digital twin for aircraft cabin design, integrating numerical vibro-acoustic modelling with immersive audio-visual rendering. The proposed approach aims to support human-centred evaluation of acoustic comfort through spatially resolved auralization, providing a more realistic and comprehensive tool for analysing cabin noise during the early design phases.
The remainder of this paper is structured as follows. Section 2. presents the overall methodology, including the numerical modelling approach, the auralization process, and the spatial interpolation strategy adopted to reconstruct the acoustic field in real time. Section 3. describes the simplified vibro-acoustic model of the aircraft cabin and the extraction of the simulation data used for auralization. Section 4. introduces the experimental campaign, including the immersive virtual environment, the test protocol, and the questionnaire used for human-centred evaluation. Section 5. discusses the results obtained for the different case studies. Finally, Section 6. summarises the main findings and outlines future developments.

2. Methodology

2.1 Overview of the approach

The methodology adopted in this work aims to establish a physically consistent link between vibro-acoustic simulations and users' experience in a virtual cabin environment. This is achieved by developing an aural digital twin, in which numerical simulation data are transformed into an immersive auditory representation.
The workflow is structured into three main stages:

1. numerical modelling of the acoustic field;
2. transformation of simulation outputs into time-domain audio signals;
3. real-time rendering within an extended reality environment.

While this general structure follows previous developments, the present work extends the approach by addressing scalability from localised cabin sections to a full-cabin representation.

The final stage of the workflow involves the real-time rendering of the auralized acoustic field within an immersive virtual environment. For this purpose, the digital twin is implemented using the Unity engine, exploiting its native Audio Mixer for sound playback and sound field rendering. The Unity engine enables the real-time experience of the reconstructed audio field, using convolved audio sources preprocessed with Python scripting. This solution frees the final platform from the heavy computational burden of real-time convolution processing, enabling the scalability needed in a full-cabin scenario and avoiding the use of external audio middleware, which is often cumbersome and difficult to integrate with virtual reality hardware.

2.2 Numerical simulation

The methodology begins with the numerical evaluation of the acoustic environment within the aircraft cabin. Vibro-acoustic simulations provide the distribution of sound pressure as a function of frequency, accounting for the coupling between structural components and the internal acoustic cavity.
A key aspect of the proposed approach is the definition of the spatial sampling strategy. The acoustic field is evaluated at a set of receiver locations (probes) distributed throughout the cabin, representing passenger positions. Unlike previous implementations based on a limited number of probes [12], the present work adopts an increased spatial resolution, extending the sampling to the entire passenger compartment.
This extended distribution of probes enables the capture of position-dependent acoustic effects, such as longitudinal variations along the fuselage or changes associated with proximity to propulsion systems. The numerical model, therefore, provides a discretised representation of the acoustic field across the entire cabin domain.

2.3 Auralization and signal generation

The transformation from numerical results to audible signals is achieved through an auralization process based on impulse-response reconstruction, implemented through Python scripting. For each probe location, the frequency-domain transfer function is converted to a time-domain impulse response, which represents the cabin's acoustic filtering effect.
These impulse responses are then applied to a reference excitation signal, representative of the original aircraft engine noise, through convolution-based techniques. This approach preserves the temporal and spectral characteristics of the source signal while incorporating the modifications induced by the cabin and the considered acoustic configurations. To ensure perceptual consistency across the cabin, a global normalisation is applied to the set of impulse responses. This guarantees that differences between positions are related to spatial effects rather than to numerical scaling artefacts.

2.4 Spatial interpolation

The discrete set of impulse responses obtained from the numerical simulations is used to reconstruct a continuous acoustic field within the virtual environment. For a given listener position, the effective acoustic response is computed as a spatially weighted combination of the impulse responses associated with neighbouring probe locations. This approach ensures smooth transitions of the perceived sound field during user movement and enables the representation of spatial gradients across the cabin.
The spatial resolution of the reconstructed field depends on the density and distribution of the probe locations, making the spatial sampling strategy a critical parameter of the methodology. Increasing the number of probes improves the spatial description of the acoustic environment but introduces potential computational challenges in real-time rendering. In a naive implementation, each probe could be treated as an independent processing chain, leading to a computational cost that grows proportionally with the number of spatial samples:

$$C_{\text{total}} \sim N_{\text{probe}} \cdot L_{\text{IR}} \log L_{\text{IR}} \tag{1}$$

where N_{probe} is the number of probe locations and L_{IR} is the impulse response length. This scaling arises from the use of FFT-based convolution algorithms, where the computational cost is dominated by the transform of the impulse response.

However, the proposed approach adopts a different strategy. Instead of associating a dedicated real-time processing chain to each probe, each signal is preprocessed before deployment, and spatial variability and fidelity are ensured through a real-time, normalised Gaussian radial basis interpolation of convolved sounds. Setting an influence area around the user, whose radius is proportional to the probes' sampling resolution, only the closest probes contribute to the acoustic field, ensuring that the number of active audio sources remains limited, independently of the number of spatial samples used to describe the noise distribution.
From a computational perspective, this leads to a significant reduction in complexity compared to a source-based convolutional interpolation. The spatial resolution can be increased without a proportional growth in rendering cost, as the acoustic field is reconstructed from a reduced set of filtering operations.
This formulation allows moving from a source-based description of spatial audio to a field-based representation, in which the acoustic environment is interpreted as a continuous quantity derived from discrete spatial samples, while supporting the scalability of the auralization process when extending the analysis to full-cabin configurations.

3. Vibro-acoustic modelling

3.1 Simplified numerical model of the cabin

The vibro-acoustic behaviour of the aircraft cabin is evaluated using a simplified finite element model designed to preserve the system's dominant low-frequency characteristics while maintaining computational efficiency.
The geometry consists of a representation of the fuselage, including the external skin and the interior lining panels. Structural components, such as stiffeners, frames, windows, detailed connections, and interior furnishings (e.g. seats and fittings), are not explicitly modelled. These elements are neglected as their influence is limited in the low-frequency range considered in this work. The resulting model provides an equivalent representation of the primary load-bearing structure and the cabin's acoustic cavity.
All structural components are modelled using shell elements with conventional material properties. The interior lining is represented through a standard Nomex panel. The thicknesses of the fuselage skin and floor (bridge) are defined using an equivalent modelling approach. A preliminary modal analysis is conducted to ensure that the fundamental structural frequency is representative of a realistic fuselage response, typically around 20 Hz [14, 15]. Based on this requirement, equivalent thickness values are selected to match the desired global dynamic behaviour.
Passenger seats are not explicitly modelled as volumetric structures. Instead, their acoustic contribution is introduced through equivalent boundary conditions. The seat surfaces are assigned a frequency-dependent complex impedance that represents the combined dissipative and reactive behaviour of the seating system and its associated materials.
Two main acoustic cavities are considered in the model: the passenger cabin and the cargo hold. These domains are explicitly defined to account for the interaction between structural vibrations and the internal acoustic field. Fluid–structure interfaces are introduced at the boundaries between the structural components and the acoustic domains, enabling the coupled vibro-acoustic solution of the system.

3.2 Simulation outputs

The vibro-acoustic problem is solved in the frequency domain over the range 20-1000 Hz, which covers the frequency regions most relevant to aircraft cabin noise. The mesh of both structural and acoustic domains is defined according to the Nyquist criterion, ensuring that the element size is sufficiently small to capture wave propagation within the analysed frequency range accurately.
The acoustic field is evaluated at a set of discrete receiver locations (probes) distributed throughout the cabin volume. These probes are positioned to represent passenger-relevant locations, typically at ear level along the cabin. The distribution of probes enables the capture of spatial variations of the sound field along the fuselage.

For each probe location, the numerical model provides complex frequency-domain transfer functions representing the relationship between the excitation source and the acoustic response at the receiver position. These transfer functions constitute a discrete spatial sampling of the sound field and serve as input for the auralization process described in Section 2.4, enabling the reconstruction of a continuous auditory environment.
Fig. 1 presents the sound pressure level at representative positions along the cabin. The results indicate weak spatial variation for unit excitation, suggesting that the observed differences are primarily driven by the system's modal behaviour rather than by source distribution effects. The spatial distribution of the acoustic field results from the superposition of multiple coupled vibro-acoustic modes. In the regional configuration, the dominance of low-order longitudinal modes leads to an increase in sound pressure level in the central region, whereas in the business jet configuration, the reduced modal separation results in a more uniform response [16, 17].

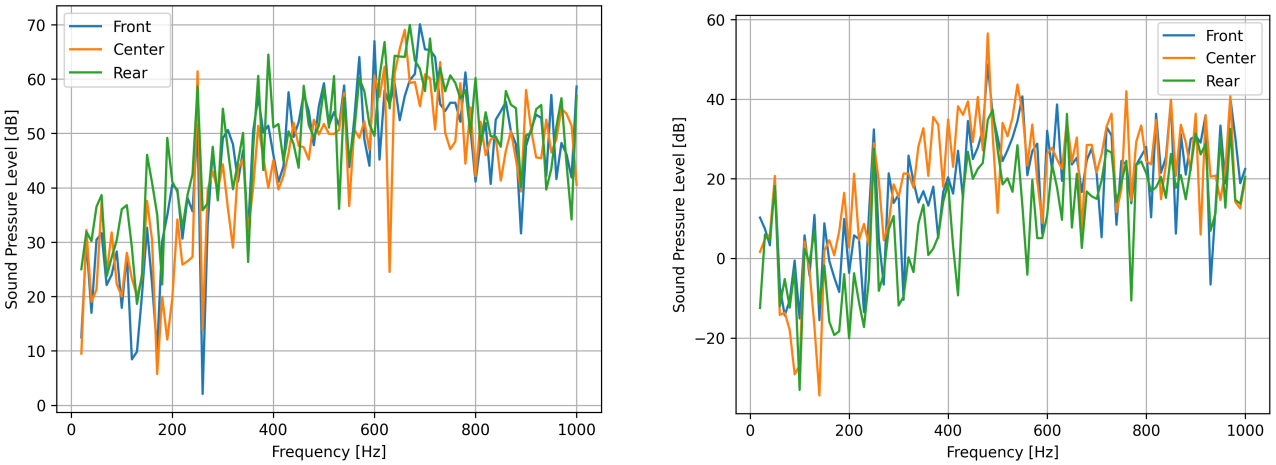


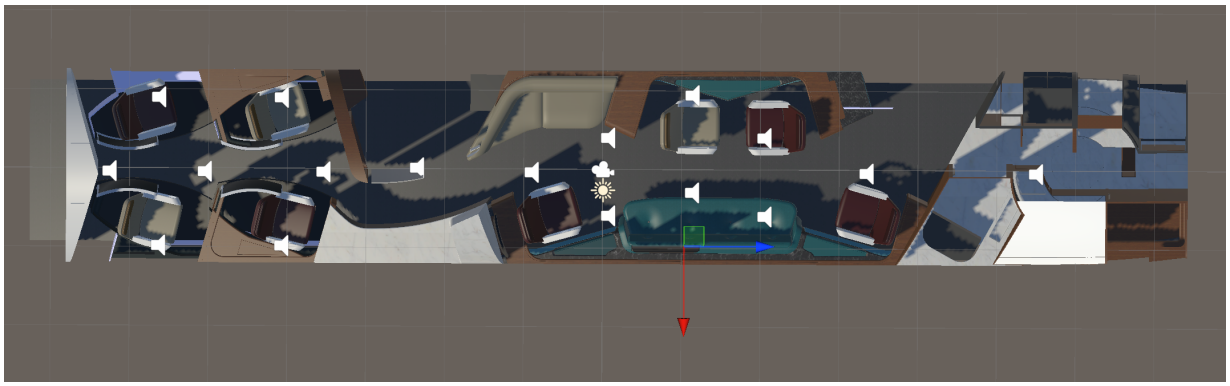
Figure 1 – Sound pressure level distribution along the cabin for the two configurations: (a) business jet and (b) regional aircraft.

4. Experimental campaign setup

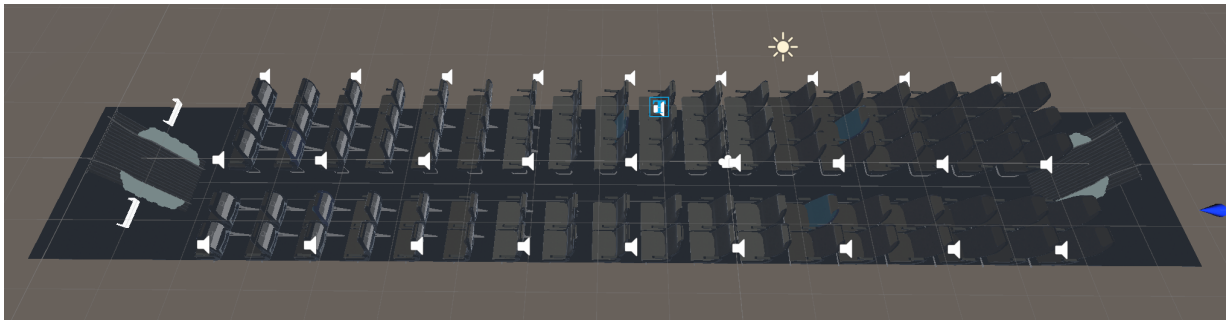
4.1 Virtual environment and implementation

The aural digital twin is implemented within an immersive virtual environment to enable perceptual evaluation of the reconstructed noise distribution. As described in Section 2.1, the virtual environment is developed using the Unity engine, which provides the graphical framework for representing the aircraft cabin and for user interaction. At the same time, audio rendering is handled by Unity's native Audio Mixer, together with the Mixed Reality Toolkit Spatializer. The sound field is reconstructed from multiple sources based on a raw engine noise sample, convolved with impulse responses derived from numerical simulations, which are dynamically interpolated based on the user's position. As the user's position varies, the acoustic field between sampled probe locations is reconstructed using a normalised Gaussian radial basis interpolation. The contribution of each probe is weighted by a Gaussian kernel based on the listener–probe distance and normalised so that the weights form a partition of unity. This approach enables a continuous variation of the perceived sound field as the user moves within the virtual cabin. Fig. 2 illustrates the layout of the virtual environments and the distribution of receiver positions used for acoustic analysis. In the regional turboprop configuration, additional internal noise sources are included, such as the air conditioning outlets, which contribute to local variations of the acoustic field. This additional component is not present in the business jet configuration due to the design's complexity.
The virtual environment adopts a hybrid configuration, combining virtual elements with physical seating. In particular, a set of real passenger seats is integrated within the experimental setup to provide a more realistic spatial and ergonomic reference during the experience. The visual layer consists of a simplified three-dimensional representation of the cabin, designed to support spatial orientation

while avoiding unnecessary visual complexity. The visual models of the cabin are derived from the EU CASTLE (CAbin Systems design Toward passenger welLbEing) project, which provided geometrical datasets used for the development of the virtual environments [18, 19]. The system is deployed on HoloLens 2 headsets, allowing users to move within a controlled physical space and interact with both virtual and physical components of the environment. Fig. 3 shows the mixed reality setup, combining virtual cabin elements with physical seating.



(a)



(b)

Figure 2 – Layout of the virtual environments and probe distribution: (a) business jet configuration and (b) regional aircraft configuration.



(a)



(b)

Figure 3 – Mixed reality view of the XR environment showing the integration of virtual cabin elements with physical seating: (a) business jet configuration and (b) regional aircraft configuration.

4.2 Experimental setup

The experimental campaign was carried out at the VLab facility of the Tecnopolo CIRI in Forlì. Participants were invited to experience two different cabin configurations, representing a business jet and a regional turboprop aircraft, characterised by distinct acoustic conditions.

Each participant experienced both scenarios in sequence. For each configuration, the participant was initially seated in the front or rear section of the cabin. Starting from this position, the participant was instructed to move along the cabin, stopping at different locations to explore the spatial variation of the acoustic field. Each immersive session lasted approximately five minutes. After completing the first scenario, participants were asked to fill in a questionnaire evaluating their experience. The procedure was then repeated for the second configuration, followed by a second questionnaire. The total duration of the experimental session was approximately 15 minutes, including an initial briefing phase and the completion of both questionnaires.

4.3 Questionnaire and evaluation metrics

Following each immersive experience, participants were asked to complete a structured questionnaire designed to assess both the perceived realism of the environment and the spatial characteristics of the acoustic field. The questionnaire includes an initial section collecting general information (not reported here), such as age, prior experience with XR systems, and familiarity with air travel. The main questionnaire items used for the quantitative analysis are summarised in Tab. 1, together with the corresponding statistical indicators. Subsequent sections investigate perceptions of cabin noise using Likert-scale questions on perceived loudness and annoyance. A dedicated set of questions evaluates the realism of the virtual environment, including the coherence of the auditory reproduction and the perceived continuity of sound variation during movement. Particular emphasis is placed on spatial perception. Participants were asked to assess whether the noise varies with position and whether differences between cabin zones can be perceived. Additional questions investigate the ability to identify the location of the dominant noise source (e.g., the engine position) and to determine which area of the cabin was perceived as the noisiest. These responses provide a qualitative validation of the spatial reconstruction of the acoustic field.
Both quantitative responses (Likert-scale and multiple-choice questions) and qualitative feedback (open-ended comments) were collected, enabling a combined statistical and descriptive analysis.

Table 1 – Questionnaire items with corresponding mean values and standard deviations for Likert-scale responses. Spatial perception questions (Q6–Q7) show lower mean values and higher variability compared to realism-related questions.

	Question	**Mean**	**Std. Dev.**
Q1	The aircraft cabin is a noisy environment	3.71	0.68
Q2	The aircraft cabin is annoying due to noise	2.97	1.14
Q3	The virtual cabin appears realistic	4.29	0.68
Q4	The sound faithfully reproduces a real aircraft environment	3.91	0.67
Q5	The sound varies smoothly when moving within the cabin	4.18	0.63
Q6	The noise varies depending on the position	3.26	1.36
Q7	Differences between cabin areas are perceptible	3.24	1.33
Q8	I was able to identify the position of the main noise source (engine)	NA	NA
Q9	It was possible to identify which area of the cabin is noisier	NA	NA

4.4 Participants

The experimental campaign involved 17 participants (34 questionnaires), recruited voluntarily among students, researchers, and university staff. All participants were adults and provided informed consent before taking part in the study. The experiment was designed as a non-invasive study with

minimal risk. Participants could interrupt the experience at any time without justification, and the sessions were conducted under continuous supervision.
The collected data were limited to questionnaire responses and general demographic information and were anonymised in compliance with current data protection regulations.

5. Results

5.1 Overview

The overall questionnaire results are summarised in Tab. 1. While the perceived realism of the virtual environment and audio rendering has been investigated in previous studies [11, 12], the present analysis focuses on the perceptual assessment of spatial variations within the acoustic field within the cabin. Likert scale responses are converted into a scale from 1 (strongly disagree) to 5 (strongly agree).
The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

5.2 Business jet case study

The results obtained for the business jet configuration indicate a generally weak perception of spatial variations within the cabin. The average scores related to spatial perception, namely the variation of noise with position and the detectability of differences between cabin zones, are moderate (around 3.2 on a five-point scale) and are associated with relatively high standard deviations. This suggests a moderate and inconsistent perception of spatial cues among participants.
In particular, several participants reported difficulty perceiving meaningful variations as they moved along the cabin, often indicating that the acoustic field appeared relatively uniform. This behaviour is consistent with the numerical results, which show a limited spatial variation of sound pressure levels for the considered excitation.
The results therefore suggest that, in the business jet configuration, the reconstructed noise distribution does not provide sufficiently strong spatial cues to enable a clear localisation of noise variations.

5.3 Regional turboprop case study

The regional turboprop configuration shows a slightly more pronounced spatial perception than the business jet case. Participants reported greater ability to identify variations in noise levels across different cabin positions, with some noting a more noticeable spatial pattern. In particular, responses related to the perception of spatial differences show a marginally higher consistency, and qualitative feedback suggests that variations are more easily detectable.
This behaviour can be associated with the spatial distribution of the acoustic field, which, as shown in the numerical analysis, presents a more distinct variation along the cabin, with increased levels in the central region. The presence of such gradients, even if moderate, appears to enhance the perceptual salience of spatial differences. Moreover, this behaviour can be partially attributed to the presence of additional localized noise sources, such as the air conditioning outlets, which introduce spatial variations in the sound field and enhance perceptual differences during movement.
However, it is important to note that the perception remains variable across participants, highlighting that the spatial cues are still relatively weak and not uniformly perceived.

5.4 Comparative analysis

A comparison between the two configurations highlights differences in the perception of the acoustic field's spatial characteristics. While both scenarios achieve a high level of perceived realism, the regional turboprop configuration shows a slight improvement in spatial perception, as indicated by both quantitative scores and qualitative feedback. In contrast, the business jet configuration is associated with a more uniform perceived sound field and weaker spatial cues.
A quantitative comparison of the spatial perception metrics is reported in Tab. 2. In addition, the ability to identify the position of the dominant noise source was evaluated as the percentage of positive responses, showing a higher localisation capability for the regional configuration. Fig. 4 provides a visual comparison of the spatial perception indicators, highlighting the higher variability and generally lower scores observed in the business jet configuration. This difference is consistent with the

underlying physical behaviour of the two systems. In the regional aircraft, the presence of additional localised noise sources, such as air conditioning outlets, increases the spatial variability of the sound field. Some participants reported that these variations were particularly noticeable when changing cabin height, suggesting the presence of vertical gradients. Conversely, the business jet configuration exhibits a more homogeneous acoustic field, resulting in weaker and less consistent spatial cues.
The localisation of the dominant noise source was also analysed. Results indicate a higher percentage of correct or partial localisation in the regional configuration, whereas in the business jet case, the localisation was often uncertain. Participants who reported being unable to identify the source location were excluded from the analysis in Tab. 2, leaving only perceptually meaningful responses. This corresponds to approximately 40% of the responses in the business jet case and about 25% in the regional configuration. It should also be noted that localisation performance may be partially influenced by participants' prior knowledge of aircraft configurations, as the sample consisted mainly of individuals with backgrounds in aerospace and mechanical engineering. Qualitative comments from participants were consistent with the quantitative trends, reinforcing the interpretation of the results.

Table 2 – Comparison of spatial perception metrics and localisation results between business jet and regional turboprop configurations.

Metric	Statistic	Business Jet	Regional Turboprop
Q6: Spatial variation	Mean	3.10	3.40
	Std. Dev.	1.30	1.40
Q7: Zone differences	Mean	3.00	3.45
	Std. Dev.	1.25	1.35
Q8: Source localisation (% positive)		15%	35%
Q9: Loudest zone (%)[a,b]	Centre	25%	55%
	Rear	50%	20%
	Front	25%	25%

[a] Participants unable to identify the source location (approximately 40% in the business jet and 25% in the regional configuration) were excluded from the localisation analysis.
[b] In the business jet configuration, the engines are located at the rear of the cabin, whereas in the regional turboprop, they are approximately in the central cabin region.

6. Conclusions

This work presented the development and preliminary validation of an aural digital twin framework for the immersive reproduction of aircraft cabin noise within an XR environment.
The main findings can be summarised as follows:

- The overall acoustic and visual realism of the experience is rated positively, confirming the capability of the proposed framework to reproduce the general characteristics of the cabin environment.
- The perception of spatial variations of the acoustic field is limited, with moderate mean values and high variability across participants.
- The business jet configuration exhibits a largely uniform perceived sound field, resulting in weak and inconsistent spatial cues.
- The regional turboprop configuration shows a slightly improved spatial perception, attributable to a more non-uniform acoustic field and the presence of additional localised sound sources.
- The localisation of the dominant noise source remains uncertain in many cases, indicating that the current spatial resolution is insufficient for robust perceptual discrimination.

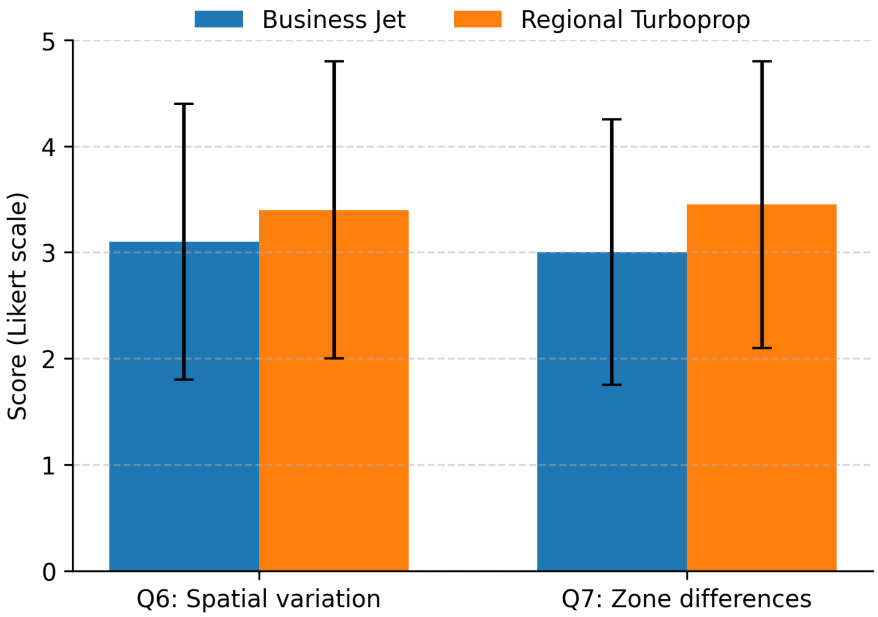


Figure 4 – Comparison of spatial perception metrics between business jet and regional turboprop configurations. Error bars represent standard deviation.

Overall, while the aural digital twin approach effectively reproduces global acoustic features, the spatial rendering obtained through impulse-response-based reconstruction does not provide sufficiently strong cues for reliable spatial perception.
Future developments will focus on improving the spatial fidelity of the acoustic rendering. Alternative strategies may include integrating calibrated sound fields, hybrid modelling approaches, and advanced spatial audio techniques to enhance perceptual cues. In addition, the inclusion of more realistic, distributed noise sources, along with user-dependent calibration procedures, is expected to improve overall spatial perception. Further experimental campaigns with a larger number of participants will also be conducted to strengthen the statistical validity of the results and better assess the link between numerical predictions and perceptual outcomes.

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