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Rethinking Acoustic Design for Immersive Educational Simulation Halls: A Perspective on Control, Clarity, and Low-Frequency Risk

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Abstract

Immersive educational environments are increasingly used to support simulation-based learning, spatial visualization, and multisensory engagement. Yet the acoustic design of such spaces is often treated as a secondary technical layer rather than as a central determinant of intelligibility, realism, and cognitive comfort. This perspective argues that immersive simulation halls should be conceived as controlled acoustic ecosystems in which reverberation management, reflection control, and low-frequency stability are integrated from the earliest design stages. Drawing on a previously modeled educational wall-mapping hall with approximate dimensions of 30.48 m × 17.50 m, a volume of about 3191.8 m³, and a highly absorptive treatment concept, the paper discusses how very low reverberation can improve narration and localization while also introducing perceptual trade-offs related to spatial impression. The discussion further highlights the persistent challenge of room modes, which remain significant even when mid- and high-frequency absorption is strong. Rather than treating speech clarity, immersive playback, and architectural treatment as separate objectives, this paper proposes a unified conceptual framework for simulation halls in education.

1. Introduction

Immersive simulation spaces are becoming increasingly important in advanced education, especially in settings where projection, mapped content, interactive instruction, and multisensory learning must coexist in a single architectural environment. In such spaces, acoustics cannot be reduced to a late-stage finishing concern. Instead, acoustic behavior directly affects narration clarity, source localization, listener fatigue, and the perceived coherence of the simulated environment.

Conventional teaching rooms may tolerate moderate reverberation or limited reflection control. Immersive halls cannot. They rely on accurate spatial cues, stable speech transmission, and controlled reflection patterns across a large listening area. For this reason, immersive educational design should be

approached not as a simple extension of auditorium acoustics, but as a distinct category of controlled listening architecture.

2. From Room Treatment to Acoustic Intent

The present perspective builds on a previously developed acoustic hall study for an educational wall-mapping environment. In that study, the modeled room had approximate dimensions of 30.48 m in length and 17.50 m in width, with a minimum height of 2.80 m, a maximum vault height of 7.34 m, and an overall volume near 3191.8 m^3. Under a highly absorptive treatment concept using ceiling and wall panels together with a carpeted floor, the mid-band reverberation time was estimated at approximately RT60 ≈ 0.33 s, while critical distance and clarity indicators suggested strong speech-supporting conditions (Sabine, 1922; Eyring, 1930).

Parameter	Indicative value	Interpretive meaning
Volume	3191.8 m^3	Large immersive educational enclosure
Mid-band RT60	≈ 0.33 s	Very controlled for speech-focused use
Critical distance (Q=2)	≈ 7.9 m	Strong direct sound support
D50 proxy	≈ 87.5%	High conceptual speech clarity
Dominant challenge	LF modes	Requires source layout and tuning

Table 1. Design values abstracted from the technical hall study

These values matter not only as engineering outputs but also as conceptual indicators. They reveal a broader principle: immersive educational halls must be designed around acoustic intent. In such environments, the target is not merely compliance with a generic benchmark, but the creation of a perceptually controlled field where speech, simulation audio, and enclosure geometry work together.

Figure 1. Conceptual acoustic layers for immersive educational simulation halls

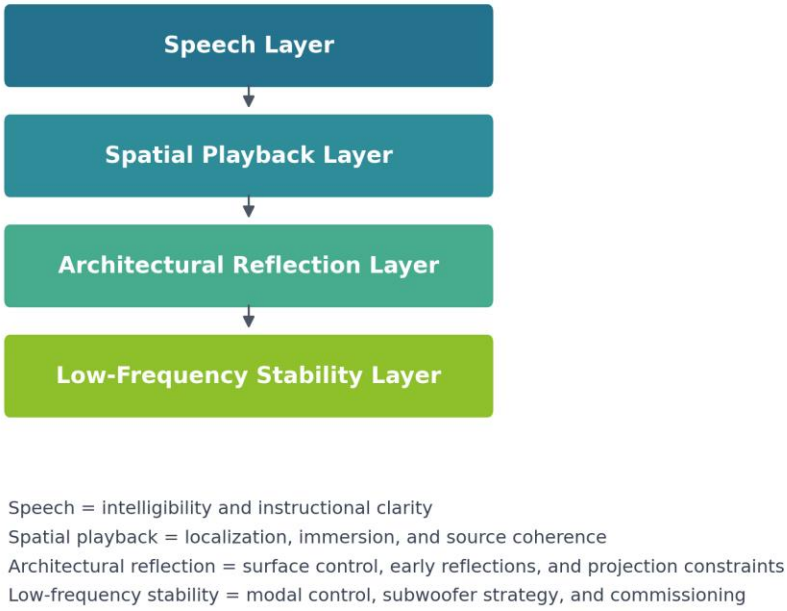

Figure 1. Conceptual acoustic layers for immersive educational simulation halls

3. Core Equations and Why They Matter

Even in a perspective paper, a small set of canonical equations helps clarify the logic of design decisions. The equations below do not reduce immersive acoustics to mathematics alone; rather, they frame the variables that govern reverberation, distance effects, and room-mode risk in large educational halls.

Eq. 1 $RT60 = 0.161\ V / A$

Sabine reverberation model used for early design comparison (Sabine, 1922).

Eq. 2 $RT60 = 0.161\ V / (-S \ln(1 - \bar{\alpha}))$

Eyring check for high-absorption conditions (Eyring, 1930).

Eq. 3 $D_c \approx 0.057 \sqrt{(Q\ V / RT60)}$

Approximate critical-distance relation linking directivity, volume, and decay.

Eq. 4 $f_n = (c / 2) \cdot (n / d)$

Axial-mode estimate for low-frequency planning in one room dimension.

Taken together, these relations explain why immersive educational halls often achieve excellent mid- and high-frequency clarity while still struggling with low-frequency non-uniformity. The variables are different, and therefore the solutions must also be different.

4. The Benefits and Limits of Very Dry Acoustic Design

The hall concept indicates that strong absorption can rapidly transform a large room into a speech-dominant environment. This creates three immediate gains: clearer narration, improved localization, and lower flutter-echo risk. Such outcomes are directly aligned with the objectives of room-acoustic control and intelligibility verification commonly discussed in ISO 3382-1 and IEC 60268-16 (ISO 3382-1, 2009; IEC 60268-16).

At the same time, extreme dryness may impose a perceptual cost. A hall with very low reverberation can feel acoustically smaller than its geometry suggests. This may be advantageous for instruction and dialogue, but not always ideal for experiential immersion. The design challenge is therefore not to maximize absorption everywhere, but to identify an intentional balance between clarity and perceived envelopment.

Figure 2. Conceptual trade-off between room control and immersive spaciousness

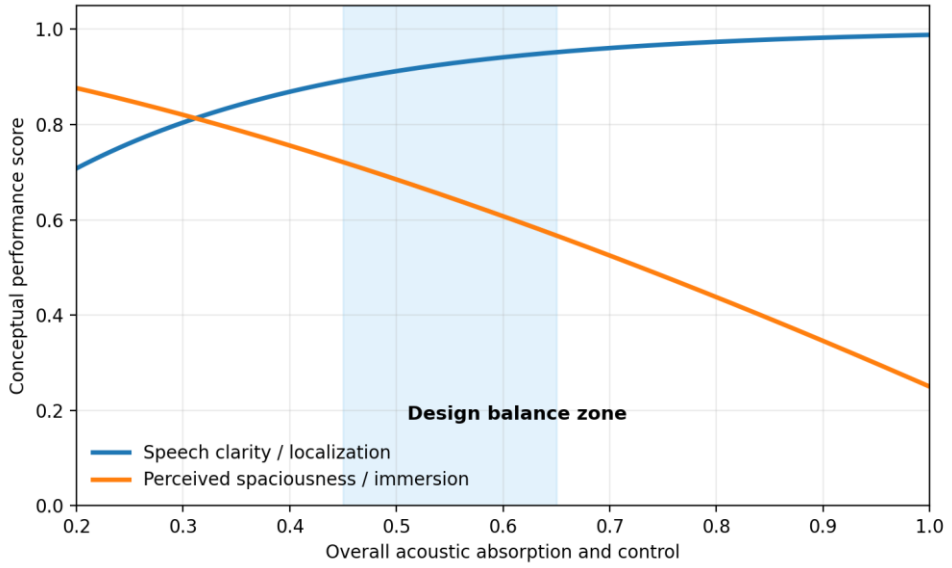

Figure 2. Conceptual trade-off between acoustic control and immersive spaciousness

5. Why Low-Frequency Behavior Still Dominates

A key lesson from the source hall study is that strong wall and ceiling absorption does not eliminate the low-frequency problem. In fact, modal estimates below approximately 125 Hz remain significant even when the room is highly controlled at mid and high frequencies. This is why immersive spaces can sound simultaneously clear and unstable: one part of the spectrum is well controlled while another remains strongly governed by geometry.

For simulation halls, low-frequency unevenness may cause seat-to-seat bass variation, loss of realism in media playback, and localized build-up or cancellation near listeners. Accordingly, immersive acoustic design should include a dedicated low-frequency strategy from the beginning, including loudspeaker placement logic, subwoofer distribution, and measurement-based commissioning.

Figure 3. Why low-frequency risk persists even in highly absorptive immersive halls

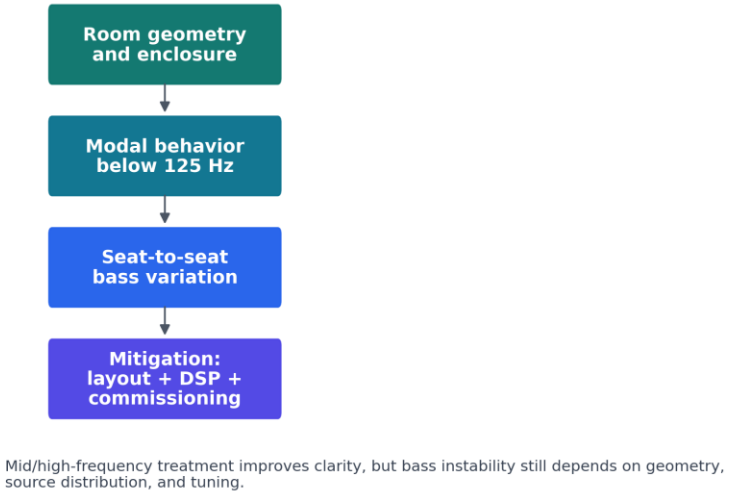

Figure 3. Why low-frequency risk persists in highly absorptive immersive halls

6. Projection Surfaces, Reflection Management, and Architectural Trade-Offs

Immersive wall-mapping environments introduce an additional complication: some surfaces must remain visually effective for projection. That requirement can conflict with straightforward acoustic absorption. When projection zones remain hard and untreated, first reflections and flutter paths may be reintroduced, especially at side boundaries or rigid end surfaces. This means the design problem cannot be solved through blanket absorption alone.

A more realistic strategy is selective control: angled absorption strips, microperforated treatments, localized baffles outside the projection field, and careful continuity of coverage at acoustically sensitive boundaries. In practice, the most successful immersive halls are often those that treat visual and acoustic performance as co-dependent rather than competing systems.

7. Educational Implications

The educational significance of this perspective is straightforward. Acoustics in immersive halls is not merely a comfort variable; it is part of the learning infrastructure itself. When speech is clearer, spatial cues are more stable, and reverberation is appropriately controlled, learners are better able to follow narrated content, interpret audiovisual signals, and sustain attention without perceptual distraction.

This means immersive acoustics belongs not only to engineering, but also to pedagogy, cognition, and human-centered design. In advanced simulation environments, acoustic strategy influences how content is understood, not merely how it is heard.

8. Conclusion

Immersive educational simulation halls require a new acoustic mindset. They should not be treated as ordinary auditoria with projection equipment, nor as purely visual environments with incidental sound reinforcement. Rather, they should be designed as acoustically intentional spaces where speech clarity,

immersive playback, architectural form, and low-frequency control are considered together from the outset.

The hall concept underlying this paper demonstrates that strong absorptive treatment can create excellent conditions for narration and reflection control, but also confirms that low-frequency modal risk remains a defining challenge. The design lesson is clear: immersive educational acoustics must move from reactive treatment toward conceptual integration. That is where acoustic realism and pedagogical performance begin.

References

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Author's note. This perspective paper conceptually reframes a prior ENOSH acoustic hall study into a journal-ready article while preserving the key design values, equations, and references that informed the underlying analysis.