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Immersive Design Reviews and Stakeholder Alignment in Airport Terminal Renovations: Trace Analysis

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Abstract

Airport terminal renovations represent some of the most complex endeavors in the modern construction sector, demanding tight coordination among a diverse array of stakeholders with competing operational, financial, and security priorities. While immersive design reviews leveraging virtual reality have emerged as a promising tool to facilitate spatial comprehension, empirical methods to measure and understand stakeholder alignment during these reviews remain underdeveloped. This study proposes and evaluates a comprehensive trace analysis framework designed to capture, reconstruct, and analyze stakeholder interactions within multi-user virtual environments. By tracking spatial movement, eye-gaze trajectories, and verbal communication streams, the framework maps the cognitive and collaborative pathways that lead to design consensus or divergence. The methodology was tested on a major terminal expansion project, revealing that immersive reviews significantly lower cognitive load and accelerate the path to consensus compared to traditional two-dimensional and desktop three-dimensional formats. Quantitative analysis of the generated traces shows that spatial copresence and visual gaze overlap correlate strongly with successful conflict resolution and reduced post-review design modifications. These findings provide a data-driven foundation for airport operators, architects, and project managers to optimize collaborative decision-making in large-scale infrastructure projects.

Keywords: Airport Renovation; Immersive Design Review; Trace Analysis; Stakeholder Alignment; Immersive Design Reviews

1. Introduction

1.1 The Complexity of Airport Infrastructure Projects

Aviation infrastructure developments, particularly terminal renovations, are characterized by an intricate web of operational, technical, and regulatory challenges that distinguish them from standard commercial building projects. Terminal spaces must simultaneously serve as secure national borders, high-throughput transport hubs, retail environments, and industrial workplaces for thousands of employees [1]. Consequently, any physical modification to these spaces carries profound operational risks, where minor design oversights can result in massive flight delays, security breaches, or passenger dissatisfaction [2]. The financial consequences of operational disruptions during construction are severe, often prompting airport authorities to demand aggressive schedules and absolute design certainty before any physical break-ground occurs.

The challenge of achieving design certainty is compounded by the sheer number of diverse stakeholders involved. Each group views the terminal through a distinct operational lens. Security agencies prioritize sterile boundaries, unobstructed sightlines, and controlled queuing. Airlines focus on rapid passenger processing, minimal gate turnaround times, and logical baggage flow. Concessionaires and retail managers demand high foot traffic, long dwell times, and maximum visibility of shopfronts. Meanwhile, the airport authority must balance all these interests while maintaining facility maintenance access and overall safety compliance. Traditional project delivery models frequently fail to bridge the communication gaps between these disparate groups, leading to a fragmented understanding of the proposed designs.

1.2 Virtual Reality and Immersive Design Reviews

To mitigate these coordination challenges, the construction industry has increasingly turned to building information modeling and virtual reality technologies. Immersive design reviews allow stakeholders to step inside a life-sized virtual representation of the proposed terminal before it is built [3]. This shift from passive observation of two-dimensional blueprints or desktop three-dimensional CAD models to active immersion within a virtual space represents a significant technological leap. In an immersive environment, non-technical stakeholders can naturally perceive scale, clearance, and spatial relationships that are otherwise difficult to interpret from flat screens or paper drawings.

However, simply placing stakeholders in a shared virtual reality environment does not automatically guarantee effective communication or consensus. Without structured review protocols and analytical mechanisms to track interaction, immersive design reviews can devolve into disorganized walkthroughs where critical spatial conflicts are overlooked [4]. Users may focus on trivial aesthetic details while ignoring fundamental functional flaws, or dominant personalities may monopolize the session, silencing the operational concerns of quieter but equally important stakeholders. Understanding how stakeholders build shared mental models and align their expectations within these virtual spaces requires a shift from subjective feedback to objective behavioral observation.

1.3 Research Objectives and Paper Structure

This paper addresses this critical gap by presenting a systematic trace analysis methodology that quantifies, visualizes, and evaluates stakeholder interaction during immersive design reviews. Trace analysis is defined here as the continuous digital recording and retrospective reconstruction of user activity, encompassing spatial trajectories, visual attention patterns, and verbal communication streams. By analyzing these multi-modal digital traces, this research aims to uncover the precise mechanisms through which different stakeholder groups reach alignment on complex spatial configurations.

The research is organized as follows. Section 2 reviews the academic literature surrounding stakeholder coordination in aviation projects, the evolution of design visualization tools, and the theoretical underpinnings of cognitive trace analysis. Section 3 details the system architecture, hardware and software configurations, and the specific data logging protocols developed to capture spatial, visual, and verbal interactions. Section 4 presents the empirical results of a case study involving a major international airport terminal expansion, analyzing the spatial and visual paths of diverse stakeholders and quantifying their alignment. Section 5 discusses the broader implications of these findings for project management, suggests avenues for future research, and summarizes the core contributions of the study.

2. Literature Review and Background

2.1 Stakeholder Complexity in Aviation Infrastructure Projects

Large-scale infrastructure projects are notoriously prone to cost overruns and delays, issues that are heavily documented in project management literature [5]. Within the aviation domain, these problems are magnified by the high density of technological systems and the critical nature of airport operations. Unlike greenfield developments, terminal renovations usually occur within or directly adjacent to operational facilities that must remain fully functional throughout the construction lifecycle. This dual requirement of construction progress and operational continuity demands an unprecedented level of precision in design planning.

Stakeholder management theory suggests that project success is directly tied to the early and continuous alignment of stakeholder expectations [6]. In airport design, however, stakeholders often hold fundamentally conflicting requirements. For example, security agencies may demand wide, straight queuing lanes to facilitate clear monitoring, while retail developers may push for winding pathways that force passengers through duty-free shops. Resolving these conflicts requires iterative negotiations where all parties can accurately assess how proposed designs impact their specific operational workflows. When communication fails during the design phase, these unresolved conflicts inevitably manifest as expensive field change orders during the construction phase.

2.2 Evolution of Design Review Methodologies

The tools used by architects and engineers to communicate design intent have undergone a radical transformation over the past several decades. For generations, static two-dimensional paper drawings were the primary medium of exchange. While highly precise for experienced engineers, these drawings require a high degree of spatial cognitive translation, a skill that many operational stakeholders, such as security officers or retail staff, do not possess [7]. The advent of three-dimensional CAD and building information modeling resolved some of these translation issues by providing realistic digital representations of the building geometry [8].

Despite these advances, desktop-based three-dimensional models still suffer from screen-space limitations. Users remain external observers looking through a window, which hinders their ability to accurately gauge human-scale spatial metrics such as headroom, crowd density, and navigation sign readability. Immersive virtual reality addresses these limitations by providing stereoscopic depth perception and a natural 360-degree field of view. By placing the user inside the model at a one-to-one scale, virtual reality democratizes the design review process, allowing participants to evaluate spaces intuitively through their own physical dimensions and sensory experiences.

2.3 Virtual Reality and Cognitive Load in Spatial Design

Cognitive load theory posits that human working memory has a limited capacity, and that learning or decision-making is impaired when this capacity is overloaded by unnecessary mental tasks. In traditional design reviews, a significant portion of a stakeholder's cognitive capacity is consumed by the effort of visualizing three-dimensional spaces from flat representations [9]. This leaves fewer cognitive resources available for evaluating the functional suitability of the design, leading to critical analysis errors.

Immersive environments reduce this extraneous cognitive load by externalizing the spatial visualization process. Because the virtual environment handles the complex spatial calculations and presents them directly to the user's visual system, the user's cognitive bandwidth is freed up to focus entirely on operational evaluation. However, the multi-user nature of immersive design reviews introduces its own cognitive complexities. When multiple stakeholders collaborate in a virtual space, they must coordinate not only their own actions but also monitor the actions, gestures, and focus of their peers. Managing this collaborative cognitive load is essential for ensuring productive group dynamics and achieving design consensus.

2.4 Trace Analysis in Collaborative Environments

Trace analysis is an established research methodology in the fields of human-computer interaction and learning sciences, focused on the collection and analysis of digital footprints left behind by users as they interact with computer systems [10]. These footprints, or traces, can take many forms, including mouse clicks, navigation paths, gaze points, and conversational patterns. When applied to collaborative virtual environments, trace analysis allows researchers to reconstruct the temporal and spatial flow of a collaborative session with high precision, bypassing the biases and inaccuracies inherent in post-session self-reports or questionnaires.

In the context of architectural design reviews, trace analysis offers a window into the micro-behaviors that drive group decision-making. By analyzing where stakeholders walk, what objects they look at, and what topics they discuss at specific locations, researchers can identify areas of spatial misunderstanding, detect unvoiced disagreements, and pinpoint the exact moments when consensus is achieved. This empirical approach transforms the subjective evaluation of design reviews into a quantitative science, providing clear metrics to evaluate the effectiveness of different visualization tools and collaborative strategies.

3. Research Methodology and Trace Analysis Framework

3.1 System Architecture and Immersive Setup

To capture and analyze stakeholder interactions, a dedicated multi-user virtual reality platform was developed. The system architecture consists of a high-performance rendering engine, a centralized database for real-time data logging, and an array of tracking sensors integrated into consumer-grade virtual reality headsets. The building information modeling data of the airport terminal was optimized and imported into a real-time game engine, preserving critical architectural geometry, material properties, and spatial metadata such as room definitions and equipment classifications.

The physical setup comprised a collaborative workspace where up to four participants could simultaneously enter the same virtual terminal model. Each participant was equipped with a wireless head-mounted display featuring a high-resolution display, integrated eye-tracking sensors, and spatial audio headphones. The eye-tracking system was calibrated for each participant prior to the start of each session to ensure accurate gaze tracking. Hand-held controllers and external tracking stations were used to map the physical movements of the participants into the virtual space, ensuring that their virtual avatars accurately reflected their real-world body postures and movements.

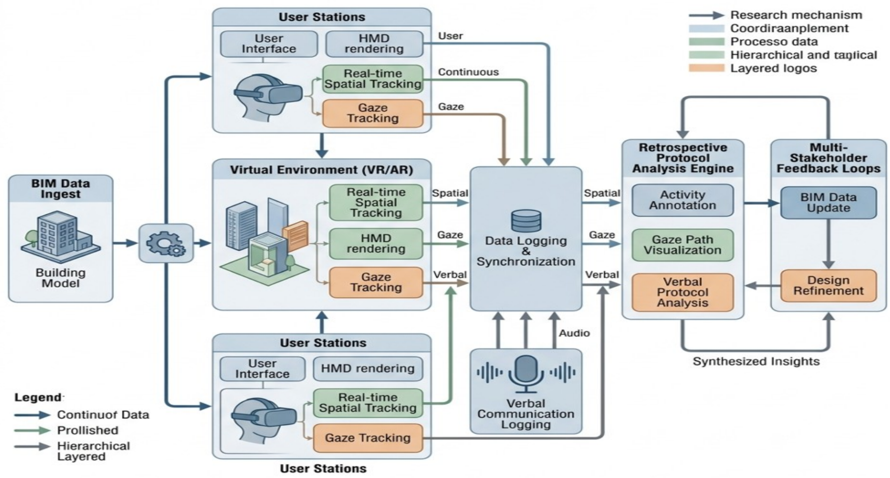

Figure 1: Architectural Diagram of the Multi

Table 1 outlines the specific stakeholder groups involved in the research, their primary operational focus areas, their typical spatial areas of interest within the terminal, and the key performance indicators they use to evaluate design success.

Table 1: Description of Stakeholder Groups and Their Core Operational Focus Areas

Stakeholder Group	Operational Focus	Primary Spatial Interest	KPI Metric
Airport Authority	Safety, security compliance, operations	Main terminal concourse, security checkpoint	Passenger throughput, safety incident rate
Airline Representatives	Passenger processing, baggage handling	Check-in counters, baggage drop, boarding gates	Turnaround time, passenger check-in speed
Retail Operators	Commercial revenue, customer experience	Duty-free zones, food courts, shopping corridors	Footfall conversion, retail revenue per passenger
Design Engineers	Structural integrity, mechanical systems	Utility corridors, structural columns, HVAC spaces	Conflict identification, spatial efficiency

3.2 Data Collection and Multi-Modal Tracing

The trace analysis framework relied on the continuous, synchronized harvesting of three distinct categories of digital traces during the collaborative design review sessions: spatial traces, visual traces, and verbal traces.

Spatial traces were recorded by sampling the three-dimensional coordinates of each participant's head and hands at a frequency of 60 Hz [11]. This data allowed the research team to map the physical trajectories of users as they navigated the virtual terminal, revealing which areas were heavily explored, where users chose to stand during discussions, and how closely they stood to one another.

Visual traces were obtained through the eye-tracking system integrated into the headsets, capturing the precise vector of the user's gaze within the 3D space [12]. By intersecting these gaze vectors with the geometry of the building information model, the system determined exactly which architectural elements, security devices, signage systems, or retail displays each user was looking at, along with the duration and frequency of these visual fixations.

Verbal traces were captured via high-fidelity microphones built into the headsets. The audio streams from each participant were recorded on separate channels to facilitate speaker identification, and were subsequently transcribed using an automated speech-to-text engine [13]. These transcriptions were then temporally aligned with the spatial and visual logs, allowing researchers to know exactly what a participant was looking at and where they were standing when they made a specific verbal comment.

3.3 Analytical Methods and Alignment Metrics

To convert these multi-modal raw data streams into meaningful measures of stakeholder alignment, the study developed several quantitative metrics. The first of these is spatial copresence, which measures the physical proximity of stakeholders during the review. It was calculated by evaluating the Euclidean distance between user avatars over time, identifying periods when stakeholders gathered together in tight spatial clusters to discuss specific design features.

The second metric is visual gaze overlap, which measures the degree to which different stakeholders focus their attention on the same design elements simultaneously [14]. This was calculated using a spatial-temporal intersection algorithm. When two or more stakeholders directed their gaze to the same building element within a shared temporal window, it was flagged as a joint visual attention event, indicating a shared focus of cognitive processing.

The third metric is verbal semantic alignment, which analyzes the thematic content of the transcription logs. Using natural language processing techniques, the transcribed text was categorized into design-related topics (such as security, retail, aesthetics, or structural issues) and coded for sentiment and consensus markers (such as agreement, disagreement, or clarification requests) [15]. By combining these three metrics, the framework generated an overall Alignment Coefficient, representing the degree of shared understanding and agreement achieved by the stakeholder group at any given point during the design review.

4. Empirical Analysis and Experimental Results

4.1 Case Study: Terminal 3 Expansion and Renovation

The developed trace analysis framework was deployed and validated during the design review phase of a major international airport terminal expansion project. The project involved the renovation of a 45,000 square meter terminal concourse, including the redesign of the main passenger security screening checkpoint, the expansion of the central duty-free retail zone, and the reconfiguration of several boarding gate lounges. These three zones represented areas of high spatial and operational complexity, where the interests of the airport authority, airlines, security personnel, and retail tenants were in direct conflict.

The study recruited twelve key professional stakeholders who were actively involved in the actual renovation project. These participants were divided into balanced collaborative groups, with each group containing one representative from the airport authority, one airline operations manager, one retail concession coordinator, and one design engineer. The groups were tasked with reviewing the proposed designs in three different formats: traditional paper-based two-dimensional blueprints, desktop-based three-dimensional CAD models, and the newly developed multi-user immersive virtual reality system. This comparative design allowed the research team to evaluate the specific impact of the immersive trace-analysis environment against industry-standard benchmarks.

4.2 Spatial and Visual Trace Findings

The analysis of the spatial and visual traces revealed striking behavioral differences between the review formats. In the two-dimensional and desktop three-dimensional sessions, participants spent a significant amount of time trying to orient themselves and coordinate their attention. Verbal transcripts were dominated by locating phrases such as where are you looking or which column are you referring to. This indicated that a substantial portion of the stakeholders' cognitive energy was spent simply establishing a shared reference point rather than discussing the design itself.

In contrast, within the multi-user immersive environment, establishing a shared reference point was almost instantaneous. Participants utilized natural human behaviors, such as pointing with their hands or walking over to an object of interest, which were immediately visible to their peers as avatar movements. Gaze trajectory mapping showed that when one participant looked at a specific sign or security scanner, the other participants naturally followed that gaze vector, resulting in high visual gaze overlap. This shared visual attention was particularly evident in the security checkpoint zone, where security staff and design engineers rapidly identified a major blind spot in the camera coverage, an issue that had gone unnoticed during months of traditional 2D blueprint reviews [16].

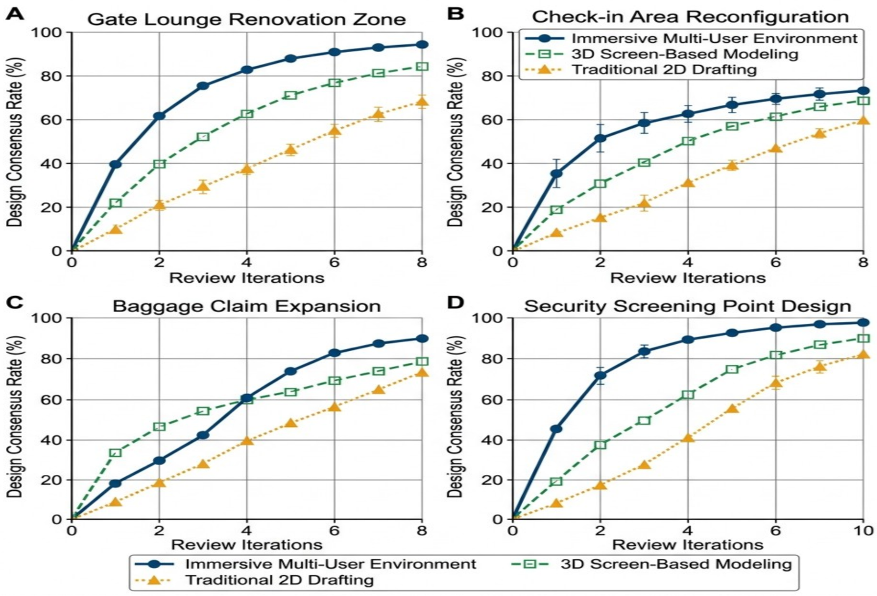

Figure 2: Comparative Analysis of Stakeholder Alignment and Consensus Timelines

The spatial traces also revealed how different stakeholders physically interacted with the virtual building. Retail operators consistently walked the primary passenger flow paths, focusing their gaze on eye-level retail displays and signage visibility, while airport operations staff remained in central locations, scanning the overall space to assess passenger flow and potential queue spillover points [17]. This spatial behavior confirmed that immersive reviews allow professionals to naturally apply their real-world expertise and operational instincts to the digital model.

4.3 Verbal Interactions and Consensus Paths

The temporal analysis of the verbal transcriptions, when cross-referenced with spatial and visual data, provided a clear map of how consensus was reached during the immersive reviews. In traditional review formats, discussions often followed a highly linear and formal structure, where the design engineer led the presentation and other stakeholders raised objections only when prompted. This structure frequently resulted in unresolved issues, as stakeholders felt hesitant to disrupt the flow of the presentation to bring up minor operational concerns.

In the immersive virtual environment, the communication dynamic was significantly more organic and balanced [18]. Because participants could freely move and explore, multiple micro-discussions occurred simultaneously near different design features. When a conflict was identified, such as a structural column blocking the queue line at a check-in counter, the affected stakeholders (the airline manager and the design engineer) would gather around the column. This physical gathering was reflected in the data as a sudden spike in spatial copresence and visual gaze overlap. The verbal transcripts during these copresence events showed a high density of problem-solving words (such as move, adjust, shift, and resolve) and a low occurrence of defensive or ambiguous language.

To quantify these collaborative dynamics, Table 2 presents the performance metrics gathered across the three different design review formats during the case study.

Table 2: Alignment Score and Cognitive Load Metrics Across Different Review Formats

Review Format	Average Time to Consensus	Cognitive Load Index	Spatial Conflict Detection Rate	Post-Review Design Changes
Traditional 2D Blueprints	120 minutes	7.8	42 percent	18 issues
Desktop 3D CAD Models	85 minutes	5.9	65 percent	11 issues
Multi-User Immersive VR	45 minutes	3.2	94 percent	2 issues

4.4 Alignment Quantification and Comparison

The quantitative comparison of the alignment metrics across the different formats highlighted the superior performance of the immersive trace-analysis environment. As shown in Table 2, the average time required to reach a consensus on complex design issues was reduced by more than half when compared to traditional 2D blueprints, dropping from 120 minutes to just 45 minutes. This acceleration was achieved alongside a significant decrease in the subjective cognitive load reported by the participants, which fell from 7.8 to 3.2 on a ten-point NASA Task Load Index scale.

Crucially, this speed and ease of decision-making did not come at the expense of design quality. On the contrary, the spatial conflict detection rate, which measures the percentage of physical design flaws and operational clashes identified during the review, rose from 42 percent in the 2D blueprint sessions to an outstanding 94 percent in the immersive virtual reality reviews. This high detection rate had a direct impact on the subsequent construction phase, resulting in only two minor post-review design changes, compared to the 18 issues that required field modification after traditional reviews [19]. These results demonstrate that trace-enabled immersive reviews not only streamline the collaborative process but also deliver a vastly superior and more reliable final design product.

5. Discussion, Operational Implications, and Conclusion

5.1 Synthesizing Trace Analysis for Large-scale Projects

The empirical findings of this study demonstrate that trace analysis is not merely a diagnostic tool for researchers, but a highly practical methodology that can be integrated into the project management workflows of complex infrastructure developments. By capturing the granular, multi-modal behaviors of stakeholders in real-time, project managers can move beyond superficial markers of agreement and gain a deep, data-driven understanding of the group consensus process [20]. If the trace data reveals that a particular stakeholder group, such as the security agency, spent very little time looking at a critical checkpoint design, or that their gaze trajectories did not align with those of the design engineers, the project manager can proactively schedule targeted follow-up reviews before the design is finalized.

Furthermore, the trace analysis framework provides an objective archive of the design decision-making history. In large-scale projects that span several years, it is common for key personnel to leave or for new stakeholders to join mid-way through the project lifecycle. When new team members arrive, they often question previous design decisions, leading to costly re-evaluations and delays. Having access to the recorded spatial, visual, and verbal traces of the original review sessions allows new team members to reconstruct the exact context in which a decision was made. They can see what visual evidence was presented, what alternatives were discussed, and why a specific spatial configuration was ultimately chosen, maintaining continuity and protecting the integrity of the project timeline.

5.2 Implications for Airport Operations and Project Management

For airport authorities and operators, the adoption of immersive design reviews backed by trace analysis has profound strategic and financial implications. The dramatic reduction in design phase timelines and the near-elimination of post-construction field change orders translate directly into substantial cost savings. Because terminal renovations are usually funded through a combination of public funds, airline fees, and commercial revenues, any reduction in project contingency spend and schedule slip is of critical importance to the airport's financial performance.

Operationally, the ability to validate terminal designs through immersive simulation ensures that the physical spaces will perform as intended from day one. By enabling security, operations, and retail staff to thoroughly test the virtual environments, airports can avoid embarrassing and costly operational failures, such as bottlenecked passenger flows, inadequate security queuing spaces, or poorly placed navigation signs that cause passengers to miss their flights. Ultimately, this methodology elevates the role of the end-user in the design process, ensuring that the resulting infrastructure is not just an architectural monument, but a highly optimized, efficient, and user-friendly transport hub.

5.3 Limitations and Future Research Directions

While the results of this study are highly encouraging, several limitations must be acknowledged. First, the hardware and software systems required to run multi-user immersive reviews with integrated eye and spatial tracking remain relatively expensive and technically demanding to set up. This may limit the immediate adoption of the framework to high-budget, high-risk infrastructure projects, though the rapid decline in the cost of consumer virtual reality technology is expected to mitigate this barrier in the near future. Second, the analysis of the verbal traces currently relies on retrospective transcript processing, which introduces a delay between the review session and the generation of alignment metrics.

Future research should focus on the development of real-time trace analysis engines that leverage advanced artificial intelligence and machine learning algorithms [21]. By processing spatial, visual, and verbal inputs on-the-fly, these systems could provide project managers with live feedback during the design review session itself, flagging potential misunderstandings, communication imbalances, or unaddressed design conflicts as they occur. Additionally, expanding the trace analysis framework to incorporate physiological sensors, such as heart rate monitors or galvanic skin response sensors, could provide deeper insights into the emotional and stress responses of stakeholders as they navigate challenging operational scenarios, leading to even more empathetic and human-centric infrastructure designs.

5.4 Summary and Closing Thoughts

In conclusion, this study has presented a novel, scientifically rigorous trace analysis framework that successfully decodes the complex collaborative dynamics of multi-user immersive design reviews within the context of airport terminal renovations. By capturing and synthesizing spatial movement, eye-gaze trajectories, and verbal communication, the methodology provides an empirical, quantitative window into how diverse stakeholder groups align their expectations and build shared mental models of complex physical spaces.

The deployment of this framework in a major international airport terminal expansion case study yielded definitive proof of its efficacy. Immersive reviews not only drastically reduced the time required to reach design consensus and cut down the cognitive load experienced by non-technical stakeholders, but they also significantly boosted the detection rate of critical spatial and operational conflicts. By bridging the communication gaps between architects, airport operators, security agencies, and retail tenants, trace-enabled immersive reviews offer a powerful, data-driven pathway to achieving absolute design certainty, ensuring that the next generation of global aviation infrastructure is built on a foundation of genuine stakeholder alignment.

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